Phytolith and starch research in the Australian-Pacific-Asian regions: the state of the art

Papers from a conference held at The Australian National University, August 2001, Canberra, Australia

D.M. Hart and L.A. Wallis
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Terra Australis reports the results of archaeological and related research within the south and east of Asia, though mainly Australia, New Guinea and island Melanesia — lands that remained terra australis incognita to generations of prehistorians. Its subject is the settlement of the diverse environments in this isolated quarter of the globe by peoples who have maintained their discrete and traditional ways of life into the recent recorded or remembered past and at times into the observable present.

Since the beginning of the series, the basic colour on the spine and cover has distinguished the regional distribution of topics as follows: ochre for Australia, green for New Guinea, red for South-East Asia and blue for the Pacific Islands. From 2001, issues with a gold spine will include conference proceedings, edited papers and monographs which in topic or desired format do not fit easily within the original arrangements. All volumes are numbered within the same series.

List of volumes in Terra Australis

Volume 2: Ol Tumbuna: archaeological excavations in the eastern central Highlands, Papua New Guinea. J.P. White (1972)
Volume 4: Recent Prehistory in Southeast Papua. B. Egloff (1979)
Volume 10: The Emergence of Mailu. G. Irwin (1985)
Volume 14: 30,000 Years of Aboriginal Occupation: Kimberley, Northwest Australia. S. O’Connor (1999)
Phytolith and starch research in the Australian-Pacific-Asian regions: the state of the art

Papers from a conference held at the ANU, August 2001, Canberra, Australia

D.M. Hart and L.A. Wallis
Dedication

Dedicated to G Baker, the first Australian researcher to identify phytoliths in Australian sediments, and to the small, select, dedicated band of phytolith and starch researchers who have followed him.
Acknowledgements

The Centre for Archaeological Research generously provided funding for the conference and publication of this volume. The Department of Archaeology and Natural History at The Australian National University also provided logistical support. To them and to the individual presenters, authors and referees, we express our thanks. We would especially like to extend our gratitude to Amanda Kennedy at the Centre for Archaeological Research for her efficient and enthusiastic assistance in coordinating aspects of administration, logistics and social events. We would also like to thank the staff at Pandanus Books for their skill and enthusiasm in producing this volume.
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THE DECISION to produce this volume of *terra australis* arose during a workshop held at the conclusion of a conference hosted by the Centre for Archaeological Research at The Australian National University in the nation’s capital, Canberra, in August 2001. The conference (*The state of the art in phytolith and starch research in the Australian-Pacific-Asian regions*) attracted participants from China, Belgium, the United States of America, Argentina, New Zealand and, of course, Australia. While in the past, meetings of scientists interested in these microfossils have been largely held in the northern hemisphere, Australia has hosted three meetings, starting with the Macquarie Phytolith Workshop and the Australian Museum Starch Workshop, both held in 1998. The third meeting in Canberra provided an opportunity for phytolith and starch researchers to come together to exchange views and address common problems. Such a meeting was considered timely given recent local developments, such as the emergence of new collaborative projects, the isolation of phytoliths and starch from important tropical cultigens, substantial progress towards the publication of a manual for starch analysis and the completion of a number of theses relating to these topics. It is worth mentioning that many of the people who have been critical in developing and advancing the fields of starch and phytolith research in this region have done so as graduate students, the results of whose work can take some time to filter out into the broader research arena. Indeed, 10 of the papers in this volume have been authored by such students and their enthusiastic embrace of this opportunity to present their results is reflected in their contributions. The volume brings together many of the papers and posters presented at the conference, as well as invited papers from Tracey Lu and Matiu Prebble, who were unfortunately unable to present papers at the Canberra conference.

An introductory paper outlining the history of phytolith researchers in Australia sets the scene, demonstrating the steady emergence of three primary local centres of excellence in phytolith research (Macquarie University, Southern Cross University and The Australian National University). The next two sections deal with techniques and taphonomy; demonstrating the ingenuity of researchers in adapting procedures, establishing the utility of phytoliths and starch and the problems involved in analysing data. It is usually the application of phytolith and starch analyses to varied external research questions that is of
primary interest to non-specialists. It is crucial, however, that we develop a deeper understanding of the processes and techniques involved in phytolith and starch preservation and behaviours, as well as greater skill in efficiently and effectively extracting and studying such microfossils. The papers in these sections of the volume demonstrate some of the recent steps taken towards meeting such challenges. Advances of this nature in baseline research, which often seem of little value to outsiders, ultimately afford us a greater degree of confidence and sophistication in utilising phytoliths and starch in applied studies.

The final selection of papers presents recent applications of phytoliths and starch to research into archaeology, palaeoenvironments and the origins of early agriculture. The final paper, contributed by Deborah Pearsall, a modern pioneer in the field who presented a keynote address at the conference, outlines current research directions and demonstrates the power of using several strands of evidence in archaeological and environmental reconstructions.

Diane Hart and Lynley Wallis
The Editors
December 2002
The history of phytolith researchers in Australia

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Keywords
Australia, phytoliths, historical development

Abstract

This paper traces the history of Australian phytolith researchers and their contributions to our understanding of silica in plants and sediments. From initial false starts in the mid-1900s, researchers gradually developed a better understanding of phytoliths and began applying their study to assist in unravelling the geology, archaeology, pedology and botany of Australia and nearby regions. The modern era of Australian phytolith research began during the 1980s, with an upsurge of interest in their archaeological and pedological applications. Through the 1990s the discipline established a strong grounding, leading to the first local meeting of interested researchers in 1998 at a workshop at Macquarie University. With an ever-increasing number of universities adding elements of phytolith studies to their offerings to undergraduate students, and the high quality of research being conducted (as demonstrated in the papers presented in this volume), phytolith research in Australia can be considered to have ‘come of age’.

Introduction

In an early review paper, Bowdery (1989) noted that in 1987 there were only two researchers in Australia actively involved in phytolith research and up until that time such interests had not been pursued with any vigour. Contrastingly, during the intervening period to the present (2001) there has been substantial growth in the number of Australian researchers pursuing...
phytolith-related studies, with a concomitant widening interest in the discipline generally by researchers in related fields such as archaeology, palaeoenvironmental studies and pedology. Phytolith research carried out in Australia generally falls into two, usually, but not always, mutually exclusive categories. The first area is that of fundamental research. This type of research is generic rather than specific in nature and consequently the results may be of direct relevance to researchers world-wide. Such studies involve research into aspects of phytolith production and their specific characteristics, as well as addressing methodological and theoretical issues (e.g. Handreck and Jones 1968; Hart 1988a; Jones and Handreck 1963, 1965a, 1965b, 1967, 1969; Jones and Milne 1963; Jones et al. 1963, 1966; Lentfer 1997; Lentfer and Boyd 1998, 1999, 2000; Wallis and Boswell 1999). Other phytolith studies fall into the category of applied research, the results of which are more specific to location. These can be separated into Australian studies and those carried out by Australian-based researchers working in other geographical locales (e.g. Baker 1961; Bowdery 1999a, 1999b, 2001; Boyd et al. 1998; Fullagar 1993; Parr 1999; Parr et al. 2001a; Wilson 1982, 1985). The purpose of this paper is to trace the developments within both types of research, so as to contextualise the papers to be presented in the rest of this volume.1 The approach adopted is temporal, beginning with the first recognition of phytoliths in Australian soils in the early to mid-1900s, and progressing through to the efflorescence of research and incorporation into undergraduate teaching programs at a number of Australian universities in the past five years. In doing so, this paper attempts to provide an overview of all major Australian-based phytolith research undertaken since the 1970s. An overview of the general phases of phytolith activity in Australia is provided in Table 1, which highlights the trends in research interests and lists key Australian phytolith researchers. Figure 1 demonstrates the increasing Australian interest in phytoliths by providing a summary of the number of related publications per unit of time.

![Graph showing the number of publications per decade](image)

**Figure 1.** Evidence for increasing research interest in phytoliths in Australia, through number of publications per decade [note that the final decadal period is incomplete, comprising one year (2001) only].

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1 Although this volume is also concerned with starch, the history of such research is dealt with by Ugent (in press) and for the sake of brevity will not be reiterated herein.
Table 1. Summary of phases of phytolith research by Australian-based researchers.

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<td>Humphreys; Simons</td>
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The early phase

Elsewhere in the world phytoliths were first recognised in soils, sediments and plants during the mid-1800s (e.g. Ehrenberg 1854; Struve 1835) and during the early 20th century in Europe (particularly Germany) researchers began to focus their attention on botanical aspects of phytolith production (e.g. Netolitzky 1929; Prat 1948; Werner 1928). It took much longer, however, for researchers to become interested in these microfossils in the Australian context. Chapman and Grayson (1903, as cited in Baker 1959a:65) are reported to have recognised siliceous elements derived from plants among a wind-borne dust in Victoria; however, others were not so familiar with the morphological characteristics of these bodies and Carroll (1931) mistakenly identified phytoliths in various Australian soils as sponge spicules. This error was compounded during the next 25 years, with subsequent researchers (e.g. Brewer 1955, 1956;
Leeper 1955; Leeper et al. 1936) also erroneously referring to these particles as sponge spicules. Their widespread occurrence led researchers into mistakenly postulating the existence of either many freshwater lakes in southern Australia or extremely high wind action to explain their ubiquitous distribution. It was not until 1959 that the status of these particles was reassessed. Baker, a CSIRO soil scientist, was introduced to phytoliths by a British researcher (Smithson) during a visit to University College of Wales (Baker 1959a:66). Baker (1959a; Baker and Leeper 1958) re-interpreted the sponge spicules as phytoliths, thereby providing a much more appropriate explanation for their widespread occurrence.

Baker (1959b, 1959c, 1960a, 1960b, 1960c; Baker et al. 1959, 1961) subsequently examined phytoliths from a variety of sedimentary contexts and plants collected across the Australian continent. His research is still internationally recognised as having been instrumental to our recognition of the ubiquitous nature of these particles. His identification of phytoliths preserved in soil beneath a basalt flow dated to 4.35 million years ago (Baker 1960a) was especially important in demonstrating to the international community their capacity for resisting weathering processes over extended periods of time. Although not taken up immediately by Australian peers, the demonstrated longevity of phytolith preservation in sedimentary contexts has been of prime importance to the ultimate emergence of applied phytolith studies in Australia, particularly those relating to long-term archaeological and palaeoenvironmental research. The unique nature of the Australian landscape and environment has resulted in the generally restricted presence of other traditional plant indicators (e.g. pollen and macrobotanics such as seeds) in many sedimentary contexts and hence phytoliths have increasingly been adopted with cautious optimism by Australian researchers as an alternative source of data.

During this early phase of Australian phytolith research, references to phytoliths start to appear in the local botanical literature, with Hely and Hallsworth (1946) noting high silica content in grasses (which was argued to possibly contribute to their low palatability by stock). Additionally, Amos (1952) discussed the silica content of timbers in relation to their hardness and suitability for economic exploitation.

In the decade after Baker’s pioneering studies, Jones, Handreck and colleagues based in the School of Agriculture at the University of Melbourne were responsible for extensive agriculturally related research that provided a wealth of fundamental information about phytoliths (e.g. Handreck 1968; Handreck and Jones 1967, 1968; Jones and Handreck 1963, 1965a, 1965b; Jones and Milne 1963; Jones et al. 1963). In particular they focussed on the uptake and deposition of silica in the oat plant, *Avena sterilis*, looking at effects on plant growth, the nature of the deposition process and the digestion of phytoliths in plant material by animals. Like Baker before them, this group of researchers led the world in studies investigating the physical and chemical properties of phytoliths.

At the same time, isolated botanical studies continued, with Norton (1966) reporting the occurrence of distinct ‘cyperaceous’ and other phytolith types in *Lepidosperma* and Bamber and Lanyon (1960) discussing silica deposition in Australian woody plants in work that followed on from Amos (1952).

Other work carried out during this period that went largely unrecognised at the time, but that would later prove to be of great significance, was Brewer’s discussion of opal phytoliths as relating to soil micromorphology in the 1968 publication *A Handbook of Australian Soils* (Stace et al. 1968). This text provided a wealth of information relating to phytolith content down soil profiles, which, is currently being used as part of the database for the Macquarie University work on phytolith depth trends (see below).
Decline

Elsewhere during the 1970s phytoliths were embraced by the international research community, particularly in the US where, not only had they been identified as a powerful tool for the reconstruction of grassland histories (e.g. Twiss 1969), but where Rovner (1971) had published a seminal article describing their potential for archaeological applications. Despite this, the Australian-based research went into a period of decline. While Bowler (1977) noted the presence of phytoliths in aeolian sediments in the Murray Basin region of south-eastern Australia, little interpretive value was placed on this observation. In the botanical realm, occasional forays into silica deposition in plants continued, with Scurfield et al. (1974) reporting on a detailed study into the deposition of silica in Australian woody plant tissues. Additionally, in their treatise on the identification of grasses, Clifford and Watson (1977) made considerable mention of the types and patternings of silica bodies in various Poaceae members.

Interestingly, around this time Kamminga (1971) considered phytoliths as part of his use-wear studies of Australian stone artefacts, including an appendix to his BA thesis on their potential for archaeological applications. This appendix was in a similar vein to Rovner’s (1971) seminal work. It is worth pointing out that Rovner (1971) and Kamminga (1971) seem to have reached their similar observations on the basis of different literature sets and approaches: Kamminga was focussed on the emerging residue and use-wear studies relating to functional analyses of stone artefacts, while Rovner had delved into the burgeoning American ecological and quaternary literature. Kamminga’s (1971) appendix was not published per se and Kamminga himself didn’t follow up with any phytolith case studies, although he did elaborate on polishes in his doctoral thesis (Kamminga 1978, 1982) and published on the related topic of ‘phytolith polished surfaces’ (Kamminga 1977, 1979). Nevertheless, as a direct result of his observations and with his encouragement, Fullagar (a PhD student being supervised by Kamminga) became highly interested in the role of silica in the formation of polishes on stone artefacts (Fullagar 1991) and was also able to recognise the presence of phytoliths on various polished stone flakes, although they were not able to be identified until much later (Fullagar 1986, pers. comm.). Fullagar has been one of the key players in the growth of phytolith-based research at the Australian Museum (see below).

Revitalisation, consolidation and expansion

From the 1980s onwards the pace of phytolith research increased overseas, as primarily North American researchers expanded their interests to encompass applied palaeoenvironmental and archaeological studies. During the same period, the modern phase of sustained phytolith research began in Australia, primarily at The Australian National University (Canberra) and Macquarie University (Sydney). Research at the former was largely archaeologically and palaeoenvironmentally driven, whereas at the latter the focus was on pedological and geomorphic applications.

The Australian National University

Growing out of his general interest in plant microfossils and vegetation change, Geoff Hope (a Quaternary palynologist) became interested in phytoliths. Although frustrated by working with a microfossil system that, at the time, was poorly researched and lacking a standardised terminology with which to describe and classify it (Geoff Hope pers. comm.), Hope was instrumental in encouraging a number of research students to further pursue this line of investigation.
Sandra Tiffin, an undergraduate student at the ANU, undertook a small phytolith project at the archaeological site of Kuk in the Papua New Guinea Highlands. Although this work reportedly resulted in an unpublished report (Geoff Hope pers. comm.), recent efforts to obtain the report have proven fruitless (Jack Golson pers. comm.).

Wilson (1982, 1985), another of Hope's students, embarked on a larger project designed to utilise phytoliths as a means of investigating the origins of agriculture also at the Kuk site for his BLitt thesis. Unfortunately, two of the major staple crops thought to have been grown at the site, taro and yam, were found to be non-silica accumulators, although Wilson was able to recognise phytoliths from a third crop of importance — bananas. The value of this work was limited by the fact that Wilson was unable to distinguish between the phytoliths of introduced banana species and those that were indigenous, however, many years later his efforts have helped stimulate further research to address this problem (e.g. Doreen Bowdery pers. comm.; Carol Lentfer pers. comm.; Mbida et al. 2000, 2001).

A spin off from the research into phytoliths at Kuk was a preliminary study investigating the potential of using phytoliths for Electron Spin Resonance (ESR) dating, conducted by Ikeya and Golson (1985). Regrettably, further results and research in this area have not been forthcoming.

Perhaps the most important student to begin phytolith research at the ANU during this time, in terms of longevity of involvement and sheer quantity of research, was Bowdery. Initially, Bowdery (1984) undertook a BA (Hons) thesis exploring whether archaeologists with limited botanical expertise could make effective use of the technique. In her thesis, Bowdery also presented the first Australian archaeological phytolith case study from the site of Graman in northern New South Wales. She accredited the overriding impediment to such studies in Australia to an absence of reference material and problems with identificatory schemes (Bowdery 1984:75). The latter is still an issue of major concern, not just within Australia, but within the wider international community and Bowdery has been involved in recent efforts to address the problem (see below).

The interest in phytoliths at the ANU during this period was further fuelled by a visit from the Japanese researcher, Fujiwara. In collaboration with archaeologists, Fujiwara became involved in a consultancy project in Kakadu National Park which produced some of the first data relating to northern Australian phytolith assemblages. Fujiwara et al. (1985) examined sediment samples collected from a variety of contexts, natural and cultural, and was able to identify specific plants within them on the basis of the phytoliths present. Again, the lack of an extensive reference collection meant results were limited to noting the presence or absence of particular morphologies; however, the work did present interesting possibilities for future applications of the approach in this region.

Bowdery (1989) subsequently published a beginner's guide to phytoliths (that synthesised the [then] current state of knowledge in the discipline) in an edited volume dedicated to the topic of plants in Australian archaeology. This volume was widely distributed and easily accessed by Australian researchers and has served to disenfranchise local archaeologists of the notion that plant remains don't preserve in Australian archaeological sites.

Around the same time, ANU-based multi-disciplinary investigations were carried out into the late Quaternary history of the Magela Creek Plain in the Northern Territory (Clark and Guppy 1988; Clark et al. 1992). Phytoliths produced by grasses, sedges and some other plants were found in varying quantities in the sediments beneath the Magela Plain. Generally, such microfossils were found to be rare or absent in the core sediments representing the period when the plain was covered by mangrove forest, and became abundant only when the freshwater wetland environment was established c. 1700 years ago. Other than recording the variation in abundance through time, no detailed studies of the phytoliths were pursued, mainly owing to time constraints and a lack of available reference material (Robin Clark pers. comm.).
One of the first extensive applied research projects undertaken in Australia was Bowdery’s (1996) PhD thesis (now published as a major monograph [Bowdery 1998]), applying phytolith techniques to questions of interest in arid zone archaeological research. Initially Bowdery examined 120 modern plant specimens for their phytolith content and developed an identification key for classifying the various morphotypes encountered. This was followed by studies of phytolith assemblages recovered from sediments collected at various locations in central and southern Australia. These included an archaeological site located on the Nullarbor Plain (Allen’s Cave [N145]) with human occupation dating between 20,000 and 440 years ago. Analysis of sediments from this site revealed a decrease in the quantities of grass phytoliths present through time, which Bowdery (1998:124) argued indicated a decrease in precipitation resulting in reduced monosilicic acid available for plant uptake. Another group of study sites included transects and adjacent archaeological ‘oven’ sediments from the Strezlecki dunefields in northeastern South Australia. These late Holocene and Last Glacial Maximum aged sandy sediments contained a variety of phytoliths indicating a mixed tree/shrub/grass environment; however, the archaeological oven sediments were devoid of phytoliths. The major focus of Bowdery’s research was Puritjarra, an important rock shelter site located in Central Australia with an occupation sequence extending back 37,000 years. Bowdery was able to demonstrate changes in the grassland component of the Puritjarra phytolith sequence, with the appearance of economically important grass species reliant on summer rainfall during the early to mid-Holocene. Coincident with the appearance of these new grasses was the appearance of small flakes and grindstone material in the stone artefact assemblage at the site.

Bowdery’s (1996, 1998) research was significant for a number of reasons. Firstly, it demonstrated that phytolith analysis could be successfully applied in the Australian arid zone context to provide information relating to vegetation change where such information is not available via other approaches (e.g. through pollen analysis). Secondly, it provided a beginning to the onerous task of assembling a comparative, modern phytolith collection for the unique Australian flora. Finally, the identification scheme developed by Bowdery serves as a basis for further studies in the region.

Since this substantial project, Bowdery has been involved in other Australian-based projects (e.g. Roberts et al. 1997), as well as broadening her interests to incorporate numerous archaeological phytolith studies in the wider Pacific and South-East Asian regions (e.g. Bowdery 1999a, 1999b, 2001; Clark et al. in prep.).

Wallis is a recently completed PhD student from the ANU whose thesis explores the potential of phytoliths for archaeological and palaeoenvironmental applications in the tropical semi-arid region of north-west Australia (2000a; see also Wallis 2000b, 2001, 2002). Her results from the main archaeological study site, Carpenter’s Gap 1, provided one of the first long-term terrestrial records of vegetation and climate change in this region. Wallis is currently involved in other environmental history projects in the north-west (e.g. Clarkson and Wallis this volume; Wallis 2000c) and the Flinders Ranges in southern Australia (Wallis 2000d), as well as collaborating on archaeological projects based in Fiji (Clark et al. in prep.) and Palau.

The most recent phytolith research to be undertaken at the ANU involves the application of phytolith studies to archaeological sites in order to explore the origins of agriculture in South-East Asia, although to date results are not yet available (Janelle Stevenson pers. comm.).

**Macquarie University**

Phytolith studies began at Macquarie University at approximately the same time as the early research at ANU. Ron Paton, an Associate Professor of pedology in the Physical Geography Department, was interested in the silica cycle and spent a sabbatical year in the 1970s in
Britain researching phytoliths. Paton was instrumental in encouraging Hart (1992) to pursue the study of these microfossils in sediments from the NSW region for her doctoral thesis. Hart’s (1988b, 1992) studies of phytoliths from plants and sediments in a swamp context demonstrated the complexity of phytolith assemblages, in that the most abundant categories of phytoliths in the modern plant species were not particularly abundant in sediments, and the most abundant phytoliths in the sediment samples were not representative of the dominant vegetation species. Another important finding of this phase of Hart’s research was the presence of a phytolith morphology (which had previously been argued to be specific to members of the Cyperaceae family) in a number of different plant families, thereby questioning the validity of the species-specific phytolith concept (Hart 1990). In addition, in a search for a characteristic of phytoliths other than morphology which might be of use in ‘finger-printing’ sediments, Hart examined the elemental composition of phytoliths, in particular the trace elements occluded within phytoliths, from two plants species growing on the same sediment (Hart 1992, 2001).

Through her studies, Hart became aware that once plants died, their disarticulated phytoliths within the sediment became attenuated from their botanical links and their role as a mineral within the sediment assumed primacy. She became strongly convinced that, while many aspects of phytolith preservation, distribution and taphonomy remained to be explored before vegetation reconstructions based on phytoliths could be accurately attempted, they could be a valuable marker in pedological and geomorphic studies. It has been in this role that they have been pursued since at Macquarie University.

Hart’s (1997) more recent research has focussed on issues of taphonomy, exploring the reasons for discrepancies between the amounts of silica produced by plants and those recovered from adjacent sediments. She concludes that fire and rain can have major detrimental effects on the quantities of phytoliths available for incorporation into sediment profiles.

Hart and Humphreys (1997) with Simons (1998; Simons et al. 2000) have also considered issues of phytolith mobility through the study of soils in the Pilliga State Forest region in northern NSW and in the Sydney Basin. Using a combination of their own research results, the data contained in the micromorphological work of Brewer in the Handbook of Australian Soils (Stace et al. 1968) and the information published by many authors world-wide, they established three major phytolith depth functions in soils and examined the processes responsible for them (see also Hart et al. in prep. and Humphreys et al. this volume). Laboratory experiments established the mobility of phytoliths in the soils examined and the processes responsible were found to be perversion (mechanical movement downwards by water) and bioturbation (movement up and down by soil fauna).

Norris is another Macquarie University researcher who has become involved in phytolith research, although her work has been oriented more towards botanical aspects, rather than pedology. Norris (1998) has investigated silica in the epidermis of the inflorescence structures of genera within the Stipeae tribe. In conjunction with other research, this has resulted in the tribe being redefined and the Australian species being classified as a new genus, Austrostipa. Norris and Hart (1998, 2000) have also used phytoliths to assist in determining the location and history of old gardens in the Pilliga State Forest.

Other centres of phytolith research

Other centres for phytolith research have been established in the past 10 years, primarily at Southern Cross University (Lismore) and the Australian Museum (Sydney), but also by individuals located at other institutions. Furthermore, researchers in other disciplines also began including passing references to phytoliths in more general publications about microfossils (e.g. Boyd and Pretty 1989; Retallack 1981; Selkirk and Adamson 1982; Williams et al. 1986).
In an unpublished paper presented at the Australian Archaeological Association conference in 1990, Boyd et al. (1991) reported preliminary results from the study of phytoliths at the burial site of Roonka in South Australia. While details were limited, the results suggested the deliberate emplacement of reeds with burials and further examination of this material is pending² (Bill Boyd pers. comm.). Subsequently, Boyd has been instrumental in developing phytolith studies as a focus of research at the Centre for Geoarchaeology and Palaeoenvironmental Research at Southern Cross University. Currently there are two principal students at this institute engaged in archaeological and palaeoenvironmental phytolith research for their doctoral theses: Lentfer and Parr. Both are researching aspects of phytoliths as they relate to the archaeology of Garua Island in West New Britain, Papua New Guinea, in collaboration with Torrence from the Australian Museum (Lentfer et al. 2001; Parr 1999; Parr et al. 2001a; and see below). Additionally, Lentfer et al. (1997) used phytoliths as a means of investigating questions of importance to historical archaeology within Australia, assessing whether the Hope Farm Windmill in south-east Australia was ever operational.

As well as being involved with applied research, the Southern Cross researchers have undertaken substantial methodological research. This research has included comparisons between various techniques for the extraction of phytoliths from sediments (e.g. Lentfer and Boyd 1998, 1999) and plants (e.g. Parr et al. 2001b), the development of new extraction techniques (e.g. Lentfer and Boyd 2000; Parr et al. 2001c; Parr and Farrugia this volume) and the assessment of specific methodological issues relating to phytolith research in the wet tropics (e.g. Boyd et al. 1998).

At the Australian Museum, Fullagar, Torrence and Field, in collaboration with others (e.g. Lentfer and Parr at Southern Cross University), are actively involved in archaeologically based projects within Australia and PNG (e.g. Veth et al. 1997). Lisa Kealhofer (an American researcher) spent time as a Research Fellow working at the museum investigating phytoliths in residues recovered from stone artefacts from West New Britain (Kealhofer et al. 1999). Further, Kealhofer (pers. comm.) has also spent time in a similar capacity at the University of New England undertaking research utilising phytoliths in Australian historically oriented projects.

As part of his BSc (Hons) thesis at the University of Tasmania, Warren (1994) used phytoliths to examine the vegetation history of a Tasmanian sedimentological site (Moxon Saddle). Modern plant specimens were examined in an attempt to identify those recovered from an 8000-year-old peat profile, which helped identify a shift in vegetation about 4500 BP from fire-sensitive species to fire-tolerant and/or fire-promoting species.

In a pedologically based study of soils in northern Queensland, Boettinger (1994) used phytoliths as a means of assessing the degree of mixing between and within soils. Her results showed considerable mixing in Vertisol soils, but not in Alfisol soils, thereby indicating phytolith mixing occurs when desiccation cracks extend from and beyond the surface in these seasonally cracking soils.

In a PhD project designed to investigate aspects of European settlement in Australia, Atkinson is using soil phytolith assemblages as indicators of vegetation change and variations in land-use patterns in the historical period (Maddy Atkinson pers. comm.).

² Note that Bowdery (1996:28) has also examined dental calculus from some of the Roonka skeletons and recorded the presence of banksia-type phytoliths. No further work has been done on this research and detailed results have not yet been forthcoming.
Collaborative projects and phytolith meetings

During the early years of the modern phase of Australian research, the small numbers of people involved meant researchers often had to travel to overseas meetings in order to engage in constructive discussions with like-minded researchers. Initially this involved travelling to the Society for American Archaeology meetings in the US, where there were often sessions devoted to phytolith research. More recently, the European and International Meetings on Phytolith Research (held in Spain 1996, France 1998, Belgium 2000 and England 2002) have seen Australian representatives attend and present posters and papers. The recent increases in numbers of Australian researchers led to the first local workshop on the topic being held at Macquarie University in 1998, enabling researchers from Australia and New Zealand to interact and share knowledge in a local forum for the first time. This workshop was supported by Macquarie University and the Australasian Quaternary Association, reflecting the upsurge in interest in phytoliths by the members of this group. Papers and posters covered techniques and phytolith applications to archaeology, pedology, environmental reconstruction and botany. A direct outcome of this meeting was the formation of a collaborative project aimed at addressing issues of phytolith nomenclature and classification (Bowdery et al. 2001; Hart et al. 2000; Lentfer et al. 2000; Wallis et al. 2000). Most recently, the conference from which the papers in this volume derive (held at The Australian National University in Canberra in 2001) attracted not only local researchers, but international participants and demonstrated to the wider scientific community that Australian phytolith research is at the forefront of the development of the discipline.

Incorporation into university teaching programs

The increasing number of researchers working either directly or collaboratively in phytolith-based projects, or with an awareness of the potential applications of these microfossils, has also led to the incorporation of phytolith knowledge into undergraduate teaching programs at various Australian universities, including the Archaeology and Geography Departments at the ANU, and the Departments of Biology, Palaeontology and Soil Science at Macquarie University. Such inclusion is highly significant in that it provides students with a basic understanding of the discipline and will ultimately result in a new generation of researchers that can further advance phytolith research in this country.

One development that illustrates the increasing high profile phytolith research is developing in Australia is the creation of the first PhD scholarship specifically offered for a phytolith-based project, as a component of an Australian Research Council grant awarded to a team based at the ANU (Janelle Stevenson pers. comm.). It is envisaged that as future researchers earn their doctorates for phytolith-related research a group of post-doctoral fellows should become established within Australian institutions, thereby further increasing the profile and knowledge base within this country.

Summary and future trends

From uncertain beginnings in the 1930s and sporadic botanical studies, phytolith research in Australia quickly gathered momentum in the 1980s and 1990s in the realms of archaeology, palaeoenvironmental studies and pedology. The quality and quantity of papers collated in the current volume is a strong indication of the progress we have made in recent years.
Today phytolith research is carried out in four major Australia centres. At the ANU emphasis is on applied studies, particularly of Australian, Pacific and South-East Asian archaeological sites. Similarly, SCU and the Australian Museum projects have been dominated by applied archaeological and palaeoenvironmental studies. As described previously, SCU researchers have also been active in exploring new methodologies and techniques, while the Macquarie University group continues to explore soil processes using phytoliths.

The South-East Asian and Pacific archaeologically based research has tended to focus on the search for specific marker types from economically important, often cultivated crop plants (e.g. banana), although Parr et al. (2001a) have recently demonstrated the value of the entire phytolith assemblage for elucidating changing land-use patterns in this region. Within Australian archaeological studies the entire assemblage approach has been more popular, given the general dominance of grass phytoliths in assemblages and lack of distinctive, species-specific phytoliths from cultivars.

It is perhaps worth noting that in recent decades the increasing emphasis on funding applied projects has been at the expense of creating solid, regional reference collections, without which little substantial progress can be made. Similarly, this bias means that much of the fundamental, baseline research such as was carried out during the 1950s and '60s has been neglected in spite of promising results from pilot studies (e.g. occluded elements in phytoliths — Hart 2001; AMS dating of phytoliths — Carol Lentfer and Doreen Bowdery pers. comm.). These lines of research are being pursued overseas (e.g. Smith and Anderson 2001; Webb and Longstaffe 1997) and offer promising alternatives to the more traditional morphological approach.

The inclusion of phytolith studies at the undergraduate level in university courses, along with the continued high-calibre research being pursued at the postgraduate level and beyond, can lead only to further growth in our understanding and knowledge base of these microfossils. Gone are the days when we had to deliver the standard spiel about ‘phytoliths being microscopic particles of silica produced by plants’ whenever we attended a conference to present our latest results. Instead we’re now being actively approached by researchers across a variety of disciplines eager to utilise these microfossils in their own research and seeking expert assistance and knowledge. Australian-based phytolith research is pursued by enthusiastic researchers whose numbers increase every year and, as illustrated in this review paper and the other papers in this volume, who have amply demonstrated their capacity to produce work of an international standard and relevance.

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3 Note that this is by no means a complete bibliography of all Australian phytolith references.


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Waste reduction and value adding during fossil phytolith extraction and palaeoenvironmental analysis of volcanic sediments and tephra using microwave digestion and ICP/MS

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Keywords
phytoliths, starch grains, microwave digestion, Inductively Coupled Plasma Mass Spectrometry, laboratory techniques

Abstract

This paper outlines two complementary methodologies for palaeoenvironmental analysis. The first is a method used for the extraction of microfossils from palaeosols and the second is for the analysis of elements in volcanic sediments. Microfossil extraction is achieved by a Perkin-Elmer Multiwave Microwave Sample Preparation System and the volcanic sediments are analysed with a Perkin-Elmer Inductively Coupled Plasma Mass Spectrometer (ICP/MS). Hence, this paper provides an introduction to an alternative technique for the extraction of fossil phytoliths from sediments that is fast, inexpensive and, most importantly, results in interpretable and replicable fossil phytolith assemblage data. In addition, fewer chemicals are required for processing samples, starch grains seem to survive the microwave processing and the digested material from the phytolith extraction may be used for ICP/MS analysis to differentiate between tephra. The methods, therefore, provide a significant reduction in waste product while extending the benefits of these methodologies by value adding.
Introduction

Palaeoenvironmental archaeology relies heavily on two major components — the preservation of evidence and the accurate interpretation of stratigraphy. Some of the main sources of microfossil evidence in terrestrial environments include phytoliths, pollen and starch grains. In this paper we discuss fossil phytolith and starch grain extraction from volcanic sediments using a closed vessel microwave digestion technique (Parr 2002) and the subsequent use of the digest extract to differentiate between layers of tephra using samples from a number of sites situated at Numundo Plantation, West New Britain, Papua New Guinea, as a case study.

Phytolith extraction

No one protocol can be expected to be suitable for the extraction of phytoliths from all sediment types (Zhao and Pearsall 1998). For the most part this is due to the variability in chemical, spatial and temporal changes to sediment composition. The clay fraction and the presence of humic colloids have to some extent been the major cause of problems encountered during the extraction of fossil phytoliths from soils (Boyd et al. 1998; Lentfer 1997; Lentfer et al. 1998; Zhao and Pearsall 1998). Previous research on West New Britain sediments highlighted a need for the modification of phytolith extraction methods to remove the clay and humic acid content (Boyd et al. 1998; Lentfer 1997; Lentfer et al. 1998). The standard method used initially involved the dispersal and deflocculation of clays with a Calgon solution. For the removal of organic matter hydrogen peroxide was used and for carbonates hydrochloric acid. Where necessary, potassium hydroxide was used to remove humic acids and heavy liquid flotation for the retrieval of phytoliths. Recent results from a comparative study between the above standard phytolith extraction method and the pressurised microwave digestion technique outlined below found that for the sediments processed in that study the latter removed the humic acids (Parr 2002).

Microwave digestion

Two main types of microwave digestion systems are currently available — focussed (open vessel) and pressurised (closed-vessel) (Jones 1994, 1998; Jones and Ellin 1998). In this study we discuss a closed-vessel system. The closed-vessel microwave digestion systems comprise a number of pressurised vessels that require a relatively uniform sample weight, processing time and temperature setting. Chemical combinations may be varied for each sample.

A recent study has demonstrated that phytoliths and starch grains may be successfully extracted from herbarium specimens and sediments using the pressurised microwave digestion technique (Parr 2002; Parr et al. 2001). In the study a number of advantages were found when using the microwave digestion technique. Firstly, it is a very quick method for fossil phytolith extraction from sediments. It provided equivalent assemblage information to that provided by existing techniques and, importantly, there are fewer steps in the microwave digestion protocol, thus limiting the opportunity for contamination of samples during processing. Smaller quantities of sample and chemicals are required for phytolith extraction, thereby making it a significantly cheaper process to use. Finally, few starch grains survive traditional phytolith extraction techniques and the digested material would normally be considered a waste product that is disposed of by decanting. Importantly, significant numbers of starch grains have been retrieved using the microwave method and, additionally, the digested component is suitable for petrochemical analysis of sediments using Inductively Coupled Plasma Mass Spectrometry (ICP/MS) or Atomic Absorption Spectrometry (AAS).
Differentiating between volcanic tephra

There are a number of methods that have been used for the identification of tephra from specific volcanic events. The most commonly employed methods include X-ray fluorescence and electron-microprobe analysis (Blake and Ewart 1974; Lowder and Carmicheal 1970; Shane et al. 1996; Torrence et al. 2000). ICP/MS and AAS are two alternative methods potentially useful for differentiating between tephra that were carefully considered in this study.

Inductively Coupled Plasma Mass Spectrometry

There were a number of advantages in the use of ICP/MS against AAS. Firstly, ICP/MS allows nearly the whole periodic table to be scanned using a method called ‘TotalQuant analysis’ in about two minutes per sample at very low detection limits. The detection limits on the AAS are much higher, therefore ruling out the detection of some rare earth elements. In addition, the AAS method requires individual analyses to be carried out for each element thus significantly increasing the time needed to process samples. For these reasons, ICP/MS was chosen as the preferred method to analyse the digested samples.

In this paper we outline some of the results from a comparative analysis between standard heavy liquid flotation and microwave phytolith extraction techniques reported in Parr (2002). In addition, data retrieved using ICP/MS and the compatibility of these two potentially efficient methods are also discussed in relation to the interpretation of palaeoenvironments.

Materials and methods

Sediment and tephra samples discussed in this paper were collected from the site locations FAAY, FABD, FABK, FAAH and FABM at Numundo Plantation, West New Britain, Papua New Guinea (Torrence 2000; Torrence et al. 1999). The sediments from these sites range in age from late Pleistocene to the present; however, the Holocene-aged palaeosols and tephra are the focus of this paper (Table 1). All samples were collected in sequential 5cm pinches. Four consecutive samples of cultural sediments from the top of the site FAAY were used to show comparisons between assemblages resulting from the standard and microwave methods of phytolith extraction. Results of a phytolith analysis of the site FAAY are outlined and chemical analyses of samples from selected tephra of all of the above sites are briefly discussed. The tephra discussed in this paper (W-K1, W-K2 and W-K3) have been described in detail and are well defined (Machida et al. 1996). Periods defined by the soil development on the tephra of sequential volcanic eruptions and associated dates are summarised in Table 1.

The standard phytolith extraction technique used closely follows that used by Lentfer (1997). This technique has been highly successful on West New Britain sediment samples for the extraction and interpretation of fossil phytolith assemblages in archaeological sites (Boyd et al. 1998; Lentfer 1997; Lentfer and Boyd 1999; Lentfer et al. 1998; Parr 1999).

For the microwave extraction of phytoliths from sediments a Perkin-Elmer Multiwave Microwave Sample Preparation system was used (Fig. 1). Due to a significant difference in sediment sample size, 5g for the standard phytolith extraction technique and 0.25g for the microwave digestion technique, there was a potential for bias and/or problems in the interpretation of results. For example, the 5g of sediment required for the standard technique would presumably produce more phytoliths than would be expected

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>STRATIGRAPHIC POSITION</th>
<th>YEARS BP</th>
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<tbody>
<tr>
<td>Period 3</td>
<td>Soil on W-K1 tephra</td>
<td>6000-3500</td>
</tr>
<tr>
<td>Period 4</td>
<td>Soil on W-K2 tephra</td>
<td>3500-1800</td>
</tr>
<tr>
<td>Period 5</td>
<td>Soil on W-K3 tephra</td>
<td>1800-1200</td>
</tr>
<tr>
<td>Period 6</td>
<td>Soil on W-K4 tephra</td>
<td>1200-500</td>
</tr>
</tbody>
</table>
from 0.25g of sediment used in the microwave technique. This hypothesis was tested and is discussed elsewhere in detail (Parr 2002). In addition, there are steps in the standard extraction technique such as the deflocculation of clay and heavy liquid flotation for maximising the assemblage composition of phytoliths that are not employed in the microwave digestion technique. In order to monitor the advantages and/or disadvantages of sample size and heavy liquid flotation, additional steps were made on sub-sample sets (Parr 2002). The most important of these steps was the addition of heavy liquid flotation to a sub-set of FAAY 1, 2, 3 and 4 microwave digested samples to determine if additional isolation of phytoliths was possible.

Since the original sample weight for the microwave digested sample (0.25g) is 5 per cent of the sample weight required for the standard phytolith extraction protocol (5g), residue weights were adjusted by either multiplying or dividing results. For example, the 0.25g results are multiplied by a factor of 20 to extrapolate their equivalent weight for a 5g sample. Alternatively, the 5g residue weight results are divided by a factor of 20 and compared with the 0.25g result.

Tephra were assessed using ICP/MS TotalQuant analysis of the digested material left over from the phytolith extraction process. TotalQuant is a quantitative method of analysis provided on the Perkin-Elmer Elan 6000 ICP/MS. The NIST Montana 2711 standard reference material was used throughout the analysis to monitor the accuracy of the microwave digestion and ICP/MS. Recovery was said to be acceptable within a range of 15 per cent either side of the known concentration. TotalQuant is useful for determining which elements are present and at what approximate concentrations they occur. Although not highly accurate, it was considered suitable for this application in that comparisons could be made between samples using a large range of elements. This technique is a quantitative research tool based on calculations to achieve a concentration value for each element in parts per billion and/or million. Some interferences cannot be adequately identified using this technique and can give erroneous results, however, we assume that because the samples from the same tephra layers should have the same petrochemical components the interference values would also be similar.

Extracted phytoliths from each sample were weighed, mounted on microscope slides and scanned at 400x magnification on an Olympus BH2 microscope. A total of 300 potentially diagnostic phytoliths (i.e. known to occur in particular vegetation types) were counted for each slide. Absolute numbers of phytolith types and starch grains were plotted. Statistical analysis was carried out using multidimensional scaling (MDS [Borg and Groenen 1997; Coxon and Davies 1982; Young and Householder 1938]) with Statistical Package for Social Science (SPSS) software. Dissimilarities between pairs of cases were calculated as chi-square measures over their phytolith frequency profiles. Values are obtained for the degree of difficulty in defining relationships (expressed as stress values) and the total variance explained between phytolith assemblages of standard and microwave methods (confidence). These results were then plotted into a two-dimensional space to display the dissimilarities between cases as Euclidean distances. Monitoring for contamination was carried out using the methods described in Parr (2002).
Results

Phytolith extraction
The comparative results of phytolith extraction summarised below are reported elsewhere in detail (Parr 2002). Excluding the crushing and drying, processing of samples using the standard protocol took approximately seven days to reach a stage where they were ready to mount on to microscope slides. Microwave extraction took approximately 45 minutes to reach an equivalent level of preparation. The cost of chemical processing was about $A4.80 per sample for the standard extraction method, the main expense being for the purchase of heavy liquid (in this case sodium polytungstate). Alternatively, chemical expenses for the microwave extraction method were about $A0.04 per sample.

Mean residue weights for each protocol are summarised in Table 2. The mean time taken to scan the slides for 300 phytoliths and the mean number of transects required to scan the slides are also outlined in Table 2. With the exception of one sample, the protocols provide very similar assemblage data. Stress values equalled 0.09297, indicating there were no significant levels of difficulty and the plotted R-squared values explain 0.96 of the total variance between protocols demonstrating a high degree of confidence (Parr 2002).

Phytolith assemblage data were very similar for the microwave and standard protocols (Fig. 2). Phytolith types clearly defined included those found in Arecaceae (palm), Cyperaceae (sedge), Musaceae (banana), Poaceae (grass), Zingiberaceae (ginger) and some arboreal and/or pioneer types (other). The results for all protocols show that the site FAAY has a strong Arecaceae component in Sample 1, which sequentially decreases in Samples 2, 3 and 4 (Figs. 3 to 6). Counts for Poaceae phytolith types in FAAY Samples 1, 2, 3 and 4 remain reasonably uniform (Figs. 3 to 6). Arboreal types have low counts in comparison with palms and grasses in Sample 1; however, they occur more frequently in samples 2, 3 and 4 (Figs. 3 to 6). A single Musaceae phytolith was recorded in each of the FAAY Samples 1 and 4 for the microwave digested samples but are absent in the sample results for other protocols (Figs. 3 to 6). Odd starch grains occur in the FAAY Sample 1 for the microwave and standard protocols but are not present in the step 1 sub-samples (Fig. 7). For FAAY Samples 2, 3 and 4 starch grain counts

Table 2. Summary of samples, pre-treatment weight, post-treatment weight and percentage of original sample weight, the number of transects required to count 300 phytoliths and the time taken for phytolith counts.

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>METHOD</th>
<th>WEIGHT (g)</th>
<th>SILICA WEIGHT (g)</th>
<th>SILICA (%)</th>
<th>TRANSECTS</th>
<th>TIME (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FAAY 1</td>
<td>Microwave</td>
<td>0.2580</td>
<td>0.1158</td>
<td>45</td>
<td>1.75</td>
<td>70</td>
</tr>
<tr>
<td>FAAY 2</td>
<td>Microwave</td>
<td>0.2629</td>
<td>0.1037</td>
<td>39</td>
<td>0.75</td>
<td>54</td>
</tr>
<tr>
<td>FAAY 3</td>
<td>Microwave</td>
<td>0.2415</td>
<td>0.0927</td>
<td>38</td>
<td>1.00</td>
<td>50</td>
</tr>
<tr>
<td>FAAY 4</td>
<td>Microwave</td>
<td>0.2703</td>
<td>0.0812</td>
<td>30</td>
<td>0.50</td>
<td>75</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.2582</td>
<td>0.0984</td>
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</table>
The state of the art in phytolith and starch research in the Australian-Pacific-Asian regions

Figure 2. Summary of phytolith and starch grain frequencies (X axis), samples and methods (Y axis).

Figure 3. Counts for each phytolith type in the sample FAAY 1 for microwave digested, standard protocol and the microwave + heavy liquid protocols.

Figure 4. Counts for each phytolith type in the sample FAAY 2 for microwave digested, standard protocol and the microwave + heavy liquid protocols.
significantly increase in the microwave digested samples. However, starch counts are comparatively low and/or absent for the other protocols (Fig. 7). A number of other inclusions were found on the slides of standard and microwave digested samples. Samples processed using both methods contained rare pollen, starch grains, carbonised particles including phytolith platelets similar to the *Asteraceae* platelets reported by Bozarth (1992) and other biogenic silica platelets, some probably of an arboreal origin and/or volcanic glass. Starch grains were found to be prolific in the FAAY Samples 2 to 4 (Fig. 7).

**ICP/MS analysis**

Although a number of the elements plotted were able to differentiate between various tephra, we have chosen the iron (Fe) and zirconium (Zr) levels in parts per million to outline the
Figure 7. Counts for starch grains in the sample FAAY 4 for microwave digested, standard protocol and the microwave and heavy liquid protocols.

possibilities of this method. Firstly, Fe levels were very consistent during ICP/MS analysis allowing monitoring of samples with the NIST Montana 2711 standard and, secondly, Zr is known for its stability in sediments. The results are summarised in Figure 8.

Figure 8. Plot of WK-1, WK-2 and WK-3 tephra based on the zirconium (Zr) vs iron (Fe) in parts per million.
Discussion and conclusion

The results demonstrate that processing by microwave digestion is significantly quicker than the standard protocol for extracting fossil phytoliths from sediments. This difference in processing time occurs primarily as a result of the large number of steps involved in the standard protocol in comparison with the relatively few steps required for the microwave digestion technique.

Starch grains are microfossils that are increasingly being used as a complementary method for the detection of anthropogenic sites and lithic residue analysis (Kealhofer et al. 1999; Lentfer et al. 2002). Importantly, the presence of starch grains in combination with Musaceae phytoliths (Fig. 2) in the microwave digested FAAY Sample 4 significantly improves the interpretive nature of this stratigraphic layer.

A major disadvantage in using the standard protocol is that it is very time consuming and large amounts of chemicals are required for processing. The larger quantity of chemicals, in particular the heavy liquid, makes each sample very expensive at $A4.80 per sample; in comparison the microwave digestion method costs $A0.04 per sample (Table 3).

<table>
<thead>
<tr>
<th>METHOD</th>
<th>COST BREAKDOWN (AUD)</th>
<th>TOTAL COST (AUD)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equipment</td>
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<tr>
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<tr>
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<td>6000</td>
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The major disadvantage of the microwave digestion protocol is the initial financial outlay for the system, which at the top end of the market is about $A32,000. On the other hand, the science faculties of many universities now have microwave systems available. Prior to using the microwave method a range of equipment was required at Southern Cross University for phytolith extraction. The current replacement value of this equipment is $A6000. Based on a 1500 samples per annum processing rate over the usual expected four-year life of equipment, the microwave works out cheaper (Table 3). Another potential disadvantage of the microwave digestion protocol is that it extracts all silica including volcanic glass which, as demonstrated, slows down the process of scanning microscope slides. If large quantities of unwanted silicates which make scanning intolerable are present, heavy liquid separation may be the only option. There is also a potential loss of small carbonised particles, nevertheless, carbonised phytoliths do remain in the samples. The presence and/or absence of carbonised phytoliths across a number of sites should therefore provide a similar opportunity for the interpretation of anthropogenic versus natural fire. Finally, owing to the small portions used during processing, a number of sub-samples would need to be treated to acquire enough phytoliths for AMS dating.

The main advantage of the microwave protocol is that it is a very quick method for phytolith extraction. It provides equivalent phytolith assemblage information to the existing method. Fewer steps are required in the microwave digestion protocol, thus limiting the opportunity for accidents and contamination of samples during processing. There is a reduction in waste with a smaller sample size required to transport and process, and smaller quantities of chemicals are used, making it a significantly cheaper method and the residue can be analysed by ICP/MS or AAS. In this study, value adding also occurs in the form of...
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retrieved starch grains providing a bonus for anthropogenic site interpretation and the chemical analysis of extraction residues allows tephra and/or non-visible stratigraphic layers to be differentiated. Another advantage in the chemical analysis of extraction residues is the potential to identify some palaeoenvironmental changes including sea level changes and/or pollution levels indicated by elements such as strontium (Sr) and lead (Pb). Evidence for possible prehistoric industrial activity, such as metalwork or bead production, may also be identified by the concentration of particular elements associated with these types of activities (Parr and Boyd 2002). Research under way at Southern Cross University indicates that dating of isotopes within the extraction residues may also be possible.

In conclusion, although highly desirable, it is doubtful that in the near future a single phytolith extraction method will be found that is suitable for all sediment types without some form of modification. The personal preferences of the researcher, the sediment types being processed, the particular question being asked, the availability of equipment and time will always suggest the most appropriate phytolith extraction procedure pursued. Thus, many modifications and improvements on the microwave extraction technique outlined in this paper are no doubt inevitable. It is important therefore, that the results, trials and errors of new and established extraction protocols and other techniques used in microfossil analysis are reported, making them accessible and providing a range of processing options for researchers to use. In this paper we have outlined results that indicate a combination of microwave microfossil extraction and the analysis of elements from stratigraphic layers using ICP/MS is a potentially powerful tool for landscape archaeology and palaeoenvironmental reconstruction.

Acknowledgements

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Phytoliths and other microfossils in tufa formations as a novel source of palaeoenvironmental data

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Keywords phytoliths, tufa, northwest Australia, limestone karst, late Quaternary, palaeoenvironment

Abstract

Tufa formations are a common element in limestone environments, although until recently their use in Australia as indicators of environment change in the late Quaternary period has been limited to dating the period of their formation. This paper reports the results of a pilot study investigating phytolith preservation in a tufa deposit from the south-west Kimberley region of Australia, which is the first report of the recovery and study of such microfossils from this type of depositional context. Although limited in extent, results demonstrate that tufas can preserve a range of microfossils including pollen and phytoliths derived from the local vegetation, and hence can be used as sources of palaeoenvironmental data beyond merely dating their period(s) of formation. This knowledge has the potential to open new avenues of investigation for researchers in northern Australia who are faced with a limited range of conventional vegetation data traps.

Introduction

One of the great difficulties facing researchers interested in the evolution of human-plant relationships in northern Australia, especially the northwest, is the paucity of local and regional palaeoenvironmental data relating to the late Quaternary period. This lack can be attributed to a combination of deleterious environmental conditions that are not suited to the preservation of organic materials, and to the limited presence of suitable data traps, such as swamps and lakes. In an attempt to alleviate this problem researchers in northwest Australia
have adopted innovative and unusual approaches in recent studies. For example, Roberts et al. (1997) and Wallis (2002) have demonstrated that mud nests constructed by wasps and birds can serve as data traps for a range of microfossils; Watchman (2000; Watchman et al. 2001) is pioneering the use of oxalate and silica crusts on rock shelter surfaces as sources of micropalaeoenvironmental data; and Wallis (2000, 2001) has explored the possibility of using macropod faecal pellets preserved in rock shelter deposits as records of changes to local grassland communities through time. The present paper reports the results of a pilot study investigating the potential use of tufa formations in evaluating past environmental conditions in the Kimberley region of northwest Australia.

The southwest Kimberley study area

The general study area is located in the inland southwest Kimberley region; specifically the Napier Range in the vicinity of the Lennard River (see Fig. 1). This range is all that remains of a Devonian-aged limestone reef system that trends approximately 300km in a north-west — south-east direction, broken by occasional gorges and narrow gaps (Jennings and Sweeting 1963).

The region is characterised as tropical semi-arid with a monsoonal climate (Beard 1979; Bureau of Meteorology 1996). The majority of the annual rainfall (600mm) occurs during the 'wet' season between November and April, often associated with cyclonic depressions. Rainfall during the remainder of the year is sporadic and it is not unusual to experience consecutive months when no rain falls at all. Annual evaporation levels are high (3000 to
Vegetation in the study area is primarily tropical savannah grasslands with a varying degree of tree and shrub cover. Sheltered gullies along the Napier Range with access to water accommodate occasional pockets of dry rainforest, although the slopes and base of the range are typically dominated by spinifex grass (*Triodia intermedia*), boabs (*Adansonia gregorii*), *Cochlospermum fraserii*, *Dodonea physocarpa* and *Grevillea pyramidalis*. The plain to the northeast of the range is dominated by a range of ephemeral and annual grasses (including *Cymbopogon bombycinus*, *Enneapogon purpurascens* and *Sorghum plumosum*), low-growing herbs and shrubs. Along the scattered, ephemeral watercourses occasional trees (e.g. *Terminalia* spp., *Grevillea* spp. and *Eucalyptus* spp.) can be sighted.

**Tufas in Australia**

Tufas are a soft, porous, calcareous, sedimentary deposit formed in limestone areas (karst), with a world-wide distribution (Lapidus 1990:519; Pentecost 1981). Within Australia important karst areas occur in the Kimberley (north-west), around Shark Bay and Cape Range (central west coast), the Nullarbor Plain (central south coast) and the Barkly Tableland (on the border between the Northern Territory and Queensland) (Gillieson 1993:129). To date few of the tufas in any of these regions have been the focus of specific investigations, except the work of Drysdale and Head (1994, 1998) on the formations at Louie Creek on the Barkly Tablelands and that of Viles and Goudie (1990; Goudie et al. 1990) on the Kimberley formations. However, in a more general sense, the limestone regions (especially the Nullarbor) have been the focus of various investigative studies (e.g. Dunkley and Wigley 1967; Ellaway et al. 1990; Gillieson 1993; Goede et al. 1990; Jennings and Sweeting 1963).

On the basis of radiocarbon and uranium-series studies, Drysdale and Head (1994, 1998) have demonstrated there have been at least three phases of travertine (tufa) deposition in the Barkly Tablelands region: immediately prior to (31 to 24 ka BP), during (24 to 11 ka BP) and immediately after (11 ka BP to present) the Last Glacial Maximum (LGM). They interpret the first and final phases as representing periods of increased moisture availability, while the middle phase represents a decrease in rainfall, although there was still sufficient moisture available in the landscape to support travertine formation.

The tufas of the Napier Range in the study area were the focus of a study carried out in the 1980s by Viles and Goudie (1990), the results of which are summarised in detail below so as to provide background information to the current investigation. Surveys along the range by Viles and Goudie (1990) revealed tufas were a common occurrence along the northeastern margin of the range (Fig. 2), where it is suggested their presence is ‘due in large part to the very high evaporation rates in the area which encourage precipitation of calcium carbonate’ (Viles and Goudie 1990:441).

A variety of tufa forms were recorded in the area including drapes (spring or waterfall features occurring on steeply dipping cliff faces), cones (spring or waterfall features occurring at cave entrances or the mouths of ephemeral streams), waterfall forms (occurring along stream beds and on pediment slopes) and stalactites and stalagmites (occurring in rock shelters). Further, it was noted that two different generations of tufas were present: relict and active. Viles and Goudie (1990) suggested the relict tufa deposits may have formed in an earlier wet phase, which was then followed by an arid phase (probably the LGM) causing tufa deposition to cease. The establishment of wetter conditions in the more recent past then permitted the resurgence in tufa formation, seen in deposits actively accumulating today. This
would imply that, unlike the Barkly Tablelands region, groundwater in the Kimberley during the LGM was insufficient to maintain tufa formation. Although they suggested it would be a useful exercise, no absolute dates were obtained from the Napier Range tufas by Viles and Goudie (1990:442).

General geochemical and petrographic characteristics of the Napier Range tufas were determined using Water Absorption Capacity (WAC) and Insoluble Residues tests, Atomic Absorption Spectroscopy (AAS) analyses, thin sectioning and Scanning Electron Microscopy (SEM) examination (Viles and Goudie 1990). Although in the field two different generations of tufas (active and relict) were observed, laboratory analyses revealed surprisingly few differences between or within tufas of the relict and active groups. Not surprisingly, the dominant constituent of all tufas examined was calcium carbonate. Goudie et al. (1990:316-17) report that at the end of the wet season algal communities cover much of the tufa deposits, with high water saturation evident, and that these communities probably contribute to the precipitation of calcium carbonate. Analysis indicated insoluble residue values were typically less than 10% by dry weight, although there were a few examples with considerably higher values than this. The primary insoluble residue was silica in the form of small quartz grains and cryptocrystalline material, which Viles and Goudie (1990:442) suggested were derived from either the limestone reef system or windblown dusts. Porosities were much higher in the active tufas compared with the relict forms. Organic material (mainly in the form of algal filaments) tended to be encrusted with calcium carbonate and therefore difficult to see, but in any case were visible only in thin sections of the active tufas.

In summary, while Viles and Goudie (1990; Goudie et al. 1990) had demonstrated the presence of numerous tufa deposits along the Napier Range, they had not obtained any absolute dates for their formation. Further, their studies demonstrated that high levels of silica were present in the deposits but did not indicate the specific presence of plant derived silica bodies among the insoluble residues. Likewise, organic material was observed in the tufas, but this was argued to be primarily in the form of algal filaments rather than windblown pollen grains.

The pilot study: description of the tufa, collection and laboratory procedures

During the course of other research being carried out in the southwest Kimberley in an archaeological rock shelter with a 40,000-year-old occupation record (see O’Connor 1995 and
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Wallis 2001), I became interested in whether further palaeoenvironmental data in the form of pollen and phytoliths might be gathered from the Napier Range tufas. Behind this interest lay a primary desire to locate a source of information relating to local vegetation history in addition to that obtained from the archaeological rock shelters I had hitherto been working on, the interpretation of which was difficult owing to the cultural bias of the preserved assemblages.

A pilot study designed to sample a tufa was therefore conducted, with the general aims being:

(a) to determine whether phytoliths might be preserved among the insoluble residue component of the Napier Range tufas;

(b) to determine whether windblown pollen grains might be preserved among the tufa deposits;

(c) to determine whether there was any visible stratification preserved within the tufa formations, thereby indicating their development through time; and

(d) if pollen was indeed preserved, to obtain an AMS radiocarbon date for the onset of tufa formation.

In the field season of 1998 the tufas along the Napier Range northwest of Windjana Gorge (Lennard River) were re-surveyed and assessed for their analysis potential. Eventually, a large active waterflow tufa situated approximately 20km to the east of Windjana Gorge along the base of the north-eastern margin of the range was selected for detailed examination (Figs. 3 and 4). This tufa was selected on the basis of its large size (compared with other observed formations) and easy access (many other highly suitable cone-form tufas were observed in shelter openings high in the cliff faces, but access to them was virtually impossible given the rugged nature of the terrain).

Initially a diamond-tipped drill was used to attempt to recover a core through the tufa to the underlying basal rock. Unfortunately, the necessity of using water to lubricate the drill tip, combined with the dry powdery nature of the deposit, resulted in the recovery of watery sediment with no stratigraphic integrity. It was decided instead to cut into the deposit using a shovel and attempt to take column samples. Once the section had been cleaned and stratigraphic details recorded, a trowel was inserted into the section wall and gently levered upwards. This forced the tufa to break away in relatively large, flat panels, approximately 1cm in thickness.

The tufa was coloured dark grey on the surface and underneath was a pale yellow, and was approximately 8cm thick. As illustrated in Figure 4, stratification was evident, although owing to the nature of the material it was not possible to collect samples in depth increments smaller than 1cm. In total, eight 1cm-thick samples were collected.

Figure 3. Photograph showing general view of tufa.
In the laboratory two sub-samples of each 1cm tufa layer were selected, one each for pollen and phytolith extraction. Prior to processing, the outer surfaces of the tufa deposit were removed and discarded so as to minimise the potential for contamination, given the collection technique. The pollen sub-samples were processed using the standard protocol employed in the Pollen Laboratory, Department of Archaeology and Natural History, RSPAS, at the Australian National University (see Appendix 5.5 in Wallis [2000]). One of the pollen sub-samples was submitted to the Australian Institute of Nuclear Science and Technology (AINSE) for Accelerator Mass Spectrometry (AMS) radiocarbon dating in order to provide an absolute age estimate for the commencement of tufa formation. The phytolith sub-samples were initially subjected to a weak hydrochloric acid bath to remove the bulk of carbonates and thereby enable disaggregation. After this, they were processed using a standard protocol for heavy liquid phytolith extraction from sediments (adapted from Bowdery [1998:Appendix 14.1]). Phytolith residues were mounted in Eukitt for viewing with an Olympus BH2 stereomicroscope. Percentages of phytolith types present were calculated by scanning transects until 1000 phytoliths had been recorded. Other microfossils such as carbonised particles, starch grains, sponge spicules and diatoms were also recorded during scans, although no attempts were made to pursue specific identifications of these particles.

**Dating**

Being an active tufa, the surface of the deposit was presumed to be modern in age. A single AMS radiocarbon date was obtained on pollen recovered from Sample 2A/15, immediately above bedrock (8cm below surface). The age determination returned was 2160±70 BP (OZD 938, uncalibrated). Presuming there have been no breaks in deposition, this indicates a tufa growth rate of approximately 1cm per 275 years (or 3.6cm per 1000 years), although see later discussion in regard to this issue.
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Percentage by weight of phytoliths

As presented in Table 1, phytoliths constitute only a minute fraction of the overall tufa deposit, at most being 0.1% by dry weight, a figure considerably lower than the IR values recorded by Viles and Goudie (1990). The reasons for such a substantial discrepancy are unclear, although possibly the IR of Viles and Goudie (1990) contained a high quantity of sand grains with a diameter larger than 300µm—grains which are typically beyond the average size of phytoliths and which are physically removed during the phytolith extraction process.

Table 1. Information relating to tufa samples, including percentage by weight of phytoliths.

<table>
<thead>
<tr>
<th>CODE</th>
<th>DEPTH BELOW SURFACE (cm)</th>
<th>ORIGINAL TUF A SAMPLE WEIGHT (g)</th>
<th>PHYTOLITH FRACTION WEIGHT (g)</th>
<th>PERCENTAGE PHYTOLITHS</th>
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<td>0.02</td>
</tr>
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<td>0.03</td>
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<tr>
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</tbody>
</table>

Phytolith assemblage1

Figure 5 shows the percentage composition of phytolith types and numbers of other microfossils within the tufa.

Most of the phytolith types encountered derive from grasses, with bilobes and spheroids increasing somewhat in importance in the upper samples. No definite non-grass phytolith types were observed. In most samples irregular plate fragments, nondescript fragments and elongates with two straight edges collectively comprise about 50% of the assemblage. Towards the base of the sequence there is a massive increase in the percentage of nondescript fragments and greater evidence of the effects of weathering (e.g. pitting, rounding, fragmentation).

Starch grains were recorded in small numbers in most samples, with a slight increase at 4–5cm below the surface. Carbonised particles were commonly encountered in the samples, reaching their highest quantities 5cm below the surface. A single fragment of siliceous sponge spicule was observed in the sample taken from 2cm below the surface. While incomplete in nature, the sponge spicule displays no evidence of other physical or chemical weathering. Diatoms were observed in abundance in the uppermost sample and were recorded in extremely limited quantities below this. Only one morphological diatom type was observed and no attempt was made to identify it taxonomically.

Discussion

The phytolith assemblage recovered from the examined tufa reveals comparatively little change during the possible 2000 years of accumulation (see below). The assemblage is almost

1 Although small quantities of pollen were recovered from the tufa samples, results from their analysis are not yet available owing to the absence of a suitable Kimberley reference collection.
entirely comprised of grass-type phytoliths, which is not surprising given that vegetation in the tufa vicinity is dominated by grasses, with very few trees and/or shrubs present. There is relatively little change in phytolith types encountered throughout the sequence, which is not unexpected given the limited temporal span of the tufa deposit. The increase in weathered and otherwise damaged phytolith morphologies towards the base of the deposit suggests that through time phytoliths in tufas may be subject to processes that may ultimately be deleterious to the assemblage.

That diatoms occur in any abundance only in the uppermost surface sample and are of restricted morphological types is of taphonomic interest. Presumably diatoms were once present in the lower levels of the deposit as well and have since been destroyed, although the mechanisms behind this remain unclear, since the presence of phytoliths indicates not all siliceous microfossils are immediately vulnerable to such destruction. This may have implications for the preservation of more fragile phytolith types within the tufa deposit. Such processes need to be studied in detail before phytolith accumulations within tufa deposits can be used for palaeoenvironmental reconstruction purposes with any confidence. Furthermore, the presence of diatoms in the tufa indicates that tufa surfaces may be a parent source of diatoms in sediments within archaeological rock shelters in the region.

The presence of a single, small fragment of sponge spicule in one of the tufa samples indicates the capacity of this microfossil type for transportation, presumably by wind from one of the nearby rivers, although not in any apparent abundance. While Devonian-aged sponges are known to occur in the limestone of the Napier Range and may therefore have been the source of the fragment in the tufa, this is highly unlikely given that the Devonian-aged sponges have all been calcified (Rigby 1986:5).

The presence of preserved carbonised particles in the tufa may prove to be of use in assessing changes in firing regimes in the local area through time. Presumably these particles are incorporated in tufa deposits during local fire events when high quantities of carbonised particles in ash are shifted via wind action. Presumably, however, this would primarily occur during the wet season when the tufas are active and susceptible to microfossil incorporation—a period when fires are unlikely to occur naturally.

Figure 5. Diagram showing phytolith types and other microfossils in tufa samples.
As far as is known there have been no previous attempts to determine the age of the Napier Range tufa deposits, although Viles and Goudie (1990) hypothesised that there were at least two generations of tufas: active Holocene examples and relict, presumably pre-LGM, specimens. The provision of a c. 2000 BP near basal date for the tufa collected in the pilot study raises several issues of interest.

Firstly, the work of Drysdale and Head (1998) on tufas on the Barkly Tablelands indicates that a hard-water effect may cause over estimations of radiocarbon tufa ages by as much as 2600 years at that site owing to the incorporation of ‘dead’ carbon from underlying bedrock. It is unlikely the Napier Range radiocarbon date has been affected to this degree — given that the tufa surface can be presumed to be modern, it is highly unlikely that 8cm of tufa would have formed in a short period (otherwise the tufa deposits along the range would be much more extensive). However, such factors have not been investigated in the current study, but are required if further studies are instigated.

Secondly, even if the 2000 BP date stands, can it be considered an accurate representation of the true age of the tufa deposit? It is likely that the extent of the tufa has increased through time to encompass a much greater area than it did initially. If so, it is possible that the sampled portion of tufa does not include a complete stratigraphic section incorporating the oldest layers of the tufa and therefore the 2000 BP date does not represent the onset of tufa formation.

If, however, the 2000 BP age is accepted as dating the (near) commencement of tufa deposition, it may have important implications for regional palaeoenvironmental reconstruction or for looking at changes in the hydrological regime at the local sampling site. The period after the LGM was one of climatic amelioration. Evidence from a range of sites within Australia, such as Puritijarra rock shelter (Bowdery 1996, 1998), Lake George (Singh and Geisler 1985; Singh et al. 1981), Lake Eyre (Magee et al. 1995), Lake Tyrrell (Luly 1993) and Lake Frome (Singh 1981; Singh and Luly 1991) in the central and southern areas of Australia, indicate the occurrence of an early to mid-Holocene warmer, wetter phase. The limited northwest evidence also suggests wetter conditions after the LGM, although there is little agreement regarding the timing. Miller et al. (2000) and Wyrwoll et al. (2000) hypothesise that the summer monsoon may have commenced in the very late Pleistocene and Wyrwoll et al. (1986, 1992) further suggest that climate in the northwest has been stable for at least the past 6000 years. Jennings’ (1975) King Sound studies suggest a period of increased rainfall from 7000 to 6000 BP. Head and Fullagar (1992) present evidence for swamp sedimentation at a number of sites in the east Kimberley from 2000 BP, with little evidence for increasing aridity over this period. Overall, what is known of palaeoenvironmental conditions in the northwest suggests favourable conditions for tufa formation may have been present from as early as 12,000 BP. If there was also an early to mid-Holocene warmer-wetter phase, it too would have presented ideal tufa formation conditions. Hence, it is difficult to reconcile tufa formation beginning c. 2000 BP with the other available evidence.

While a single date that has not been corrected for the hard-water effect does not provide substantial evidence on which to base reconstructions for the onset of higher rainfall availability, it has demonstrated the potential of radiocarbon dating such deposits in this region of Australia. A much expanded research program, including studies of the nature of tufa formation, investigations of the local hard-water effect and multiple sampling of single tufa deposits (incorporating detailed stratigraphic investigations), is required in order to address these issues. Dating of numerous tufa deposits is needed in order to determine the time of commencement of widespread tufa formation in the southwest Kimberley and assess the significance of this event for palaeoenvironmental reconstruction and changes to the local hydrological regime, in a similar vein to the work carried out by Drysdale and Head (1994,
1998) in the Barkly Tablelands region. Such an undertaking was beyond the scope of this project, but would provide useful palaeoenvironmental information for the local Kimberley region.

Conclusions

The results of this, albeit restricted, pilot study of a tufa deposit from the Napier Range has provided a range of useful information, the most salient points of which are reiterated below:

- Tufa deposits in limestone areas may contain small quantities of microscopic particles including pollen, starch, phytoliths, carbonised particles, diatoms and sponge spicules.
- Preserved pollen may be recovered and dated using AMS radiocarbon techniques to provide a chronological framework for tufa formation, although hard-water effects should be taken into consideration. The dating of tufa deposits can provide information relating to palaeoenvironmental and local hydrological conditions, given that tufas form under warm-wet conditions of high evaporation.
- The recovered microfossils (pollen and phytoliths) may be analysed to provide information relating to palaeoenvironmental conditions in the tufa vicinity, provided a sequence of suitable time depth is recovered.

Despite these positive results, the study has also demonstrated that a great deal more research into phytolith assemblages and tufa formation needs to be carried out in order to effectively use these deposits as a source of data. The purpose of this paper has been merely to elucidate the potential of this approach, as well as some of the critical avenues for future research, for researchers working in limestone areas with an interest in palaeoenvironmental change.

Acknowledgements

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References


Quantitative palaeoenvironmental reconstructions using phytolith analysis: A review

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Keywords
phytoliths, palaeoenvironmental records, transfer functions, New Zealand

Abstract

The inclusion of phytolith analysis in palaeoenvironmental research has become more common in the past decade, where phytoliths have primarily been viewed as proxies for vegetation. With the high preservation of phytoliths in palaeoenvironmental deposits where other proxies are poorly represented, the exclusion of phytolith analysis from research is difficult to justify. However, the current lack of taxonomic precision in the technique has invoked suspicion about its potential to provide additional insights into the palaeoenvironmental record that other analyses provide (e.g. palynology). Recent analyses of modern phytolith assemblages from New Zealand in a quantitative transfer function approach to palaeoenvironmental reconstruction provide an additional incentive for the technique to be utilised as a proxy for environmental change. These findings are reviewed, comparing the phytolith-pH based transfer function with the highly developed pollen, diatom and scaled chrysophyte based transfer functions for the northern hemisphere (high-latitude Europe and North America). The performance of the phytolith-pH transfer function highlights the potential of the technique, with expanded datasets and improved taxonomic resolution, to act as an acidification proxy for soil and sediment. Developmental requirements in phytolith taxonomy and the understanding of taphonomic processes for quantitative phytolith analysis are also addressed. Suggestions are made regarding the potential application of quantitative phytolith analysis for additional interpretation of palaeoenvironmental records.
Introduction

Phytolith analysis has provided new insights into the interpretation of palaeoenvironmental records, especially where other environmental proxies (e.g. pollen) have been poorly preserved. Although the technique has considerable potential, studies have often been entirely descriptive lacking quantifiable and testable interpretations (Prebble et al. 2002). Birks (1995) suggests that in order to test hypotheses concerning past environmental changes and also evaluate biological and climate models, palaeoenvironmental data needs to be quantified. Most palaeoenvironmental studies involving phytolith analysis have been qualitative, focusing on the division between either short and tall grasslands (e.g. Alexandre et al. 1997), or, arboreal and non-arboreal vegetation (e.g. Barboni et al. 1999; Carter 2000) as broad measures of climate change. Few attempts have been made to assess modern phytolith assemblages for quantitative palaeoenvironmental reconstruction.

As for any palaeoenvironmental reconstruction where the contemporary ecology of an organism, or fragment of an organism (e.g. phytoliths), is comparable with the fossil record, its value is dependent on the quality and extent of information obtained. In the case of phytoliths, this means defining the relationship between phytoliths and environmental parameters as well as the contribution of taphonomic processes to fossil phytolith deposition. Developments in applied statistical techniques, particularly for palaeolimnological research of lakes, have provided a platform for understanding contemporary species ecology in a form directly comparable with the fossil record for quantitative palaeoenvironmental reconstruction (Birks 1995). The construction of transfer functions (or inference models) that connect present-day biological assemblages or sedimentary variables to modern environmental parameters (response models) is one widely used methodology. This methodology is based on robust statistical techniques that can adequately model the complex environmental relationships involved. Much of the work in the development of quantitative transfer functions for palaeoecological reconstructions has been derived from palaeolimnological studies involving diatoms as a proxy for lake acidification records (e.g. Birks 1995; Birks et al. 1990). Techniques derived from diatom studies have been directly transferred to other proxies of palaeoenvironmental change (e.g. Lotter et al. 1997; Korhola et al. 2000) allowing for a host of species-environment relationships to be defined. Although phytoliths generally lack specific affiliations with the plant species from which they are derived, comparison of phytolith assemblages from modern and fossil settings may be utilised in the same way.

Prebble et al. (2002) have applied the transfer function methodology to quantify the relationship between modern phytolith assemblages and environmental parameters for the quantification of a palaeoenvironmental record (Prebble and Shulmeister 2002) from the Lower Taieri Plain, east Otago, South Island, New Zealand. For this review, the phytolith-based pH training set and transfer function (Prebble et al. 2002) are compared with northern hemisphere modern pollen-pH (Birks 1994), diatom-pH (Bigler and Hall 2002) and scaled chrysophyte-pH (Paterson et al. 2002) studies. These studies are used for comparison for three reasons. Firstly, comparable quantitative palaeoenvironmental studies are lacking in New Zealand (see below). Secondly, these transfer functions are based on data-rich training sets and are characterised by precise taxonomic, spatial and modern environmental data. Finally, the ecology of pollen and diatom and scaled chrysophyte taxa from the northern hemisphere, particularly boreal Europe and North America, is well understood. In many ways these northern hemisphere datasets can be regarded as an empirical base for any quantitative palaeoenvironmental reconstruction using the transfer function technique.

Despite the methodological and ecological constraints on making such a comparison, in order to gain some impression of the potential of phytolith analysis in a quantitative
palaeoenvironmental approach, such an examination is useful. The ability of phytolith assemblages to adequately reflect changes in any given environmental variable is the fundamental question addressed here. This review is structured as follows:

1. A summary is given of quantitative approaches that have been applied to phytolith analysis.
2. The development of transfer functions from palaeoenvironmental proxies in New Zealand is described.
3. A summary and comparison of phytolith, pollen, diatom and scaled chrysophyte training sets and transfer functions is provided.
4. An interpretation of the environmental proxies and their ecological relationship with pH is presented.
5. Finally, the requirements for improving phytolith-based transfer functions are addressed.

As the application of statistical techniques for quantitative palaeoenvironmental research has been extensively reviewed (e.g. Birks 1994, 1995, 1998; Lotter et al. 1997; ter Braak 1995), it is not discussed here in detail.

Quantitative approaches to phytolith analysis
Kurmann (1985) was the first, in part, to examine modern phytolith assemblages for the quantification of a palaeoenvironmental record, using analysis of variance to quantify differences between phytolith assemblages from modern soils of short-grass prairie, tall-grass prairie, deciduous forest and a late Quaternary palaeosol from Kansas, US. Although limited in scale, Kurmann’s study showed the potential for a quantitative approach to phytolith analysis by statistically demonstrating the affinity of modern short-grass prairie phytolith assemblages to that identified from the palaeosol. Many attempts at quantitative phytolith analysis in palaeoenvironmental research have focussed on the North American Great Plains where quantitative estimates of climate change are based on the distribution of phytolith morphotypes specific to C3 and C4 (subfamily) grasses (e.g. Fredlund and Tieszen 1994, 1997). Kelly et al. (1991) used δ13C values of occluded carbon within phytoliths, which reflect proportions of C3 and C4 grasses, to quantitatively measure climate change from phytoliths within mid-Holocene sediments from the Great Plains. Some quantitative numerical techniques have also been applied to phytolith analysis for the interpretation of stratigraphic records. For example, Bush et al. (1992) applied rate-of-change analysis (Jacobson and Grimm 1986), a technique based on Detrended Correspondence Analysis (DCA) (Hill and Gauch 1980), to phytolith-stratigraphical data from a late Pleistocene-Holocene palaeoecological record from Lake La Yeguada, Panama. Quantitative approaches have been used to examine the characteristics of phytolith morphologies for classification purposes (e.g. Wilson 1985). In spite of these efforts, studies involving phytoliths have yet to fulfill all of the ‘basic requirements’ for robust quantitative palaeoenvironmental reconstruction (Birks 1994, 1995).

Apart from Prebble et al. (2002) and Prebble and Shulmeister (2002), no attempt has been made to quantify phytolith assemblages for the interpretation of the palaeoenvironmental record using quantitative statistical techniques in New Zealand. For a recent summary of phytolith research in New Zealand see Carter (2002).

Transfer function development for palaeoenvironmental research in New Zealand
Transfer functions have been developed for the reconstruction of sea-surface temperatures from marine sediment records near New Zealand. These have been based on modern assemblages of marine microorganisms including foraminifera (e.g. Nelson et al. 2000; Thiede et al. 1997) and dinoflagellates (e.g. Marrett et al. 2001). However, the development of transfer functions for reconstruction of the terrestrial palaeoenvironments of New Zealand is in its
developmental stages. Charman (1997) has developed water table and soil moisture transfer functions using testate amoebae from ombotrophic peatlands. Xiong and Palmer (2000) developed transfer functions for average late-summer temperature using tree ring chronologies of the conifer *Libocedrus bidwillii*. A diatom-salinity transfer function for the reconstruction of relative sea level has been developed (Ursula Cochran unpub. data), but not for any other environmental parameters.

As yet, no transfer functions have been developed from modern pollen data in New Zealand. Quaternary pollen records have been restricted to qualitative (i.e. most New Zealand pollen records) and semi-quantitative (e.g. Hall and McGlone 2001) interpretations. This is partly a result of the apparently poor relationship between modern pollen rain and environmental variables in New Zealand (e.g. Norton et al. 1986). Notably, similar problems have appeared in quantifying modern pollen rain-environment relationships elsewhere in the southern hemisphere (e.g. Kershaw and Bulman 1996). In addition, pollen analysts worldwide have opted for quantitative approaches that contrast with transfer function-based environmental reconstructions; for example, climate response surface models have been developed using only a set number of pollen taxa as opposed to the entire pollen assemblage (e.g. Huntley 1993). Hall and McGlone (2001) have recently applied a similar technique to modern pollen taxa from south-eastern New Zealand.

The training sets and transfer functions

Birks (1995) has outlined the number of modern training set samples, biological taxa and associated environmental variables necessary for the construction of robust transfer functions (Table 1). Values for the above components for the initial developmental training sets of the four studies used in this review are presented in Table 1. The Prebble et al. (2002) modern phytolith training set is lacking on two counts. Firstly, it is derived from replicate samples from 28 sites taken from under a range of depositional environments (e.g. forest soils and modern lake bottom sediment). Secondly, the number of phytolith morphotypes (13) falls well below the recommended 30, immediately suggesting that the explanatory ability of the modern phytolith training set to reflect changes in environmental variables is limited (see below for discussion).

The main features of calibrated training sets and pH-transfer functions developed in the four studies used in this review are presented in Table 2. The selection of linear or unimodal response models (Birks 1995) for each training set was determined by measuring the compositional gradient lengths using detrended canonical correspondence analysis (DCCA, Hill and Gauch 1980). As the gradient lengths of the phytolith and scaled chrysophyte

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<tbody>
<tr>
<td>Modern training set (number of samples)</td>
<td>30-300</td>
<td>10†</td>
<td>124</td>
<td>100</td>
<td>53</td>
</tr>
<tr>
<td>Modern biological data (e.g. number of taxa)</td>
<td>30-500</td>
<td>13</td>
<td>229</td>
<td>157</td>
<td>25</td>
</tr>
<tr>
<td>Associated environmental variables</td>
<td>1-20</td>
<td>13</td>
<td>2</td>
<td>19</td>
<td>1</td>
</tr>
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</table>

Table 1. Initial training set characteristics of the four studies compared with the recommendations of Birks (1995).

Note: † = 4 replicate samples from 27 sites (108) and 2 replicate samples from 1 site (2).
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Table 2. Calibrated training set and transfer function data for the phytolith, pollen, diatom and scaled chrysophyte studies.

<table>
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<tbody>
<tr>
<td>Number of samples</td>
<td>63</td>
<td>123</td>
<td>100</td>
<td>53</td>
</tr>
<tr>
<td>Number of taxa</td>
<td>12</td>
<td>223</td>
<td>157</td>
<td>25</td>
</tr>
<tr>
<td>pH minimum</td>
<td>4.8</td>
<td>&lt; 4.5 *</td>
<td>5.79</td>
<td>5.61</td>
</tr>
<tr>
<td>pH mean</td>
<td>6.29</td>
<td>n/a</td>
<td>6.66 **</td>
<td>6.58</td>
</tr>
<tr>
<td>pH median</td>
<td>6.2</td>
<td>n/a</td>
<td>6.72</td>
<td>6.63 ***</td>
</tr>
<tr>
<td>pH maximum</td>
<td>7.5</td>
<td>&gt; 6.5 *</td>
<td>8.07</td>
<td>7.3</td>
</tr>
<tr>
<td>pH standard deviation</td>
<td>0.6</td>
<td>n/a</td>
<td>0.43</td>
<td>0.41 ***</td>
</tr>
<tr>
<td>DCCA gradient length (standard deviation units)</td>
<td>0.7</td>
<td>n/a</td>
<td>2.84</td>
<td>1.07</td>
</tr>
<tr>
<td>% Variance explained by pH when sole constraining variable</td>
<td>5.8% in RDA</td>
<td>3.4% in CCA</td>
<td>8% in CCA</td>
<td>n/a</td>
</tr>
<tr>
<td>Statistical significance under 99 unrestricted permutations</td>
<td>p=0.086</td>
<td>p=0.01</td>
<td>p=0.01</td>
<td>n/a</td>
</tr>
<tr>
<td>Model type</td>
<td>PLS</td>
<td>WA-PLS</td>
<td>WA-PLS</td>
<td>PLS</td>
</tr>
<tr>
<td>Number of model components</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>( t^2 ) (jack-knifed)</td>
<td>0.4</td>
<td>n/a</td>
<td>0.77</td>
<td>0.8</td>
</tr>
<tr>
<td>RMSE (pH units)</td>
<td>0.39</td>
<td>0.75</td>
<td>0.15</td>
<td>0.16</td>
</tr>
<tr>
<td>RMSEP (pH units)</td>
<td>0.47</td>
<td>0.78</td>
<td>0.19</td>
<td>0.21</td>
</tr>
<tr>
<td>Maximum bias (pH units)</td>
<td>0.83</td>
<td>n/a</td>
<td>0.30</td>
<td>0.16</td>
</tr>
</tbody>
</table>

data were below two standard deviation units, linear response models were selected (i.e. partial least squares [PLS], ter Braak 1995). By contrast, unimodal response models were selected (i.e. weighted averaging partial least squares [WA-PLS], ter Braak 1995) for the pollen and diatom datasets (although no gradient length was determined in the pollen study of Birks 1994). Consequently the variance explained by the pH dataset was determined using redundancy analysis (RDA, ter Braak 1994) for the phytolith training set, and correspondence analysis (CCA, ter Braak 1987) for the pollen and diatom training sets.

No ordination data were presented for the scaled chrysophyte training set in Paterson et al. (2002). Although the ordination techniques contrast in a number of ways, the ability of the pH dataset to explain the percentage variance was highest for diatoms (8%), followed by phytoliths (5.8%), then pollen. However, the percentage of variance explained in the phytolith data is significant only at the 90% level \( p = 0.086 \) under 99 unrestricted Monte Carlo permutations.

The ability of the modern microfossil training sets to distinguish changes in pH is compared using a range of performance statistics generated in the transfer function process (see Table 1). The ordination results above are highlighted in the root-mean-squared-error of prediction (RSMEP) results, a value often used to assess transfer function performance. The additional scaled chrysophyte RSEMP result (0.21), although in a PLS model, is comparable with the diatom-based model (RSMEP = 0.19). Significantly, the number of PLS components in the phytolith model (4) in conjunction with the high maximum bias may reduce the value of the phytolith-pH transfer function (Birks 1998; Prebble et al. 2002).
Discussion

Pollen, diatoms, scaled chrysophytes and phytoliths, and their ecological relationship with soil pH

Pollen data inherently reflects those environmental variables that influence vegetation change (Cheddadi et al. 1997). Guiot et al. (1993) suggest that environmental variables such as soil pH influence vegetation only indirectly and may be poorly represented by the pollen record. Despite this, increased inputs of base cations into a system after fire (increasing pH) and the subsequent input of humic acids (lowering pH) from forest succession of acidic leaf litter from, for example, Pinus and Betula forest, has been inferred from a number of pollen-based studies (e.g. Korsman and Segerström 1998; Rhodes and Davis 1995). The post-depositional taphonomy of pollen assemblages may also be linked indirectly to pH through its influence on the oxidation process (Pennington 1996), preferentially degrading pollen grains depending on the concentration of oxidation-resistant sporopollenin (see review by Cambell 1999). This lack of identified direct ecological responses of pollen assemblages to changing pH may be reflected in the poor performance of the pollen-pH transfer function (RMSEP = 0.78). Notably, the Birks (1994) paper is the only study in which pollen-pH transfer functions have been developed.

The relationship between diatoms and pH, particularly lake water pH, has been well described (e.g. Battarbee 1984; Birks et al. 1990). As numerous diatom taxa are ecologically sensitive to changes in pH and are often well preserved in lake sediments, they have been exploited since the 1980s for quantifying the changing acidification of lakes (e.g. the Surface Water Acidification Project [SWAP], Birks et al. 1990). However, the primary cause of differential preservation of diatoms in most hydrochemical settings is dissolution (Ryves et al. 2001), where pH is only one contributing factor. In some environmental settings pH may be the dominant factor in dissolution or may be only a surrogate for other factors such as ionic concentration and nutrient availability (Battarbee 1984). In light of this, continuing experimental attempts are being made to quantify the dissolution of diatom silica in solutions with variable pH, temperature, salinity and ionic composition to improve the quantitative environmental inferences of diatom assemblages (e.g. Barker et al. 1994; Ryves et al. 2001). Nevertheless, the performance of diatom-pH transfer functions when compared with historical records of changing pH has in many instances been reliable (e.g. Hall and Smol 1996). The Fennoscandian diatom study (Bilger and Hall 2002) presented in this review is no exception.

Like diatoms, scaled chrysophytes are sensitive to changes in hydrochemical environments but are more commonly found in lacustrine settings (Paterson et al. 2001). Also composed of a biogenic silica skeleton, they are an important component of the phytoplankton of lake ecosystems. Studies of North American lake systems have found lake water pH to be the most important environmental parameter influencing scaled chrysophyte assemblages (Dixit et al. 1999; Paterson et al. 2001). Under some limnological settings, scaled chrysophyte assemblages have been found, using the transfer function approach, to provide equivalent estimates of changing pH to diatoms (Paterson et al. 2002). This finding is brought out in the comparison of the diatom and scaled chrysophyte transfer functions presented in this review ($r^2 = 0.77$ and $0.8$, respectively).

The influence of environmental variables on the formation of phytolith assemblages in soils or sedimentary deposits is difficult to quantify. As with pollen, there is an inherent relationship between phytoliths and the environmental variables that influence the parent vegetation. Unfortunately, for many regions such as New Zealand, where the taxonomic resolution of phytoliths is low, and vegetation-environment relationships are complex, this
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relationship is difficult to assess (Prebble et al. 2002). Prebble et al. (2002) assert that variation among phytolith assemblages can identify changes in environmental variables even when the phytolith-vegetation relationship is poorly understood.

Like pollen, changes in pH may be reflected in the composition of phytolith assemblages indirectly through changes in vegetation. This is, however, dependent on the ability of phytolith assemblages to identify changes in vegetation or, more specifically, to distinguish vegetation types, for example, with acidic soil characteristics. Prebble et al. (2002) found it difficult to establish this relationship in the New Zealand environment. The influence of pH in hydrochemical systems on diatom and scaled chrysophyte assemblages may be analogous to pH and phytolith assemblages in soils. There is a direct relationship between pH and the durability of biogenic silica in soils. The presence of Fe²⁺ and Al³⁺ under highly weathered conditions may increase phytolith durability by preventing silica dissolution (Birkeland 1999), and in very high or low pH soils may decrease phytolith durability by enhancing silica dissolution (Barber and Shone 1966; Piperno 1988). Under pH values between 3 and 9, soils are more independent of these effects. Extremely high or low pH soils, although rare, may have a marked effect on phytolith assemblages particularly as some morphotypes are more prone to dissolution than others (Piperno 1988). Interestingly, all of the pH values observed by Prebble et al. (2002) (pH measurements of soil in water from the top 5cm of the surface soil sample) were within the range of values that may be independent of the effects of intensified dissolution. The pH values obtained by Prebble et al. (2002), however, rely on only one measurement and may not represent the range of values possible for each site.

Constraints in the analysis of modern phytolith assemblages

In order to develop high-quality modern training sets there is an implicit need for high sampling and taxonomic resolution in quantitative palaeoenvironmental reconstructions (Birks 1994, 1995). Modern phytolith assemblage training sets could be improved by increasing the resolution of field sampling within a more comprehensive sampling strategy. Prebble et al. (2002) selected modern sites on the basis of their vegetation type, not their depositional characteristics. Birks (1995) recommends that modern proxy assemblages be sampled from sites with comparable sedimentary settings. The development of a phytolith-pH transfer function may be improved in a sampling strategy based along a modern soil acidity gradient. The expansion of the modern training set is essential to increase the diversity of modern analogue samples available for the interpretation of palaeoenvironmental records.

The current low taxonomic resolution of phytolith analysis in New Zealand limits the ability of relationships between environmental variables, plant distribution and phytolith assemblage composition to be defined. Currently only one phytolith morphology (Nikau palm Rhopalostylis sapida) found in palaeoenvironmental records in New Zealand has been identified to plant species level (Carter 2002). An improved system of classification and taxonomy would allow the relationship between phytoliths and a range of environmental variables to be quantified within the confines of phytolith formation processes in plants. The proposed ‘universal phytolith key’ (Bowdery et al. 2001) may assist in quantifying this relationship. Suitable taxonomic precision of phytoliths may already exist for some regions where phytolith systematics is developed (e.g. Panama, Piperno 1988). For transfer function development, an improved taxonomy would potentially increase the compositional gradient of the phytolith training sets to a level where more ecologically realistic response models can be utilised. Using RDA ordination, Prebble et al. (2002) identified only one morphotype with a statistically significant relationship with pH (elongate forms).

Paterson et al. (2002) provide a comparison of modern scaled chrysophyte assemblage training sets when the number of samples and taxa have been increased. In this
case the modern training set was expanded from 53 samples and 25 taxa (training set presented in Table 2) to 117 samples and 34 taxa. The expanded dataset incorporated samples from a broader region with sample-pH variability. The compositional gradient measured by DCCA was increased from 1.07 standard deviation units to 2.23 allowing the incorporation of the more ecologically realistic unimodal response model into the data analysis. The statistical performance of the expanded transfer function measured by RMSEP did not improve, although when applied to a palaeoenvironmental record the number of appropriate modern analogues matching fossil samples increased, suggesting the expanded training set and transfer functions are more reliable.

Reiterated in a number of phytolith studies is the need for a greater understanding of taphonomic processes. In order to effectively utilise the transfer function approach to environmental reconstruction the response of phytolith assemblages to taphonomic processes needs to be quantified. These processes in many instances may have a comparable influence on other siliceous microfossils (e.g. dissolution of biogenic silica) where the quantitative effects of taphonomic processes are often well documented through extensive experimental examination (e.g. Barker et al. 1994; Ryves et al. 2001). Taphonomic processes in phytolith analysis could be examined along similar experimental lines.

In addition, the environmental variable records required for environmental reconstruction need to be improved. In this study pH measurements were taken at a single time interval whereas pH can vary seasonally and annually (Battarbee 1984). Incorporating more representative environmental data into the transfer function approach has been addressed by Birks (1998).

**Implications for phytolith-based transfer functions**

Despite its limitations relative to the strong pH affinity of diatom and scaled chrysophyte assemblages (RMSEP = 0.19 and 0.21, respectively), the phytolith-pH transfer function appears to be more reliable than that derived for pollen (e.g. RMSEP = 0.47 and 0.78, respectively). Although the calibration process employed by Birks (1994) was minimal, the ecological relationship between pH and pollen may in some part reflect the poor pollen-pH transfer function. To my knowledge, no pollen-pH transfer functions have been undertaken since Birks' analysis. This may mean that phytoliths provide the best biological proxy measures of past acidification changes in soils adjacent to bodies of water. This relationship between phytolith assemblages and soil chemistry variables needs to be explored alongside independent proxy sources including the soil/sediment record.

The potential of phytolith analysis to obtain palaeoenvironmental information from soils and palaeosols was recognised early in the development of the technique (e.g. Rovner 1971). The suite of information that can be obtained from phytoliths in soils has continued to develop. Apart from recording past vegetation signals, phytoliths have recently been used to obtain signatures of bioturbation (Grave and Kealhofer 1999; Humphreys et al. this volume) and particle percolation processes in soils (Humphreys et al. this volume). Kurmann's (1985) initial discovery that modern phytolith assemblages can be utilised for the quantification of a palaeoenvironmental record in soils has been extended by Prebble et al. (2002) and Prebble and Shulmeister (2002), where phytolith assemblages potentially provide a direct proxy for past soil chemistry processes (e.g. soil weathering and conductivity). The potential exists for phytolith-based transfer functions to incorporate bioturbation and percolation processes as part of a quantitative approach to the reconstruction of past soil processes.
Conclusions

The exploration of modern phytolith assemblages using the quantitative transfer function approach can provide an additional means of estimating past environmental change. It can also provide additional information on the taphonomy of phytolith assemblages and the ecology of phytolith morphotypes that may otherwise remain unexplored. The preservation of phytoliths in soils in contrast to other biological proxies makes soils an ideal environment in which to test the efficacy of the quantitative transfer function approach. For many palaeoenvironmental reconstructions, particularly for terrestrial environments, it is difficult to justify the exclusion of phytolith analysis in a multiproxy approach. In order for the utility of phytolith analysis to be effective it must progress alongside the advances made in other microfossil analyses, using comparable analytical techniques (e.g. transfer functions), producing comparable results. On the back of such advances is the continuing requirement to understand the empirical relationship between phytoliths, vegetation and environmental variables.

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Design, methods and initial results for microfossil research in Kahikinui, Maui, Hawaiian Islands

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Keywords
microfossils, phytoliths, Hawaii, Polynesia, prehistoric agriculture

Abstract

In this paper the research design, field techniques, laboratory methods and initial results for microfossil research taking place as a component of the Kahikinui Archaeological Project, Maui, Hawaiian Islands, are presented. This doctoral research forms a component of this project and is based on the explicitly conjunctive use of multiple lines of archaeological and palaeoecological evidence. These are being used to address a series of research questions involving the spatial and temporal distributions of pre-contact agricultural practices, as well as the history of ecological change in the region. Archaeological evidence includes site settlement patterns derived from large-scale project surveys and investigation of individual sites interpreted as ‘agricultural’ in function. Palaeoecological data is being recovered from archaeological site contexts, as well as from a series of surface-to-bedrock trenches excavated systematically at 41 locations. While these trenches are generally shallow, profiles have nonetheless provided interpretable stratigraphic sequences and a body of soil and sediment samples that are currently being processed and analysed for their microfossil content. In this paper I present initial ‘quick scan’ microfossil data from analysed trench profiles at two sites of archaeological investigation, and discuss how patterning in these assemblages may assist in interpretation of the formation, chronologies of use and abandonment, and localised landscape histories of these site locations.
Introduction

In this paper I review my research design, field and laboratory methods, and emerging results for microfossil research taking place as a component of UC Berkeley’s Kahikinui Archaeological Project. The project’s principal investigator is Kirch (1997), with the collaboration of archaeologists from the State of Hawaii Department of Hawaiian Home Lands (Dixon et al. 1997) and Northern Illinois University (Kolb and Radewagen 1997). As a contribution to this larger project, the current research attempts to understand the spatial and temporal dynamics of past agriculture and ecology in a region of Maui (Hawaiian Islands) called Kahikinui (Fig. 1). Archaeological, archaeobotanical and palaeoecological research in this region has been designed to address several broad local and regional research questions, including:

(a) To what degree can we reconstruct Kahikinui’s pre-human patterns of native vegetation using evidence from archaeological contexts?
(b) What were the spatial and temporal distributions of Hawaiian agricultural practices in Kahikinui?
(c) What were the ecological effects of such economic practices as well as later impacts from post-contact cattle ranching?
(d) What can the relationship between patterns of Kahikinui’s geological, climatic and ecological variability, and human land use histories, tell us about how pre-contact Hawaiian communities adapted to a regional landscape which can be described as environmentally marginal (Kirch 1998) and environmentally complex (in terms of parent material ages, microtopography, rainfall, wind exposure or shelter, and operative sediment transport processes)?

Figure 1. Map showing islands of the Hawaiian Archipelago. Box superimposed on southeast Maui represents the area shown in Figure 2 (after Kirch 1985, Stearns 1946 and Zimmerman 1947).
The Kahikinui study area

Since its inception in the 1960s, archaeological research in Kahikinui has been based on its potential to represent a relatively undisturbed archaeological settlement pattern across an entire ancient land district (moku) (Kirch 1997). Elsewhere in Hawaii, most areas have had at least a portion of the archaeological record impacted by resort development, plantation agriculture or other modern development. Kahikinui is also an ideal place to conduct palaeoecological research focused on retrieval of evidence from archaeological contexts since sites occupy a set of environmental gradients, largely based on altitude and microtopography, wherein rainfall, temperature, soil development and nutrient cycling vary in a complex but reasonably controllable manner. Also, Kahikinui’s modern surfaces have been formed by in situ weathering of multi-aged basaltic lava flows (in the study area, ~50 to 8 kya) (Bergmanis 1998, pers. comm.) stratigraphically superimposed upon one another, and layerings of volcanic pyroclastic deposits (tephra and cinder) which pre-date human occupation of the area. While this certainly complicates the study of stratification in Kahikinui’s sub-surface soil and sediment profiles, it also provides opportunities to examine localised settings where archaeological settlement patterns and environmental variables can be directly compared and contrasted.

Although historic period impacts on the archaeological sites have been fairly minimal, the area’s native vegetation has suffered greatly under 150 years of cattle ranching and browsing by feral goats, as well as a perpetual state of general ecosystemic disequilibrium instigated by human activities and floral and faunal introductions (Meideros et al. 1986; Staples and Cowie 2001; Stone et al. 1992). Human impact on vegetation change in Kahikinui probably began with colonisation, and even areas colonised late in the sequence may have been impacted in advance of local settlement by the spread of the Polynesian rat (Rattus exulans), which may have thrived in the competition-free environment and decimated keystone taxa dominant in the pre-human ecosystems (Athens pers. comm.). This situation makes a systematic analogue approach to microfossil interpretation especially difficult for Hawaii, where intact modern examples of xerophytic or mesophytic native plant communities are almost entirely non-existent.

Previous research efforts in Kahikinui have focused mainly on two central ahupua’a (narrow contact period native Hawaiian land division units which run from coast to mountain) called Kipapa and Nakaohu. This sub-region (Fig. 2, shaded box) has undergone full coverage survey by the Chapman, Kirch and Dixon archaeological teams (Dixon et al. 1999; Kirch 1997).

Research design

While research questions involving agriculture and palaeoecology continue to form the focus of numerous researchers in Polynesia (e.g. Kirch and Hunt 1997), hard archaeobotanical evidence with which to address these generally plant-related subjects is restricted in nature. Organic remains in Hawaii tend to preserve poorly and efforts at interpreting assemblages of carbonised seeds using traditional palaeoethnobotanical flotation methods have had limited success. Also, for Kahikinui and many of Hawaii’s other more arid regions, ‘wet-site’ sediment coring locations are few and far between. This is due largely to the inability of the region’s relatively young, highly porous and permeable volcanic soils, sediments and parent materials to hold standing water (Bergmanis 1998; Stock et al. in press). Wood charcoal is commonly recovered from archaeological excavations throughout Hawaii, however, when used alone,
such evidence is subject to several biases (Boyd 1988; Hather 1994; Thompson 1994).

During formulation of the current research design, it was recognised that the research questions were in many ways similar to those of sediment coring/palynologist colleagues at UC Berkeley’s Department of Geography, whose research foci involved prehistoric agriculture, vegetation change and landscape histories. Our methods and available data sets were quite different. While the interpretive strengths of sediment coring data, derived ideally from stratified sequences in lake floors or anaerobic terrestrial sediments, are acknowledged, a goal for the current project has been to determine the extent to which it is possible to address ‘pollen coring’ questions in an environment without suitable coring locales. It has also been intended to take advantage of the unique spatial potential of sampling from site and trench excavations across a broad archaeological landscape, rather than from an off-site lake bottom.

Figure 3 represents an early attempt to schematically summarise the target data sets and their contexts. Three years later, and despite some adjustment in the relative importance or availability of some of the outlined data sets (for example, regional pollen data cannot yet be incorporated), this figure still represents the backbone of the overall research design. In addition to samples collected from excavated household and ritual archaeological sites, trench excavations and the study of profiles and soil and sediment samples collected from them are also emphasised. Trench digging as a means by which to investigate agricultural, environmental and geomorphological questions has a long and reputable history in Hawaiian archaeology (and elsewhere in the Pacific Islands — see Kirch and Hunt 1997). The first five trenches excavated as part of the current study were dug in tandem with Kirch and Yen, two participants in many of the early settlement pattern/ecologically oriented Hawaiian archaeological projects pioneered in the late 1960s (e.g. Kirch and Kelly 1975; Yen et al. 1972). Expanding upon these early efforts, 36 more trenches (shown as black dots in Fig. 2) were excavated (with the help of numerous assistants).

Trench locations were chosen according to four criteria:

1. Areas of sediment aggradation in order to expose stratified (rather than deflated) soil and sediment profiles. These were generally excavated in microtopographic ‘concave situations’ or else behind natural or constructed sediment trap features.
2. To sample a systematic range of elevations and substrates.
3. To more closely investigate sites with architectural remains suggestive of use for cultivation, sediment retention or erosion control.
4. To sample off-site ‘control’ locations which appeared free of anthropogenic modifications.

It should be noted that aeolian erosion and deflation in more coastal areas has completely stripped upper soil horizons from large areas subject to heavy feral goat browsing.
and disturbance, so some areas had to be carefully explored for locations with any degree of topsoil retention. After trench excavation, profiles were photographed, drawn and sampled using bulk sampling of visually apparent strata and more intensive column sampling to accommodate less visible variation.

Because only a small number of Polynesian crop plants produce identifiable silica phytoliths (Pearsall 1990), the goals for how microfossils could contribute to the project were relatively modest and involved the type of broad reconstruction and stratigraphic interpretation of vegetation types found in studies such as Pearsall and Trimble (1984) or Alexandre et al. (1999), such as grass-dominated, arboreal or mixed, with the potential to add information from more detailed taxonomic identifications as possible.

**Laboratory methods**

As was the case for Pearsall and Trimble (1983), microfossil extraction problems with the Hawaiian sediments were immediately encountered. These details are discussed more specifically in another paper (Coil et al. in press), and hence specifics are not provided here. Eventually, a successful protocol for simultaneous extraction of phytoliths, pollen, diatoms and microscopic charcoal was developed, adapted from earlier efforts in this direction by researchers including Fredlund (1986) and Lentfer and Boyd (1998). Unfortunately, starch granules did not seem to survive this protocol, probably because of the addition of a hot KOH
step to help contend with the high humic colloids content found in many of the Kahikinui samples and typical of many tephra-derived soils (Ugolini and Zasoski 1979). Since starch evidence remains a desirable component of this research, further efforts to extract starches, perhaps in a separate process applied only to targeted contexts, will be attempted in the future.

The use of prepared tablet spore markers to allow absolute quantification of microfossil types (Powers and Gilbertson 1987), staining with blue and red dyes to highlight pollen details and identify cellulose-based microfossils (Ruzin 1996), and steps to derive elastic particle size data were incorporated into extraction protocols with varying degrees of success. Including dyed spore markers such as prepared spore tablets or aliquots to allow absolute quantification of microfossil types is a goal that will continue to be pursued. Early attempts were encouraging but need further refinement (see Fig. 6).

**Emerging results**

Microfossil extractions, which have been performed on a fairly wide range of soil and sediment samples from Kahikinui, usually reveal preservation of high densities of silica phytoliths (of varying morphological types), with some preservation of pollen and spores in most samples, and variable presence of microscopic charcoal particles and diatoms (Fig. 4). In this section I demonstrate how microfossil data is beginning to play its role in supplementing other archaeological and archaeobotanical data sets. As more formal counting and identification procedures are still being refined, the results presented herein should be considered as preliminary and will be subjected to more formalised quantitative and taxonomic testing in the future. Already, however, it is clear that the presence of many palm-dominated samples (Fig. 5), as well as many samples with palm phytoliths present but less dominant (see Fig. 4), when studied in their spatial distributions, should present a data set without precedent in Hawaii (Athens 1997) or elsewhere in Polynesia. AMS radiocarbon dating of such assemblages (Mulholland and Prior 1993), which it is planned to perform in the future on targeted samples, may add critical temporal data on palm distributions.

Other distinctive assemblages, such as those dominated almost exclusively by what appear to be wood-derived phytoliths (Fig. 6), are also noteworthy. While the phenomenon of silica particle accumulation in wood cells is well documented for a wide range of arboreal taxa

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**Figure 4.** Microfossil assemblage showing diverse phytolith forms. Scale bar = 50µm.

**Figure 5.** Microfossil assemblage dominated by palm morphotypes. Scale bar = 50µm.
(e.g. Amos 1952; IAWA 1989; Scurfield et al. 1974), there seems to be little existing research on the occurrence of these morphological types in modern or ancient soil and sediment samples. Many samples in Kahikinui, however, appear to contain these almost exclusively. While these do tend to have similar morphological characteristics as wood phytoliths illustrated in published photographs, the interpretation of these assemblages as deriving from arboreal wood is tentative at present.

Case studies

In the section to follow I discuss two trench profiles where rough, ‘quick-scan’ microfossil counts (especially silica phytoliths) are beginning to demonstrate how variability in microfossil assemblages may be stratigraphically patterned.

Site 70

Site MA-A35-70 (Fig. 7) is an impressively large, long stone-faced terrace which lies adjacent to (and may have previously dammed) a presently dry stream channel in the Kahikinui uplands. Located in an area dense with some of the region’s most elaborate heiau (religious temple or shrine sites) and ‘elite’ residential architecture, this site appears to have had an agricultural function on a relatively grand scale. Three surface-to-bedrock trenches were excavated in the site’s upper surface, revealing a sequence of several visually identifiable stratigraphic layers. Figure 8 shows a sediment profile drawing from Trench 2 at Site 70, and Figure 9 presents quick-scan microfossil count data (mainly silica phytoliths) for eight stratigraphically arranged samples from this profile. An AMS radiocarbon date on wood charcoal recovered from Layer VII orients use of this site in a two-sigma calibrated age range of AD 1660 to 1740 (post-AD 1800 intercepts are not considered, since, based on historical records, the region’s upland settlements are thought to have been largely abandoned by then). This result places this site’s use in a similar time period as several other dated sites in the immediate area.

Layer 1 is a modern soil O-horizon which was not processed, although microfossils in this sample would probably reflect modern vegetation, which consists of
Figure 8. Profile drawing, Site 70, Trench 2, west and north walls. See text for layer composition.

Figure 9. Site 70, Trench 2. Raw counts of generalised microfossil types from $n = 200$ 'quick-scan' phytolith counts, Layers I to VIII.
grasses and scattered low exotic shrubs. Layer II contains several thin beds of alluvial silts, sands and gravels, while Layer III is especially gravel-rich. Layer V is distinctive in containing a rich deposit of scattered macroscopic charcoal fragments, which were recovered and identified to several wood taxa including native and cultivated tree and shrub taxa. This layer, interpreted to represent a buried cultivation surface, probably received its charcoal through either 1) alluvial deposition during occasional flooding of the terrace after burning events; 2) in situ burning of vegetation on the site before cultivation commenced; or 3) deliberate mulching by Hawaiian cultivators with charcoal coming perhaps from nearby hearth or oven features.

Comparison between the Trench 2 stratigraphy and Trench 1 (not shown), which is more closely associated with site architecture, suggests that Layers V and above were deposited after the terrace construction (in Trench 2, Layer V probably represents a mix of earlier surface soil horizons and addition of materials during cultivation). Layers below V probably represent soil horizons on top of which the terrace was constructed, which themselves may represent sequences of complex pedogenesis because of the occurrence of pre-human tephra-fall events (although the chronology and distribution of these is poorly known). These sediments all contain predominantly ‘arboreal’ phytolith types. The apparent influx of palm phytoliths with alluvial sediments in the upper profile of Site 70 may suggest that these were in fact commonly growing in the area’s shallow intermittent stream channels, which may have been the source of increased levels of spring- or seep-fed moisture in the relatively recent past (Stock et al. in press). Their low occurrence in Layer V and below may indicate that palms did not necessarily dominate all pre-human arboreal vegetation communities in the area.

Site 1303

Site MA-A35-1303 is the horticultural heart of a low-lying swale surrounded by several pre-contact residential site clusters. The floor of this ~20 x 60m swale (which is a palaeo-‘kipuka’, a Hawaiian geological term for topographic gaps or holes left uncovered by newer lava flows which otherwise cover surrounding territory), has several parallel, low terrace walls. Several lines of evidence allow us to approach a reconstruction of the localised landscape history in this area. Excavation and stratigraphic examination of five surface-to-bedrock trenches at Site 1303 and adjacent Site 1304, and radiocarbon dating of charcoal from deep in two of these trench profiles (and biostratigraphic dating of upper layers by a large goat bone), suggest that this area has experienced alluvial and colluvial erosional inputs beginning c. AD 1500 and continuing into the post-contact period. Again, these results correspond closely with a larger body of radiocarbon dates from sites in the surrounding area.

Figure 10 shows Site 1303 Trench 1 during excavation (the wall was later bisected to better reveal relationships between sedimentary strata and site architecture), and Figure 11 is a field drawing of the resulting profiles of two walls. Figure 12 is a bar graph presenting raw quick-scan microfossil count data (mostly silica phytoliths) of eight samples collected from this trench profile. While trends in the variation in proportions of generalised vegetation types are not as visually striking as in the Site 70 example above, some rough interpretations are possible. Layer I was a surface O-horizon sample which had very low microfossil recovery (and count), and mostly grass type phytoliths probably representing the most recent surface vegetation. Layers II, IV, V and VI show fairly equivalent proportions of grass, herbaceous, 2

1 Most of the types recorded as ‘arboreal’ in these samples represent types interpreted as ‘wood’ in origin. However, because this correlation is tentative, samples dominated by arboreal forms here must be treated as similarly speculative and possibly subject to revision.

2 A ‘herbaceous’ group was used here to represent common small, non-spinulose spherical phytoliths.
palm and arboreal phytolith types. The Layer VII samples (a and c) differ markedly from the others, containing the largest proportions of grass phytoliths in the buried strata. This layer overlies a slightly darker sediment layer resting directly on bedrock, where proportions of the various general types again appear roughly equivalent. Based on this data, as well as on-site architecture and the nature of sediment textures in the upper strata, it appears Layer VII represents sediments accumulated and cultivated during the earliest period of human use of the local area. The largely grass derived nature of the phytoliths may perhaps reflect either grass growing during fallow periods among non-silica accumulating crop plant cycles, or perhaps as added grass mulch, a commonly recorded practice in Hawaii and elsewhere in the Pacific Islands (e.g. Handy 1940; Yen 1974). In their Hawaiian study, Pearsall and Trimble (1984) suggest that these somewhat ‘indirect’ indications of cultivation might be all that can be expected in many Pacific Island cases. Grass phytoliths with a burned appearance (Kealhofer and Penny 1998) also appear in the upper sample from ‘cultivated’ Layer VII, as well as immediately above it. This upper layer, and the next three superimposed strata, appear to be erosional in origin, and probably reflect influxes of sedimentary material during occasional flooding after site abandonment. Notably, the soils being eroded in this case seem to contain similar phytolith proportions to the buried Layer VIII which lies below the ‘cultivated’ layer.
Does this perhaps imply that with the onset of heavier sediment erosion during the post-contact period (due to wider burning, deforestation and cattle impact), fairly intact pre-human palaeosols are being eroded continually from ridges into low-lying topographic areas, burying previously cultivated soils which remain in situ in lower-lying topographic settings?

**Other microfossils**

The count data presented above is focussed mainly on silica phytolith data, although attempts to recover other microfossil types from Kahikinui soils and sediments have also been variably successful. Pollen grains commonly occur (although in quite low numbers relative to phytoliths) in samples processed using a joint phytolith-pollen protocol, and rough microscopic charcoal counts can be compared with evidence of phytolith burning or macroscopic charcoal data to help reconstruct the association of burning with erosional events or cultivation practices. Diatoms occur only occasionally in these samples, but more data on their distribution could help establish the presence of more moist conditions in particular layers, perhaps in co-occurrence with the also common (but in low numbers) sedge phytoliths.

Starches were successfully recovered from Kahikinui samples during experiments carried out at the Australian Museum in 2000, although unfortunately there has not yet been time to follow up these initial promising results. Similarly, recovery of large quantities of ‘faecal spherulites’ (Canti 1997, 1999) from a rock shelter deposit, using a special no-acid laboratory protocol (Coil et al. in press), suggests that these microfossils could serve as biostratigraphic markers for introduction of larger mammals in other Hawaiian and Pacific Island contexts where, like elsewhere in the world, the introduction of large herbivores closely followed the earliest European contacts (Crosby 1986).
Conclusion

Kahikinui, while from one perspective a somewhat typical arid, leeward Hawaiian mountainside, must also be seen as a complex physical mosaic of parent materials, tephra deposits, sediment transport histories, subsurface hydrological features and microclimates. Because of this, any ability to generalise about human-environment relations in the Kahikinui study area must be built up as a composite of smaller, more localised landscape histories, such as those now emerging at Site 70 and Site 1303, in part through microfossil research.

Incorporating microfossil evidence into my doctoral research design has required a great commitment of time and effort, and has also had to represent something of a third priority in research activities (behind wood charcoal identification and site survey and investigation). Emerging results, however, promise to provide a facet of data otherwise unobtainable through a more narrow focus on archaeological sites themselves and macroscopic plant remains excavated from them. Furthermore, understanding the meaning of the complex stratigraphic sequences revealed in many trench profiles is being aided by the recovery and interpretation of microfossils contained in the various strata, which provide vegetation information not obtainable through more common geoarchaeological analyses such as grain-size analysis or measurements of organic and carbonate content. Finally, microfossil evidence continues to represent a source of otherwise elusive environmental evidence regarding Kahikinui’s pre-human vegetation (Athens 1997) and ‘natural’ landscapes (Sauer 1925).

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References


Starch grain damage as an indicator of food processing

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Abstract

Current knowledge of processes affecting the structure, morphology and rate of survival of starch grains in archaeological contexts is limited. Furthermore, our knowledge of how ancient cultural practices can alter these particles is even less understood. In this paper the focus is on starch grain injury and modifications that may be caused by food-processing activities such as air dehydration, roasting, charring, freezing, desaponification and milling by analysing experimentally obtained and home-made Andean food products. Results demonstrate that particles having some starch features, but that are typically counted as dubious or non-starch, could and should be identified as damaged starch grains resulting from food processing. Additionally, it seems possible to link the different patterns of damage observed in granules to different procedures. This information could be used to acquire details about cultural behaviour based on the damage to starch recovered from archaeological tools.

Introduction

As most recent starch research relates to grains preserved on archaeological tools, it has focussed mainly on the possibilities of recovering and identifying starch grains taxonomically (e.g. Fullagar and Field 1997; Loy et al. 1992; Piperno 1998; Piperno and Holst 1998; Piperno et al. 2000), and on contamination and taphonomy issues (e.g. Barton et al. 1998; Therin 1994). However, current knowledge about processes affecting the structure, morphology and rate of survival of starch granules is scarce. Some researchers have dealt with how certain physicochemical processes alter starch. Such papers have been concerned mainly with how grains lose their structure and birefringence properties through contact with caustic chemicals, heat in the presence of water, endogenous enzymes during seed germination and
underground organs sprouting (Cortella and Pochettino 1994; Juan-Tresserras 1992, 1998; Loy 1994; Therin 1994). Cortella and Pochettino (1994) were also interested in the feasibility and reliability of taxonomic identification of starch grains in samples differentially preserved. Juan-Tresserras (1992, 1998) and Checa et al. (1999) reported on the effects of beer elaboration and milling on starch. Investigations by Babot (2001; Babot and Apella 2003; Babot and Würschmidt 2000) have similarly detected granules on grinding tools that have also probably been affected by milling.

In this paper the focus is on the morphological and optical effects on starch caused by several food preparation processes that have not previously been systematically studied. This is of interest to archaeologists because of the possibility of using patterns of damage in starch recovered from archaeological tools as an indication of certain cultural behaviours.

Methodology

Starch responses to specifically traditional Andean methods of preservation, elaboration and cooking of food were tested, although it is recognised that these processes have parallel cultural habits elsewhere. Since the botanical source has a strong impact on the physicochemical properties of starch (Fredriksson 1998), research focussed on several American domesticated plant species (Figs. 1 to 5):

- Cereals; maize (Zea mays L.)
- Pseudocereals; amaranths (Amaranthus mantegazzianus Passer., A. caudatus L.) and quinoa (Chenopodium quinoa Willd.)
- Tubers; white potato (Solanum tuberosum L.)
- Legumes; common bean (Phaseolus vulgaris L.)

The starchy materials used in the study vary in their origin. They include dry vegetal organs (seeds and tubers) observed before and after experimental processing, as well as home-made and industrial food and non-food products. Some were purchased at traditional markets and some were recovered from archaeological sites, while others were collected during fieldwork.

Each specimen was sampled several times and mounted on clean slides in a glycerine medium to improve the observation of starch grains (water was not used in order to prevent the loss of diagnostic features due to dehydration). The iodine test (Loy 1994) was also employed. Slides were observed with transmitted polarised and non-polarised light at several magnifications using a Zeiss Axioskop petrographic microscope. Additionally, some materials were also examined with phase-contrast microscopy.

Starch from each sample was observed, photographed and compared with reference collections. The results of each processing task were described in terms of expected sets of diagnostic features appearing in granules. The attributes taken into account for starch characterisation were contour and surface traits; hilum shape and size; fissure location and shape; lamellae visibility; individual grain size and set size range; birefringence properties; extinction cross features; relief depth; grain visibility by normal light; completeness; emptiness or fullness appearance; packing of compound grains; presence of clumps; and other indicators (charcoal particles, vegetal tissues, medium modifications).
Figure 1. Maize non-processed starch grains. Views with normal (left) and polarised light (right). Scale bar = 20µm.

Figure 2. Amaranth (Amaranthus mantegazzianus) non-processed perispermatic cells compactly filled with starch grains and medium-sized grains. Views with normal (left) and polarised light (right). Scale bar = 40µm.

Figure 3. Quinoa non-processed compounded starch grains. Views with normal (left) and polarised light (right). Scale bar = 40µm.

Figure 4. White potato non-processed starch grains. Views with normal (left) and polarised light (right). Scale bar = 20µm.

Figure 5. Common bean non-processed starch grains. Views with normal (left) and polarised light (right). Scale bar = 20µm.
The state of the art in phytolith and starch research in the Australian-Pacific-Asian regions

Results: Food processing damage and modifications to starch

Air dehydration and rehydration effects
Air dehydration implies the natural loss of water content in mature vegetal organs (Bewley and Black 1994). It is included here, despite its natural origin, because it is often a consequence of preservative strategies and constitutes a prerequisite for further food processing tasks and therefore becomes part of an intentional, cultural process.

Air dehydration effects on modern and archaeological naturally dried white potato tubers and seeds of maize, common bean, quinoa and amaranths were analysed. Morphological and birefringence alterations were observed in just a few starch grains. In all cases it was noticed that the sharper the intensity of air dehydration, the more frequent dehydration features became. Some dehydrated grains showed a flat relief in the mounted medium when compared with fresh grains. Dehydrated potato starch showed no lamellae. The occurrence of isolated, small fissures other than the ones typically found in certain species (*Phaseolus vulgaris* and *Zea mays*), and the slight opening of the hilum and its related fissures, were sometimes observed in common bean, maize and white potato starch. Nevertheless, owing to small grain sizes, the features previously mentioned were not observed for quinoa and amaranths since individual grains were barely visible.

Loy (1994) states that grains may sometimes be so dehydrated as to lose the necessary birefringence properties to generate the cross effect and therefore the extinction cross becomes obscure or invisible. Such an effect is apparent as dark centres in the Maltese cross and as partially or not birefringent areas in the damaged regions in air-dehydrated samples. These alterations, however, were only rarely recorded in the present study.

Even ordinary air-dried starch contains a varying and considerable amount of moisture, depending on starch origin and air humidity. Hygroscopic water is very hard to extract and a temperature above 100°C is required to remove its last traces (Radley 1943), but sometimes the natural loss of water is enough to generate fissures (Cortella and Pochettino 1994; French 1984; Radley 1943), an absence of lamellae (French 1984), increased hilum size (Atkin *et al.* 1999) and grain shrinkage (Atkin *et al.* 1999; French 1984; Loy 1994). Birefringence alterations might be related to the flat relief of some desiccated grains, since the apparent intensity of double refraction depends, to some extent, on grain thickness, water content and crystallinity (Atkin *et al.* 1999; French 1984).

Starch grains swell or shrink in the presence or absence of cold water in a reversible process different from the one of gelatinisation (Radley 1943). They are hygroscopic in the dried state (Radley 1943) and, when rehydrated, they recover their properties and the extinction cross reappears (Atkin *et al.* 1999; Loy 1994).

Roasting effects
Roasting refers to placing dry seeds in a container which is then heated so the seeds receive heat indirectly. Although roasting usually precedes milling, edible grains or by-products such as rosettes (see below) are sometimes consumed immediately after heating.

The effects of roasting on modern kernels of *capía* maize (*Zea mays* var. *amylacea* Sturt) — called *maíz tostado* or *tostao* — cooked in hot ashes to avoid charring were studied. Flour may be obtained from these kernels, although other varieties of maize can also be roasted to obtain popcorn called *ancua* or *auna* (Carrizo 1945; Dupuy 1952; Ochoa de Masramón 1977; Storni 1942). When roasted, quinoa grains also produce rosettes, called *rosetas de quinoa* (Hunziker 1952), and these were also examined.
Samples of roasted corn showed intact starch grains in and out of the vegetal tissue, charcoal particles and several flat relief grains that were less visible than the normal and air dehydrated ones. Some starch showed a weak birefringence and partial loss or deformation of the extinction cross. Many grains looked like the gelatinised ones and clumps could frequently be seen. The most important or typical feature of starch from roasted corn kernels was the occurrence of pronounced rounded, irregular or star-shaped projections at the hilum. These appear as a dark centre under normal and polarised light (Fig. 6).

Figure 6. Starch of maize tostado showing roasting effects. (a) A charcoal particle, a very flat relief grain, clumps of gelatinised granules and grains with pronounced projections at the hilum are marked with arrows. View with normal light (left). (b) A starch grain with weak birefringence is marked with an arrow. View with polarised light (right). Scale bar = 40µm.

For all different sizes of quinoa rosette starch grains the only damage observed were alterations in the shape of the extinction cross, a slight gelatinisation and the conformation of compound granule clumps.

Different degrees of temperature and water content of samples appear to be responsible for the amount of damage observed. Flat relief, as well as birefringence alterations and fissures, could be due to heat dehydration. Gelatinisation-like features and hilum projections could be related to the action of heat on dry starch having a remnant content of water (Radley 1943). The action of heat begins by modifying the hilum (which is more soluble than the outer margins of the grain) and moving the starch polymers out of the granule (Atkin et al. 1999; Loy 1994). Gelatinisation features were not apparent in all grains because each individual grain has its own gelatinisation temperature (Radley 1943).

Charring effects
This process involves charring parts of plants by exposing them directly to fire, either as a consumptive or a post-discard practice.

Charring effects were examined on samples of llipta or llucta, comprised of ashes of quinoa seeds mixed with water to form a paste. Llipta can also be made with quinoa leaves and stems, as well as parts of other plants (Hunziker 1952). It constitutes an alkaline additive to coca leaves (Erythroxylum sp.) that helps chemical reactions in the Andean traditional practice of coqueo (Martínez Ungria 1989).

Charcoal particles and clustered quinoa grains in different stages of disjoining, including disjoined individual grains, could be seen within the llipta sample. No extinction crosses were observed, but the intensity of birefringence appeared to be greater than that of common reference samples, except in medium-sized grains which looked obscure. Charring
manifested itself mainly through the occurrence of clumps of starch grains that appeared to have been gelatinised. The degree of gelatinisation seemed to be more intense than that which occurs in roasting, possibly due to the higher temperatures involved with charring. Owing to the water added to produce *llipta*, starch clumps looked swollen, a fact favoured by the low amylose content of quinoa (Atkin *et al.* 1999; Lorenz 1990) (Fig. 7).

Similar to the process that occurs in roasting, heat-dehydration and the combined action of heat and remnant water may be the factors that produce the alterations evident in charred samples. In addition, grain size appears to play a key role in affecting the rate of birefringence damage.

Cortella and Pochettino (1994; Pochettino and Cortella 1989) have argued that starch grains are seldom found in charcoal samples. In the current study, however, it was noticed that, while damaged, small starch grains at least appeared to survive the direct impact of fire. Nevertheless, it is believed that the temperature reached during charring is a key factor in determining the degree of damage and survival of starch.

**Freezing effects**

Freezing effects are those alterations that occur as a result of freezing plant parts. We are specifically concerned here with the deliberate freezing process that takes place in naturally frozen soils. The inhabitants of the high Andes store their tuber crops in a desiccated, light and less voluminous form called *chuño*: tubers are repeatedly frozen and thawed, by placing them on soils that freeze at night and then in the sun during the day; then they are trodden on to eliminate any remnant water content (Babot 1999; Cortella and Pochettino 1995; Parodi 1991). There are variants of the freezing conservation process such as *tunta*, obtained by freezing tubers and burying them in a wet hole covered with straw; finally they are laid in the sunshine (Babot 1999; Cortella and Pochettino 1995; Parodi 1991).

Samples of traditionally frozen white potatoes (termed *chuño de papa* and *tunta de papa*) were examined. Several starch grains in the *chuño* sample had a very flat relief and were scarcely visible, making it necessary to observe them using phase-contrast microscopy. It was impossible to see lamellae. Many grains had lost the necessary birefringence properties to generate the cross effect and therefore the extinction cross was not visible or appeared highly modified with irregular, sinuous and broken arms. Also present were grains with damaged regions that were obscure, being partially or not birefringent. These effects were qualitatively similar to those eventually caused by air dehydration or heat dehydration, but they appeared more frequently and intensely in frozen samples. In all cases, larger grains appeared to be more severely affected than smaller ones (Fig. 8).

Vegetal tissue and disjoined grains were also observed. Sac or vesicle-like grains appeared to be wholly or partially empty, with a hole or line at the hilum. There were many fragmented, fissured, broken or burst grains present. These had apparently released inner
Figure 8. Starch of white potato *chuño* showing freezing effects. (a) A very flat relief grain with a hole at the hilum, a sac or vesicle-like grain that appears partially empty with damaged surface and a fragmented grain are marked with arrows. View with normal light (left). (b) Grains with highly modified extinction crosses and obscure damaged regions are marked with arrows. View with polarised light (right). Scale bar = 20µm.

material that caused them to have an increased size, rather than a decreased or shrunken one.

In *tunta* samples the above mentioned effects appeared less frequently, probably due to the marked rehydration that takes place during *tunta* elaboration, thereby restoring the lost properties. The main features observed were altered shapes of extinction crosses, the occurrence of fissures and holes at the hilum, and the fragmentary state of some grains. Their general aspect, however, was that of hydrated grains that sometimes showed lamellae (Fig. 9).

Deteriorated starch grains of *chuño* and *tunta* were most probably due to potato dehydration (Cortella and Pochettino 1994) and tissue disruption from ice-crystal formation (Cortella and Pochettino 1994; Loy 1994). It is possible that birefringence alterations are related to the loss of inner material (Atkin *et al.* 1999), modifications in grain thickness, degree of crystallinity and orientation of crystallites (French 1984) during the freezing process. In addition, it would appear that the action of treading on potatoes fractures and fragments starch grains in *chuño*, just as milling does. This hypothesis is further strengthened by the fact that unpressed *tunta* starch retained whole grains that looked comparatively more complete than *chuño* starch.

**Desaponification and non-desaponification effects**

Saponin-bodies are particles that occur in the pericarp cells of quinoa fruit. They are about 6.5µm in diameter and appear as aggregates of four or five small granules (Prado *et al.* 1996). Saponins are extremely bitter and must be removed by laborious hand scrubbing in water or by mechanical abrasion, a process termed desaponification (Lorenz 1990; Prado *et al.* 1996) in order to make quinoa edible. Hence it is a common practice among quinoa consumers to wash, scrub and peel the fruit before eating or any further processing (Hunziker 1952; Martínez Ungria 1989; Varriano-Marston and Defrancisco 1984).

Figure 9. Starch of white potato *tunta* showing freezing effects. Grains with altered shapes of the extinction cross and a fragmentary grain are marked with arrows. View with polarised light. Scale bar = 40µm.
Unwashed and washed, drained and peeled quinoa seeds were observed in order to identify the effects of desaponification on starch grains. Saponins are not completely eliminated by washing (Martínez Ungria 1989) and peeling or cleaning takes place when grains are clearly visible. The only, but remarkable, feature of unwashed or unpeeled seeds was the milky appearance of the mounted medium, and the impossibility of clear visualisation of starch grains due to the property of saponins to generate a soapy solution in water (Lorenz 1990).

**Milling effects**

Vegetal milling is defined as the process carried out by applying friction to plant parts and their by-products. The effects of such a process in samples of coarse flour made of dry maize, ripe corn, quinoa and *chuño*; fine and coarse common bean, corn, quinoa and amaranth flour experimentally obtained in the laboratory, and commercial corn and white potato starch were observed.

Milling may have several consequences for starch, since the harder milling is the more extensive grain damage becomes. One effect is the separation of starch grains from cellular tissue to produce single, isolated entities. Another main consequence is an abundance of highly damaged granules which appear incomplete, truncated, fractured and collapsed or burst, joined to debris of their outer layers. Relative homogeneity of grain size, scarcity of large granules, and loss of some characteristic shapes are typical features due to fragmentation and abrasion. Several starch grains with flat relief either looked empty or were in the midst of releasing their content; others showed striated, rough and dented surfaces. A hole, line or star fissure could be seen at the hilum and a cavity-like damage sometimes also appeared in a central position. The occurrence of fissures, different from those of natural origin, located on the edges or elsewhere in a radiated, parallel or random way, also took place (Checa et al. 1999; French 1984). No lamellae could be seen (Figs. 10 and 11).

Some species, such as white potato and quinoa, have compounded starch grains; that is, composed of a group of single grains simultaneously developed within a single amyloplast or composed of distinct granules fused or stuck together (Cortella and Pochettino 1990, 1994, 1995; French 1984; Loy 1994; Varriano-Marston and DeFrancisco 1984). When subjected to milling such clustered grains suffered a disjoining that became more severe with extended

Figure 10. Starch of maize flour showing milling effects. (a) Incomplete and fractured grains and grains with a star fissure, radiated fissures and a cavity-like damage are marked with arrows. View with normal light (left). (b) Grains with low intensity of birefringence, defects in the shape of the extinction cross and a dark depression in the centre are marked with arrows. View with polarised light (right). Scale bar = 20µm.
Starch grain damage as an indicator of food processing

Babot

Figure 11. Starch of common bean flour showing milling effects. (a) Highly damaged granules which appear incomplete, fractured and collapsed with damaged surfaces and contours and a grain with a hole at the hilum are marked with arrows. View with normal light (left). (b) Partially obscure grains with low intensity of birefringence and defects in the shape and integrity of the extinction cross are marked with arrows. View with polarised light (right). Scale bar = 40µm.

Figure 12. Starch of quinoa flour showing milling effects. (a) Compounded grains in different stages of disjoining and a disjoined individual grain are marked with arrows. View with normal light (left). (b) View with polarised light (right). Scale bar = 20µm.

milling. This effect was apparent in white potato, corn and quinoa starch granules, the latter being pulled away from the surrounding protein bodies and covering material (Varriano-Marston and DeFrancisco 1984) (Fig. 12). Disjoining also occurred to closely packed grains of amaranths, and it was possible to see starch leaving the perispermatic cells that it had been compactly filling (Cortella and Pochettino 1990). Owing to the packing effects, individual grains in a compound structure usually have a combination of rounded shapes and flattened facets (Loy 1994) that are clearly visible only when disjoining takes place. The typical bell-shapes in disjoined starch grains of subterranean organs could specifically be seen (Piperno et al. 2000).

A gamut of birefringence alterations was typical of the milling process: many conspicuous grains appeared wholly or partially obscure; some had a dark depression in the centre. Whole and fragmented grains could show low intensity of birefringence and defects in the shape and integrity of the extinction cross (Figs. 10 and 11). The small grains of quinoa and amaranth frequently did not show the cross pattern, but sometimes birefringence was preserved and, to some extent, became more shiny (Fig. 12). Again, in all the cases, hydrated or rehydrated samples showed less damage than the dehydrated ones.

terra australis 19
Friction may be responsible for the majority of collapsed, fragmented, broken and fissured grains in the same way as crushing and pressing may. Structural damage, disorganisation of the crystalline lattice of starch and conversion of amylopectin into amylase also result from mechanical deformation by grinding (Buttrose 1960; Cortella and Pochettino 1994; French 1984; Radley 1943), and can also cause alterations in birefringence and radial appearance of grains. Dehydration also appears to play a key role in the occurrence of birefringence damage.

Several processes that may modify starch grains can take place before milling and may cause some superposed patterns of damage. Dried material to be milled may have features that are due to air, freezing and heat dehydration, washing (such as desaponification), peeling and slight rehydration (Babot 1999).

Discussion and conclusions

Throughout this research the focus has been on culturally conducted processes (other than heating in water, enzyme action and laboratory chemical manipulation). Results have demonstrated that, although modified, starch survives several food elaboration procedures. As a matter of fact, the processes of dehydration, heating, tissue disruption from treading, friction and ice-crystal formation generate physicochemical changes in starch that modify its completeness and degree of crystallinity, bringing about morphological and optical modifications in some granules.

While the injury provoked by more than one food processing technique may look similar, and while sometimes the same process may alter starch of varied biological origin differently, it has been demonstrated that, in a general way, different patterns of damage appear to be related to each process (Table 1). Furthermore, it has been shown that the harder the processing is, the more severe the damage caused. In addition, sometimes it is possible to see the consecutive stages in food processing occurring as superimposed patterns of damage on the same individual grain or in different grains in the sample. Although this research was carried out on American plant species, it is considered that these results may be extended to other taxa, providing they have been subjected to similar tasks as those described in this work.

On that basis, several observations of archaeological concern may be made:

(a) Damaged grains should be identified and counted with other starch grains when they appear in archaeological samples, in spite of their degree of injury.

(b) Since several features in granules are due to damage rather than genetic variables, the modified and undamaged ones appearing in the same sample should be assigned to the same taxa.

(c) Injured starch may contribute further to archaeological studies by providing information on cultural behaviours.

(d) Damage analysis can become a new way to eliminate the contamination hypothesis if coherence exists between the kinds of damage and the particular context of finding it.

Since damage features similar to those of cultural origin may occur due to natural processes, we have to be certain to discard them before assigning damage on grains to cultural behaviour. We require a better understanding of soil and sediment taphonomic processes, such as intense heating produced within tephra, friction of sand grains and natural freezing in soils, or natural events like fire, flood or drought, to extrapolate our results to archaeological materials, especially soil samples. Nevertheless, in areas where plant processing and tool use took place, at least some of the grains extracted from soils might be expected to be damaged owing to cultural actions. While extraction techniques used to produce reference samples may
Table 1. Starch injury and modifications due to food processing showing the different patterns of damage. Increasing intensity and frequency of each kind of damage for a given process is indicated by one, two or three crosses (+).

<table>
<thead>
<tr>
<th>STARCH DAMAGE OR MODIFICATIONS</th>
<th>AIR DEHYDRATION</th>
<th>ROASTING</th>
<th>FOOD PROCESSING</th>
<th>FREEZING</th>
<th>NON-DESAPONIFICATION</th>
<th>MILLING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fissures</td>
<td>+</td>
<td>+</td>
<td></td>
<td>++</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Fractures</td>
<td></td>
<td></td>
<td>+++</td>
<td></td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Hilum alterations</td>
<td>+</td>
<td>+</td>
<td>***</td>
<td>++</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Flat relief</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Less visibility</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>+++</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Bursting</td>
<td></td>
<td></td>
<td></td>
<td>++</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Surface damage</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Contour damage</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td>+++</td>
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<tr>
<td>Emptiness</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td></td>
<td>+++</td>
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<tr>
<td>No lamellae visibility</td>
<td>++</td>
<td></td>
<td>***</td>
<td></td>
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<tr>
<td>Disjoining</td>
<td></td>
<td></td>
<td></td>
<td>++</td>
<td></td>
<td>+++</td>
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<tr>
<td>Gelatinisation</td>
<td>++</td>
<td></td>
<td>+++</td>
<td></td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Clumps</td>
<td>++</td>
<td></td>
<td>+++</td>
<td></td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Birefringence alterations</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Extinction cross alterations</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td></td>
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<td>+++</td>
</tr>
<tr>
<td>Individual size alterations</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td></td>
<td></td>
<td>+++</td>
</tr>
<tr>
<td>Size average alterations</td>
<td></td>
<td></td>
<td></td>
<td>++</td>
<td></td>
<td>+++</td>
</tr>
</tbody>
</table>

be responsible for some fractured, fissured, disjoined or obscured grains, their occurrence is likely to be limited.

Damaged starch grains are argued to be more susceptible to the influence of hydrolytic agents and fungal activity than ordinary starch, a feature ascribed to the easier access permitted by fissures to the granule interior (Cortella and Pochettino 1994; Radley 1943). Nevertheless, research findings have demonstrated that it is possible to recover damaged starch grains from modern and archaeological contexts.

Acknowledgements

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Abstract

A comparison of phytolith assemblages in the termite sheeting above the surface of an Australian soil and down the profile of the underlying soil was undertaken using cluster analysis. Faunal channels within the soil were mapped and found to be at a maximum in the A1, diminishing down the profile. Sediment particle size analysis and examination of phytolith assemblages showed that termites were using the A horizon material in construction of their sheeting in tree stumps. The faunal channels in the B horizon of the soil, however, were enriched in clay-sized material and their phytolith assemblage was very different from that of the surrounding B horizon. This study concludes that soil fauna are capable of moving phytoliths within soils and sediments and, in conjunction with other pedological processes such as pervection and weathering, bioturbation is an important mechanism which must be considered when analysing soil phytolith assemblages in archaeological and palaeoenvironmental studies.

Introduction

Phytoliths initially reside in the litter layer and move down into the soil as a result of mixing processes. The initial assemblage present in the litter layer is changed. Attrition due to dissolution, mechanical breakage and abrasion, and removal by soil fauna dominate initially, but other processes such as pervection (the mechanical movement of particles through soil voids) and penetration into soil cracks may also occur (Boettinger 1994; Hart and Humphreys 1997). Researchers have observed that soil fauna including worms, termites and ants move phytoliths (Hart 1992; Hart and Humphreys 1997; Jones and Beavers 1964; Simons 1998; Verma and Rust 1969). In reviewing the effect ants and termites have in soil modification, Lobry de Brun and Conacher (1990) found that these species appear to select clays and silts in...
preference to sands when rearranging soil particles. Phytoliths fall into the silt and clay size ranges and thus may be transported deep into the soil in channels, to the surface in runways and to mounds above and within the soil.

This study examines the changes in phytolith assemblages in a soil in relation to soil faunal activity. It investigates the changes to general soil particle size consequent upon bioturbation (mixing by soil fauna) and changes to phytolith morphology. While movement by soil fauna may not be the only mixing method within a soil, the study concentrates on a highly bioturbated soil where the construction of mounds, channels and sheeting by termites plays a dominant role.

The field site

The field site is located in the Pilliga East State Forest in New South Wales, Australia (grid reference 711500mE 6605800mN on the Topographic Map, Cubbo, 1st edition 1:50 000 series, 8736-N, 1974). The surface geology comprises upper Jurassic Pilliga sandstone and derived sediments and the soils are solodized solonetz (Stace et al. 1968). Annual rainfall averages 625mm with a summer maximum and is greatly variable. The vegetation is a sclerophyllous closed to open-forest with a heath understorey and comprises a mosaic of vegetation communities.

The site is located along Dunwerian Road on the upper western slope of a ridge in Pilliga sandstone in a mallee community comprising *Eucalyptus viridis* (green mallee) in the mallee (many stemmed) form (height to about 7m), a shrub layer dominated by *Dodonaea viscosa* spp. *cuneata* (hop bush) and a herb layer containing various grasses. It is a closed to open-woodland with crowns just touching and it has an abrupt boundary with the surrounding broom plain. Bioturbation and phytolith distribution in this soil has been described in Hart (1992) and Hart and Humphreys (1997).

The surface of the soil comprises a thick layer of bark, litter and wood and the workings of ants and termites. Large mounds partly bury the bases of trees and shrubs to a depth of 200 to 500mm giving a hummocky appearance to the spongy surface. The A1 horizon of the soil is a very bioturbated brown earthy loam containing large amounts of charcoal. The A2 is conspicuously bleached, cemented and penetrates down the side of columns in the clay B horizon to form domes. The B horizon is a mottled sandy clay with a columnar structure derived *in situ* from the underlying weathered sandstone at 1m (Hallsworth and Waring 1964; Hart 1992; Hart et al. 1996).

The origin of the soil and its dominant processes have been discussed in Hart *et al.* (1996). The A horizon is a mobile biomantle (Johnson 1990) overlying a B horizon weathered *in situ* from the underlying sandstone. In this texture contrast soil (Paton *et al.* 1995) the dominant processes in the A horizon are bioturbation (where the soil fauna bring material to be exposed on the surface) and lateral surface movement (where this material is winnowed by rain and wind, leaving behind a coarser A horizon). In the B horizon the dominant processes are weathering, leaching and new mineral formation (Hart and Humphreys 1997).

Methods

The litter layer to just above the depth where mixing occurred between it and the underlying soil, was removed from 10 x 1/16m² random quadrats located within a 100m² sampling grid at the site. The litter was carefully washed, dried, crushed and mixed, and phytoliths were
The influence of soil fauna on phytolith distribution in an Australian soil

Hart

Phytoliths were separated from a fourth sub-sample from the 2 to 250µm size range covering very fine silt through to fine sand and were mounted for assemblage analysis in light microscopy and for SEM examination as described above. This size range is used because it has been found to give a more complete cover of phytolith morphological types in a sediment (Hart 1992).

Phytoliths from the litter and the sediment were counted using a phytolith key for disarticulated shapes (for details see Hart 1992). Regular (shapes occurring in the sample repetitively) and non-regular (platey pieces and multi-celled phytoliths, other silica) were counted until 200 regular phytoliths more than 2µm in diameter were counted and placed into a category according to the key. Each morphological type score was expressed as a percentage of total regular grains and Cluster Analysis was used to show similarity between samples. UPGMA (unweighted pair-group method using arithmetic averages) using the Euclidean distance was used. The analysis was performed using the MVSP (MultiVariate Statistical Package) of Kovach (1998). Selected categories of morphological types were expressed as a percentage of the regular count and as a percentage of the whole count (regular and non-regular) and used to examine differences in morphology between the samples.

Results

The particle size distribution of the sediment samples and phytolith content are shown in Table 1. The phytolith content is calculated by the usual method of multiplying the proportion of phytoliths present in one size fraction by the proportion of that size material in the soil as a whole. Phytolith content decreases down the profile into the B horizon (Type 1 Phytolith Distribution Function; see Humphreys et al. this volume), but faunal channels within the B horizon and termite sheathing in adjacent stumps contained the largest amounts of phytolith material.

The percentage of faunal channels in the impregnated undisturbed samples is shown in Figure 1. The channels are at a maximum in the A1, fall to a minimum in the A2 or domes, rise slightly below the domes and fall through the B horizon.
Table 1. Sample particle size distribution and phytolith content. (Code: * = proportion of phytoliths in silt fraction of soil multiplied by the proportion of silt in total soil).

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>PARTICLE SIZE DISTRIBUTION</th>
<th>PHYTOLITH CONTENT*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Depth below surface (mm)</td>
<td>% Sand</td>
</tr>
<tr>
<td>Sheetimg</td>
<td>above soil</td>
<td>60.6</td>
</tr>
<tr>
<td>A1 horizon</td>
<td>50</td>
<td>65.6</td>
</tr>
<tr>
<td>A2 (dome)</td>
<td>100</td>
<td>71.1</td>
</tr>
<tr>
<td>B horizon</td>
<td>200</td>
<td>53.8</td>
</tr>
<tr>
<td>Faunal channels</td>
<td>300</td>
<td>33.1</td>
</tr>
</tbody>
</table>

Figure 1. Depth distribution of faunal channels in the solodized solonetz.

Figure 2. Dendrogram showing the results of a cluster analysis of the phytolith assemblages from the soil and termite sheeting.
Figure 2 is a dendrogram showing the results of a cluster analysis of the phytolith assemblages from the sediment samples only, since the litter assemblage did not form any close associations. The clustering method used is minimum variance, which combines those pairs of groups with the lowest variance. Thus in Figure 2 the A horizon and sheeting are most similar, followed by the domes and B horizon.

In Table 2 selected morphologies of regular (repetitive) phytoliths are expressed as a percentage of the 200 regular shapes. These illustrate the similarities between the A1 and sheeting on the one hand and the B horizon and domes on the other, and also show the differences between the litter and soil in smooth compound spheres, and between the faunal channels and surrounding B horizon in platey sheets, ridged thick rods, jigsaw platey rods and smooth compound spheres (Fig. 3A). Table 2 also presents the non-regular platey sheets in each sample as a percentage of the whole count. This tends to decrease down the soil profile, but the percentage rises by a factor of three when the faunal channels are compared with the surrounding B horizon.

Table 2. Percentage of selected phytolith morphologies in the 2 to 250 µm size range.

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>Platey sheets</th>
<th>Thick rods</th>
<th>Thin rods</th>
<th>Platey rods</th>
<th>Compound spheres</th>
<th>Non-regular platey sheets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%) REGULAR</td>
<td>ridged</td>
<td>ridged</td>
<td>jigsaw</td>
<td>smooth</td>
<td></td>
</tr>
<tr>
<td>Litter</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>15.5</td>
<td>52.9</td>
</tr>
<tr>
<td>Sheetling</td>
<td>2.5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>57.1</td>
</tr>
<tr>
<td>A1 horizon</td>
<td>0</td>
<td>1.5</td>
<td>0</td>
<td>0</td>
<td>1.5</td>
<td>44.4</td>
</tr>
<tr>
<td>A2 (dome)</td>
<td>2.4</td>
<td>1.9</td>
<td>0</td>
<td>0</td>
<td>1.4</td>
<td>23.7</td>
</tr>
<tr>
<td>B horizon</td>
<td>1.4</td>
<td>0.5</td>
<td>0.5</td>
<td>0</td>
<td>1.8</td>
<td>17.1</td>
</tr>
<tr>
<td>Faunal channels</td>
<td>25.2</td>
<td>5.6</td>
<td>0.9</td>
<td>1.9</td>
<td>0</td>
<td>58.1</td>
</tr>
</tbody>
</table>

Figure 3. SEM micrographs of phytoliths from the field site. (A) smooth compound sphere from the litter, scale bar = 1 µm; (B) regular platey sheet from Calytrix tetragona, scale bar = 1 µm; (C) and (D) phytoliths from termite carton, scale bar = 10 µm.
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Discussion

In studies such as this phytoliths are utilised as a soil constituent and their botanical ties, attenuated when the phytoliths became disarticulated, are not considered. This study traces the silt-sized phytolith particles as they move from the litter layer into and through the soil and uses their shapes and assemblages of shapes to examine process once in the soil.

The meso-fauna in this soil includes large numbers of ants and termites (possibly *Amitermes* spp. and *Coptotermes* spp.). Most of the termites are subterranean species living in small colonies on dead and living wood and litter. Lee and Wood (1971) comment that some species of termite have feeding preferences; however, very little is known.

Termites pack topsoil cemented with excreta into logs and around twigs to construct above-ground runways or sheeting under which they forage for food. Many termites and ants select particular particle sizes, often clays and silts, when constructing nests and galleries or channels within the soil (Lee and Wood 1971; Lobry de Bruyn and Conacher 1990). In a literature survey of soil modification by ants and termites, Lobry de Bruyn and Conacher (1990: Table 3) found that silt content rose between the soil and 33 out of 38 termite mounds where sufficient information was given to assess this. Material may also be brought into mounds and faunal channels from outside the layer in which they are built or transported out of the layer (Lobry de Bruyn and Conacher 1990). Stoops (1964) found that the termite *Cubitermes* spp. swallowed soil particles of <100 µm and deposited them by regurgitation from their crops. Some ants have been found to make up aggregates of fine sand and clay in building mounds (Humphreys and Mitchell 1983). Excreta is commonly used as a cement by termites and, when mixed with mineral soil particles and undigested, comminuted plant tissue, forms a material called carton which is used in the construction of nests and lining of galleries (Figs. 3C and D).

Table 1 shows that the particle size distribution of the A horizon is very similar to that of the termite sheeting at this site, although the sheeting contains a higher percentage of phytoliths. This is probably caused by the addition of excreta to the A horizon soil material by termites when constructing the sheeting. The cluster analysis (Fig. 2) shows the A horizon and sheeting phytolith assemblages are closely linked, thus the derivation of the above-ground sheeting would appear to be largely from the A horizon.

The faunal channels are of particular importance when examining the question of whether soil fauna influence phytolith assemblages. It is not known which species of ant or termite constructed these channels, which are the most recent of the faunal disturbance in the B horizon and therefore the question of their contents having originated from an earlier climatic period is not an issue. The particle size distribution of the faunal channels is very different from that of the surrounding B horizon (Table 1). In particular there is considerably less sand and silt but a much greater proportion of clay. This may be due to importation of clay particles by soil fauna when constructing the channels, and by the presence of clay-sized phytoliths in the black lining of material, which is probably excreta, and faecal pellets which partially infilled the channels. The presence of this phytolith material cannot be confirmed due to problems with separation of clay-sized particles (Wilding and Drees 1974).

There are marked differences in concentrations of some phytolith morphologies between the faunal channels and the surrounding B horizon. Platey sheets are 18 times more common in the faunal channel phytolith assemblage than that of the surrounding B horizon. Many of the plates are regularly perforated, and their derivation is unknown, however, *Calytrix tetragona*, a common understorey species at the site, contains such plates (Fig. 3B). Similarly, the percentage of non-regular plates (including multi-celled pieces) rises in the faunal channels to a similar level found in the A horizon and sheeting (Table 2). These
irregularly shaped platey phytoliths are often formed in plants between cells. It was found in a study at this site that the surface area of non-regular platey phytoliths decreased to 10% of their original surface area in moving between the litter and the first 5cm of the A horizon (Hart 1992). This implies that they are easily broken up and destroyed, and their presence and that of the regular platey phytoliths in the faunal channels would seem to indicate that they have been transported there in faecal material directly by soil fauna, bypassing the soil. The faunal channels also contain an appreciably higher proportion of other morphologies that might point to a similar source and an absence of smooth compound spheres that are a major morphology in the litter and present down the profile (Table 2).

Hart (1995) found at this site termites were responsible for the addition of 2250kg/ha year⁻¹ of sediment to the surface of the soil during the creation of covered runways or sheeting. The litter half-life is 2.5 to 3 years; that is to say that half of the litter on the surface disappears in this time (Hart 1995). The total litter in storage in the litter layer at the site was 12,011kg/ha and the average amount of phytolith material present in the litter was 164.6kg/ha (Hart 1992). However, the amount of phytolith material to enter the soil on an annual basis is of the order of 20kg/ha due to removal through fire and grazing. Weathering and dissolution quickly remove much of this (Hart 1992). It would appear from the present study that soil fauna are effectively changing the soil phytolith assemblage of the remaining phytolith material as a consequence of their feeding and construction habits. Some soil faunas are selecting parts of plants containing a particular assemblage of phytolith morphologies and depositing them at depth in the profile.

The obvious sorting (in the faunal channels) of the phytolith assemblages (i.e. morphology) in this soil profile is paralleled by a change in particle size distribution when comparing the faunal channels with the surrounding B horizon. Sampling techniques purposely made sure that very little of the B horizon was included in the faunal channel sample and vice versa. This was assisted by the B horizon being in situ developed from the underlying sandstone, with areas of relatively recent faunal disturbance being discrete and easily identifiable. This is not always the case since, over time, bioturbated material tends to blend with its surroundings and it may be difficult to tell, when sampling, the derivation of the material. In time the faunal channel material will become well mixed into the surrounding B horizon by other species within the soil. In addition to movement by bioturbation, particular morphologies of phytoliths have been shown to move through soil voids and to accumulate above areas of denser material (Humphreys et al. this volume; Simons 1998).

In relation to assessing the possibility of artefact movements within archaeological sites, Graves and Kealhofer (1999) suggest that a combination of soil morphology and phytolith analysis may provide a measure of bioturbation. They suggest that macro- and micro-features in undisturbed soil samples will indicate the extent of bioturbation, and phytolith analysis the scale of movement, which in their example is considered to be complex and extensive at these two levels but not at the intermediate meso-level. Phytolith analysis is generally carried out on the silt size range, and it is these materials which are transported in the mandibles of ants and termites. Any disturbance (soil faunal included) which is visible at the macro-level (<10× magnification, i.e. in a hand lens in the field) will manifest itself in disturbance of materials at the meso- (10 to 40× magnification) and micro- (>40× magnification) levels. It is, however, not so much the homogenisation or sorting of particle size which is important in this context but the changes in phytolith assemblages, which can be observed only in a small fraction of the complete sediment particle size range. Is it the discrete separation or the mixing of assemblages between archaeological layers which is indicative of bioturbation? The present study would tend to indicate it may be both; separation occurring in those instances where faunal channels are comparatively recent and mixing where sufficient time has passed for the channels to homogenise with the surrounding soil.
(see Humphreys et al. this volume). This presents a problem for archaeological and palaeoenvironmental researchers. How do we know when assemblages are the product of bioturbation and not indicative of a discrete environment? This is a question which, as yet, remains unanswered, although refined sampling techniques and a better understanding of soil processes and their effects on phytolith assemblages may help.

Conclusion

This study examines the changes in soil phytolith assemblages in relation to bioturbation. It finds that soil fauna are capable of concentrating phytoliths in areas throughout a soil and in moving phytoliths and changing the assemblages with depth in the soil. The implications of this research, not only to phytolith assemblage studies but to archaeological and palaeoenvironmental research, generally need careful evaluation.

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Phytoliths as indicators of process in soils

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Keywords
phytoliths, phytolith depth function, soils, soil process, pervection, bioturbation

Abstract

Two hypotheses concerning the mobility of phytoliths are evaluated in this paper. The first describes an implied assumption that phytoliths remain with the host sediment/soil and is referred to as the static phytolith hypothesis. The alternative recognises the potential for movement, especially downwards, and is referred to as the mobile phytolith hypothesis. Both hypotheses were evaluated on three soil types in three different ways utilising the concept of phytolith depth functions (PDFs) on (i) trends in concentration, (ii) trends in diversity of the assemblage and (iii) trends in concentration of spherical and platy morphologies. The results indicate general support for the mobile and not the static phytolith hypothesis. In detail, a complex picture emerged. In two soil types (a podzol and a yellow podzolic) a consistent PDF occurred between total concentration and diversity but not with concentration of platy or spherical forms. The other soil type (solodic) revealed little consistency in trends between the different indices. In all cases there is strong evidence for biomixing, and in the sandy podzol for pervection.

Introduction

The distribution of phytoliths in soils has long been of interest in palaeoenvironmental studies where they have been treated as a palymorph (plant fossil) to shed light on changes in vegetation and climate. The use of phytoliths, however, requires an understanding of the morphological, chemical and physical properties of phytoliths, as well as an understanding of their relationship to the sediment in which they are found. This latter theme is especially important but it has been afforded little research. Early researchers focussed on two features of this relationship: (i) the distribution pattern from the surface downward, and (ii) the amount of phytoliths in any given layer. In terms of the former, the concentration of phytoliths was often found to be at a maximum in the topsoil and to decline in abundance with depth (e.g. Wilding and Drees 1971; Witty and Knox 1964). This type of distribution pattern, termed a
Type-1 phytolith depth function (PDF) (Hart and Humphreys 1997), was assumed to reflect contemporary conditions involving the addition of phytoliths to a relatively stable surface together with limited admixture into lower soil layers by fauna (e.g. Jones and Beavers 1964). In other situations a high concentration of phytoliths was also found below the surface soil (Type-2 PDF) and this was considered to indicate the presence of a former topsoil or buried soil/palaeosol (e.g. Beavers and Stephens 1958; Retallack 1981). It was also reasoned that phytolith content could be expected to increase with soil age and therefore be related to soil maturity (e.g. Beavers and Stephen 1958); to differences in vegetation type such as grasslands versus forest (e.g. Wilding and Drees 1971); or to the rate of phytolith accumulation in relation to the rate of sediment accretion (Jones and Beavers 1964). It is apparent, however, that much of this initial research was conducted in loess regions and that the Type-1 PDF was considered the normal situation. Hence, it is not surprising that differences in distribution of phytoliths in similar soils (similarity being expressed in terms of belonging to the same soil group) were related to speed of loess accumulation, differences in soils’ internal drainage and differences in vegetation history. As a consequence, these early studies formed an important framework for interpreting trends in phytolith concentration even though the explanations were offered in the context that, once entering the soil, the phytoliths were relatively stationary. In recognition of this implied assumption, Hart and Humphreys (1997) referred to these explanations collectively as the static phytolith hypothesis.

Against this framework was the recognition of lateral mobility of phytoliths in dust and water, which has long been recognised, and the possibility of vertical displacement of phytoliths down through the soil profile. This possibility was realised by Bartoli and Guillet (1977) and Bartoli et al. (1980). They examined the distribution of phytoliths in podzols in France and suggested that phytoliths migrated down through the E (A2) and accumulated in the Bh (humic pan) horizons but not the underlying Bs (iron pan) horizon, which was considered to be a barrier to further migration. Subsequently, Rovner (1986) challenged this interpretation even though he provided little criticism of their data. It would seem that his objection stemmed from whole-hearted acceptance of the static phytolith assumption. More recent experimental work on several different soils in Australia and Russia provides support for vertical mobility, particularly in sandy soils with good interconnectivity between voids (Gol’yeva 1996; Hart 1992; Hart and Humphreys 1997; Simons 1998; Simons et al. 2000).

These later studies also showed that considerable mixing of phytoliths occurred via various soil fauna (bioturbation) such as ants, earthworms, termites and a host of others. Nevertheless, Grave and Kealhofer (1999) have challenged the role of bioturbation. They found strong evidence of insect activity and percolation (i.e. pervection), but contended that particles between 5–50 µm (i.e. the size range of the phytoliths under examination) exhibited no evidence of mixing. This allowed them to conclude that insect activity had not affected the general microbotanical sequence. Yet this interpretation remains questionable, for if particle selectivity by soil animals of this type occurs, i.e. particles coarser than 50 µm and finer than 5 mm are mixed but not the intermediate size, it represents a very unusual form of biomixing that has not been reported previously. The usual situation is where there is an upper size limit of particles that can be carried or ingested, which is often about 500 µm for termites and smaller earthworms and somewhat larger for ants, but not a lower limit (see Edwards and Bohlen 1996; Humphreys 1994; Lee and Wood 1971; Paton et al. 1995). Selectivity of the type inferred by Grave and Kealhofer (1999) can occur only when different carrying mechanisms are employed by the dominant mixing organism and/or where mixing is dominated by groups that avoid the 5-50 µm fraction. Thus Stoops (1964) showed that, in comparison with the surrounding soil, termite mounds of Cubitermes spp. in parts of Africa were enriched with particles <100 µm and >500 µm, which was interpreted as corresponding to the maximum size.
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ingested and carried, respectively. More direct proof of biotic mixing is the presence of phytoliths within faecal pellets, a situation observed in several different soils (Hart 1992). This association is hardly surprising given the feeding habits of fauna such as earthworms and termites. The vertical movement of phytoliths represents a very different viewpoint to that engendered by the static phytolith hypothesis and it was recognition of this that prompted the mobile phytolith hypothesis (Hart and Humphreys 1997).

This brief survey indicates that there exists in the literature two very different viewpoints on the behaviour of phytoliths in soil/sediment after their initial incorporation, which were labelled the static and mobile phytolith hypotheses (Hart and Humphreys 1997). The contribution that phytolith studies can make to the examination of the dominant pedological processes, as illustrated by a comparative study of three different soils, forms the basis of this paper. We start by providing a simple description of each soil type and a summary of major soil transporting and mixing processes at each site in order to place our investigation of phytoliths into context.

The study area, soils and site processes

Three soil types from different locations in New South Wales, Australia, were employed in this study. To assist communication these soil types are named with reference to the Australia “great soil group” nomenclature of Stace et al. (1968) and are prefixed by their general location as follows: Cattai podzolic, Narrabeen podzol, and the Pilliga solodic (Fig. 1). More details are provided by way of two other Australian classifications (Isbell 1996; Northcote 1979) and via two international systems (Soil Taxonomy, Soil Survey Staff 1998; World Reference Base, Spaargaren 1994) (Table 1).

The Cattai podzolic

The site is close to the ridge crest near the top of the Hawkesbury sandstone about 38km northwest of Sydney. This texture contrast soil has fine sandy loam A and E horizons to a depth of c. 15 and 37cm respectively, underlaid by a pedal, fine sandy medium clay B horizon up to 30cm thick developed in saprolite of micaceous sandstone. The site receives on average about 900–1000mm rain annually and supports a woodland vegetation dominated by Myrtaceae tree genera of Angophora and Eucalyptus. Detailed geomorphic processes studies indicate annual rates of mounding (soil deposited at the surface) by ants and other invertebrates amounts to 500–600g/m²/y (Humphreys and Mitchell 1983), with most biomixing confined to

Figure 1. The location of the study sites.
Table 1. Classification of soils at the study sites.

<table>
<thead>
<tr>
<th>CLASSIFICATION</th>
<th>CATTAI PODZOLIC</th>
<th>NARRABEEN PODZOL</th>
<th>PILLIGA SOLODIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stace et al. (1968)</td>
<td>Yellow Podzolic</td>
<td>Podzol</td>
<td>Soloth</td>
</tr>
<tr>
<td>Northcote (1979)</td>
<td>Dy2.41</td>
<td>Uc2.36</td>
<td>Dyl1.11, Dyl1.41</td>
</tr>
<tr>
<td>Isbell (1996)</td>
<td>Kurosol (bleached mesotrophic, brown)</td>
<td>Podosol (parapanic, humic/ humosesquic, semiaquic)</td>
<td>Kurosol (vertic, magnesic, grey)</td>
</tr>
<tr>
<td>Spaargaren (1994)</td>
<td>Acrisol</td>
<td>Podsol</td>
<td>Lixisol</td>
</tr>
<tr>
<td>Soil Survey Staff (1998)</td>
<td>Ultisol</td>
<td>Spodosol</td>
<td>Alfisol</td>
</tr>
</tbody>
</table>

the A and E horizons (Humphreys 1994) and with rates of subsurface mixing about 10–14 times the mounding rate (Humphreys and Field 1998). The A and E horizons form a biomonol that, based on stratigraphic relationships, forms a mobile mantle over an in situ developed B horizon (Humphreys 1994).

The Narrabeen podzol
This site is in a part of a colluvial mantle in Hawkesbury sandstone terrain located 18 km north of Sydney near Narrabeen Lagoon. It consists of a loamy sand A horizon c. 30 cm thick, a porous sandy and conspicuously bleached E to a depth of c. 80 cm, which overlies organic (Bh) and iron (Bhs) pans. The C horizon consists of sand with occasional patches of textural lamellae that in turn overlies sandy clay at a depth of c. 150 cm. The site receives an average annual rainfall of c. 1000–1200 mm but, like Cattai, is affected by dry and wet spells. It supports an open forest to woodland of Myrtaceae tree genera of Angophora, Corymbia and Eucalyptus. No geomorphic process studies have been undertaken at this site though it has been the subject of detailed soil stratigraphy, dating and geochemical analysis (Field and Humphreys 2002). This work indicates that the sand containing the A, E, and upper pan horizons is up to c. 10,000 years old, whereas the base of the lower pan and C horizons is 20,000 BP and older. This age difference indicates that the podzol has developed in the Holocene. A mass balance approach to geochemistry indicates that the podzol is unlikely to have formed by in situ redistribution of grain coatings (Field and Humphreys 2002).

The Pilliga solodic
The site is positioned on a gentle hillslope formed on Pilliga sandstone flanking an extensive depositional plain within the Pilliga State Forests, 420 km northwest of Sydney (Humphreys et al. 2001). Annual rainfall is c. 625 mm but highly variable and the sample site supports a mallee patch dominated by Eucalyptus viridis, which is surrounded by the ironbark and cypress forest. The soil consists of a 10–15 cm thick sandy clay loam A horizon overlying sandy heavy clay B horizon with large prominent columnar peds 25–35 cm wide. A thin (c. 1 cm thick) E horizon of sandy loam to sandy clay loam with pebbles (stone layer) separates the A and E horizons and penetrates to a depth of 45 cm between the domes. Geomorphic process investigations have centred on termite activity and the overturn of the upper 10 cm of soil is estimated about 261 years (Hart 1995). There is a degree of controversy surrounding the origin of this type of soil in the Pilliga region. Hallsworth and Waring (1964) suggested that the B horizon formed from an original sandy material on to which clay and silt were added from flooding and washed through to form a clay-rich layer. At the same time the accumulation of sodium with the clays was thought to enhance shrinkage and swelling to form the columnar peds. Subsequent research on adjacent depositional terrain has indicated that the sandy deposits and topsoils are much younger than the clay units they overlie (Hesse and Humphreys 2001) and there is no evidence to support the in-washing explanation. On the actual study site soil-stratigraphic investigations indicate that the B horizon is derived from

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saprolite as noted above with the A and E horizons comprising a mobile biomantle (Hart 1992; Hart et al. 1996). In addition, Hallsworth and Waring (1964) reported the presence of phytoliths and suggested that the fine sand and silt component of the E horizon, which has a pinky-white colour, represented an accumulation of phytoliths with the implication that there would be a higher concentration of phytoliths in this layer than immediately above or below, i.e. a Type-2 PDF. Hart and Humphreys (1997), however, showed that a Type-1 PDF occurred.

Methods

Each soil was sampled at 5–10 cm intervals down the profile taking care to sample each horizon and to avoid obvious faunal channels. Phytoliths in the silt fraction (2–63 µm) were extracted using the method of Hart (1992). Phytoliths were mounted on slides in Eukitt (RI 1.51) and examined in plane polarised light at 400× magnification with a total of 200 counts per slide. Phytoliths were assigned to a morphological type using the key of Hart (1992) and counting the number of types in each sample assessed morphological diversity. For each sample, the percentage of spheres and platey forms was calculated. Phytoliths were extracted from parallel sets of samples, weighed and the average phytolith content at each depth calculated (Hart 1992; Simons 1998).

Bioturbation at each site was assessed by estimating the percentage of faunal channels in slices of resin impregnated samples 10 × 10 × 5 cm (Humphreys 1994). Previous experimental work has established that the topsoil at each site was capable of pervecting phytolith-sized opaline material (Hart 1992; Simons 1998).

Results and discussion

The two texture contrast soils, i.e. the Cattai podzolic and Pilliga solodic, display a Type-1 PDF with the concentration of phytoliths declining exponentially with depth from the soil surface (Figs. 2a and 2b, respectively). In contrast, the sandy soil at Narrabeen displays a typical Type-2 PDF (Fig. 2c) with a marked increase in concentration in the upper pan (Bh) horizon. Above the pan the concentration of phytoliths increases towards the surface, i.e. it parallels the trends in the topsoil (A and E horizons) in the texture contrast soils (Cattai podzolic and Pilliga solodic). Below the upper pan in the podzol and in the saprolitic subsoils of the texture contrast soils (B horizons) the concentration changes very little. There is also a difference in the phytolith concentration in absolute terms since the Pilliga site has about a tenth of the amount of phytoliths as the other sites which, despite having very different soil characteristics, share a more humid environment.

As noted above, our previous studies have demonstrated clear evidence of bioturbation in terms of rates of mounding at the Cattai and Pilliga sites. At the former site mixing then mounding by invertebrates is the dominant soil transporting process (Humphreys and Field 1998; Humphreys and Mitchell 1983) and it is likely that the same occurs at the other sites. The measure of bioturbation used in this study represents a static picture and records the proportion of soil that clearly displays animal tunnels/burrows and pedotubules (infilled tunnels) in relation to the amount of soil that is not obviously bioturbated, together with any roots, stones, etc. Despite this limitation, the results generally show that the proportion of bioturbated soil parallels the trend in phytolith concentration and decreases with depth (Fig. 2). In all soils there is a stronger decrease towards the base of the E horizon. In the case of the podzol this may reflect the difficulty in determining pedotubules,
which relies to a large extent on colour differences between the pedotubule and the surrounding soil (Humphreys 1994). In a thick, uniformly coloured soil such contrasts become more problematic. Nevertheless, despite this difficulty, it is evident that there is a marked increase in bioturbation in the Bh horizon of the podzol, which coincides with an increase in phytolith concentration.
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Figure 3. Phytolith morphological diversity with depth.

This preliminary analysis indicates that, as expected, bioturbation is probably a major factor in redistributing phytoliths within the soil. This idea is further tested below, although with mixed results. Thus a profile dominated by bioturbation should, in theory, exhibit a similar level of phytolith morphological diversity with depth such that there is little change in the variety of phytolith morphologies between samples (Simons 1998). This expectation is best shown at Cattai where below the uppermost sample there is little change to a depth of 50cm...
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(Fig. 3a), the maximum depth sampled. In contrast the Narrabeen podzol displays a 40% decrease between the pans (Bh versus Bhs horizons), with this change persisting with depth (Fig. 3c). The Pilliga solodic (Fig. 3b) is similar to the Cattai podzolic in displaying relatively little change in diversity with depth but differs in that maximum diversity is in the thin E horizon.

This analysis assumes that the array of different phytolith morphologies produced at each site is equally affected by bioturbation and hence that bioturbation alone does not favour certain morphologies. While most individual bioturbing animals may exhibit feeding preferences, the overall effect of all bioturbing animals bringing phytoliths into the soil and redistributing them within the soil will be an even distribution of phytolith morphologies. Given the relative small size of the phytoliths in relation to the size of particles ingested or carried (typically up to and exceeding 500µm; Humphreys 1994; Paton et al. 1995) it is unlikely that this assumption is invalid.

If this is the case the podzol is clearly very different from the texture contrast soils and implies that a different mixing mechanism is involved. As noted above, this is likely to be the downward movement of phytoliths along the interconnecting voids (packing voids) between the larger framework grains, i.e. pervection (Paton 1978). This void space is likely to be highest in better-sorted and coarser material and to decline with increased clay content. Hence the potential for pervection in the A and E horizons is highest in the Narrabeen podzol, and least in the Pilliga solodic. To test this more closely two morphologies were selected for closer examination: platey and spherical, since it was assumed that different shaped morphologies would respond to pervection differently. In particular it was assumed that the smaller (10-20µm) smooth spherical phytoliths would pass through porous soil and perhaps be trapped where porosity declined whereas the platey forms would be prone to trapping. The podzol demonstrated this effect with a general increase in spherical forms with depth reaching a maximum at the boundary with the pan (Fig. 4c). The same effect, however, is not evident in the texture contrast soils. The smooth sphere morphology at Cattai decreases with depth to the boundary with the B horizon and conforms to a Type-1 function (Fig. 4c) though the increase with depth in the B is not readily explained by either mechanism. A different pattern is displayed in the Pilliga solodic, in which smooth spheres decrease in the A but increase in the E (Fig. 4b). Nevertheless, the trend of the platey forms parallels the smooth spherical forms in this soil. This indicates that the prevailing mixing processes treat both forms similarly in this soil. This is not the same for the Cattai or Narrabeen soils. In the former the platey forms increase slightly in the lower E but not at the base, whereas in the podzol there is a secondary peak in the upper pan (Bh horizon). Neither of these patterns can be easily explained. Thus if the smooth spherical forms are more readily transported than the platey forms in the podzol, we would expect the concentration peaks around the base of the E and Bh horizons to be reversed.

There are also differences between the complementary data sets between the three sites. The Narrabeen-podzol displays Type-2 PDF for concentration (Fig. 2c) and diversity (Fig. 3c), whereas the individual morphologies (Fig. 4c) cannot be categorised this way. The same sort of association is found at Cattai in that concentration and diversity display a Type-1 PDF (Figs. 2a and 3a) but not the separate morphologies (Fig. 4a). In contrast, the Pilliga soil reveals little similarity between the same types of data (Figs. 2b, 3b and 4b). This analysis indicates that on an individual soil type/site basis, and collectively, there is little evidence to support a static phytolith hypothesis. Indeed the complexity in the observed trends indicates that different types of mixing are operating. At Cattai the concentration and diversity trends conform to an expectation of biomixing whereas at the Narrabeen podzol the same data types support biomixing and pervection. At both sites the spherical and platey forms indicate a
different balance of mixing processes as does the Pilliga site. Hence, despite not being able to account for all of the patterns, it is apparent that there is considerable support for a mobile phytolith hypothesis.

The above analysis is based on several assumptions in terms of the main mixing processes as identified above. A complete understanding, however, is limited also by other constraints. In comparison with the Cattai and Narrabeen soils, the Pilliga soil contains fewer

Figure 4. Phytolith depth functions of selected morphologies.
sample points and this reduces the certainty of any comparison. In addition the three very different results between the sites in the distribution of spherical and platey phytoliths may be influenced by the texture and hence the degree of connectivity between voids. This is even evident in the topsoil (A and E horizons), in which connectivity is assumed to be highest in the podsol (sandy material) and least in the Pilliga topsoil (sandy clay loam). In addition, the analysis has not taken into account site history differences. The texture contrast soils have saprolitic B horizons and dating of the topsoil indicates ages of <10,000 years. In contrast, the podzol is developed in a sandy colluvial mantle with ages extending beyond 20,000 years (Field and Humphreys 2002). Hence, the major disjunction in diversity and spherical and platey forms across the pans in the podzol (Figs 3c and 4c) may also reflect differences in the late Quaternary environments at this site and hence different vegetation associations.

Conclusions

In terms of the application of phytoliths to studies in the archaeological, environmental and earth sciences there are several important implications. The assumption that phytoliths remain with the original host deposit after initial incorporation is probably not justified. Hence, age relationships based on the presence/absence and even dates of phytoliths become questionable. It seems that phytoliths exhibit varying degrees of mobility and that the extent of mobility is probably influenced by the type of soil and the existing (or even former) mixing mechanisms, as well as the size and shape of different phytolith morphologies. Nevertheless, it appears that potential for downward movement of phytoliths increases with grain size and sorting of the host sediment (e.g. E horizon of the podzol), but even in this situation other factors are at play, as evidenced by the unexpected trends between spherical and platey forms. Finally, it is probably the case that different combinations of mixing and site history can produce similar PDFs and hence they should be used as a guide not an end in themselves.

The utility of phytoliths in studies where process is being examined will be greatly enhanced if careful choice of phytolith size range is made. For example, the dimensions of spherical and platey phytolith might be chosen with regard to the actual average pore dimensions when these morphologies’ distributions are being considered. Thus, the consideration of spheres larger than the average pore size compared with smaller spheres might be enlightening, and, where pervention dominates, less weathering should be observed on easily pervected morphologies at depth compared with those less easily pervected.

This paper demonstrates the application of phytolith depth functions to questions of soil process. In particular, the comparison of individual morphological groups’ PDFs and their expected behaviour under differing dominating processes has the potential to provide, with refinement, another tool for unravelling soil genesis.
References


Taphonomy in the laboratory: Starch damage and multiple microfossil recovery from sediments

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Keywords
starch granule damage, archaeology, laboratory procedures, microfossil recovery, sediments

Abstract

Archaeological sediments from cultivated fields in northwestern Argentina contain starch granules with different kinds of alterations which render their taxonomic identification difficult. Given the possibility that they may have been affected by different natural and cultural processes, including laboratory manipulative processes, the control of laboratory taphonomic processes is necessary. Control tests using modern and archaeological samples have been carried out in order to account for factors that might affect starch during multiple laboratory microfossil extraction. This paper focusses on heavy liquids as a possible factor in starch granule damage. As a result of this study, archaeological micro-remains with at least two properties lost (lamination and sharp surface edges), and hence initially considered only as probable starch given the ambiguity of identification criteria, can now be safely considered as starch in spite of the intense morphological alteration. Our results also suggest that we can confidently count incomplete ('damaged') starch from artefacts and soils as starch, knowing that this kind of laboratory protocol is not responsible for those alterations.

Introduction

Current knowledge of taphonomic processes affecting the structure, morphology and survival rate of starch granules in archaeology is limited. Most starch research has been conducted in respect to its presence on archaeological tools, and has focussed mainly on the possibilities of recovering and taxonomically identifying the starch (e.g. Piperno et al. 2000), as well as on
contamination issues (e.g. Barton et al. 1998). Some taphonomic processes, however, have been identified and studied relative to the production of beer and the milling of grains and acorns in the Iberian peninsula (Juan Tresserras 1990-92, 1998), and to farinaceous food processing in South America (Babot this volume).

In recent studies of sediments recovered from agricultural sites in northwestern Argentina, we have observed starch granules with different kinds of alterations that render their taxonomic identification difficult. Rather than examining the origins of starch in these open-air sites, or transformations due to natural processes, it is potential laboratory damage due to manipulation and the use of chemicals as a causative factor of starch granule damage on which we focus in this study. In other words, this preliminary study is not concerned with site formation processes that might affect the origin and transformation of starch, but only on possible cultural damage/destruction factors during laboratory procedures.

Among taphonomical concerns, some researchers include all the stages that may affect or damage organic remains during laboratory protocols and manipulation (e.g. Lyman 1994). These actions may impinge directly on the results of our observations. For that reason it is necessary to distinguish ‘stages’ or damage categories as a first step towards the inquiry into the origin and taphonomic changes of starch specifically.

Three main factors have been reported as chemical/physical natural taphonomic variables, which might imply changes in starch granules (Cortella and Pochetino 1994; Juan Tresserras 1990-92; Pearsall 1989; Therin 1994):

(1) Temperature: high temperature (above 50°C) may cause starch gelatinisation, which might in turn bring about the loss of birefringence properties and the extinction cross. Very low temperatures may also alter these properties.

(2) Extremely arid conditions: desiccation has also been reported as one of the factors that might eliminate or obscure the extinction cross, but it may reappear as starch is rehydrated.

(3) Humidity / pH: starch is preserved in calcareous, permanently humid contexts, while not in acidic ones.

Laboratory procedures for multiple microfossil extraction from sediments

Laboratory procedures for obtaining as many types of microfossils as possible in one single extraction have been explored in a previous paper (Coil et al. in press). The archaeological sediments of agricultural fields and corrals in northwestern Argentina commonly represent advantageous conditions for preservation (Korstanje 1996). Soils are usually sandy, pH about 7, and the environments are semi-arid. These conditions provide a suitable opportunity to use an extraction protocol run with the help of minimum possible chemicals, to obtain silica and non-silica microfossils (e.g. silica phytoliths, calcium oxalate phytoliths, diatoms, cryophycean, palynomorphs, starch, spherulites).

During the initial stages of research we could readily see that such sediments contained at least some well-preserved starch granules. For example, samples sieved through a 200µm mesh only for spherulite recovery contained some starch granules (Fig. 1). Some well-preserved starch was also recovered from samples that underwent the complete protocol (Fig. 2). In the latter case, however, most of the granules were damaged to the point that taxonomic identification, even their belonging to the starch group, was dubious (Fig. 3).

It should be recognised that taxonomic recognition, even if desirable, is not critical to our research, as we are working at the level of microfossil assemblages, i.e. the density of each type of microfossil in different archaeological productive structures, in order to infer general environmental patterns. Nevertheless, we needed to initially establish specimens as belonging to
the starch category, even if their alteration prevented finer taxonomic recognition. General criteria typically used for starch identification, i.e. birefringence and the polarising cross (after Therin 1994:49), did not seem adequate for identifying specimens as starch grains in some cases in our research; the granule surface was either too damaged or the movement of the extinction cross was unclear or random. For this reason we decided as well to compare grain alteration resulting from milling or other food manipulation processes with our results from sediments (Babot and Korstanje 2001).

Samples were processed after a multiple microfossil extraction protocol, described below. As this protocol has not been designed specifically for the recovery of starch, certain steps might produce some damage to such microfossils. Those critical procedures are highlighted in italics in the protocol and are discussed in more detail below.

Samples are dried in the oven at low temperatures (maximum 80°C), until weight is stabilised. Equivalent samples (10g) are deflocculated by adding sodium hexametaphosphate overnight. Clays are separated and eliminated by gravity using distilled H₂O in liquid columns. Decantation times are checked according to Stoke’s Law. Before separating and fractionating silts into three classes (fine, medium and coarse) with the same method, samples are sieved (50–55µm mesh) for sand removal (which is stored for larger phytolith scanning). The three silt classes are floated, either together or separated, in a ZnI₂ heavy liquid solution at a density of 2.3. If the solution displays a precipitation of a hydroxide by-product (‘snow dispersion’), warm distilled H₂O (less than 50°C) or a few drops of glacial acetic acid is used to avoid the problem.

1 Carried out in the Laboratorio de Estudios Cuaternarios in UNCIEP dependencies of the Universidad de la República del Uruguay, and improved with heavy liquid floatation procedures during a Fulbright Visitor Scholarship at the Archaeological Research Facility, University of California, Berkeley.
The use of this protocol has provided interesting results regarding the recovery of microfossil assemblages, as shown in Figure 4. These two graphics (same sample, same slide, counts made out of standardised densities) show that the improvement of the flotation step was critical for recovering most of the microfossil types except cellulose rings. In the case of starch, no specimens at all were found in the non-floated sample, while 22 were recovered from the floated sample.
We were not certain whether this low-chemical protocol, which has shown to be fine for multiple microfossil extraction, was good enough for silica phytolith recovery and specific morphotype identifications. To check we ran a sample (V90) comparing our protocol with one using KOH + HCl + H2O2 steps (Fig. 5). Even if this sample did not contain any starch or spherulites, the comparison has shown that the more aggressive chemical protocol does not imply a better recovery for the silica assemblage either, and it clearly damaged most of the non-silica assemblage in our case study.

![Figure 5. Microfossil recognition and recovery in regular protocol (floated) and more chemically aggressive protocol. The number of specimens is shown on the vertical scale.](image)

Finally, we tested whether the protocol was adequate for microfossil identification purposes (in the sense of clear slides), or whether the high chemical impact protocol allows more identifiable specimens. Again, if we project our numbers to equivalent density measurements, the comparison shows that the protocol used is correct even for the more specific silica phytoliths identification purposes (Fig. 6).
But is this laboratory procedure good enough for starch recovery?

As we have mentioned above, many starch granules extracted with this procedure were affected in terms of their morphology. The reasons could be either natural site formation and diagenetic processes, by cultural manipulative processes (see Babat this volume), or due to the laboratory extraction manipulation itself. As our target population is microfossil assemblages generally, natural and ancient cultural damage is not considered a problem in our samples, but laboratory damage is. In the latter, the most probable agent was the ZnI₂ used for the flotation step. While there are references in the literature to indicate CsCl might cause gelatinisation and ZnBr₂ would dramatically affect the number of starch granules (thereby reducing the possibilities of recovery [Therin 1994]), we had no such information relating to the behaviour of ZnI₂ with regards to starch.

Apart from the question of ‘damage’, a most stunning situation arose during a photography session two months after scanning and studying the permanent slides (immersion oil mounting medium, at least six hours scanning each), when starch granules were quite difficult to relocate. This apparent ‘disappearance’ is another reason why this laboratory taphonomic research was initiated, as it was also possible that ZnI₂ was affecting the starch population after some time.

We developed four control tests on modern and archaeological samples to ascertain if the heavy liquid flotation step might be considered a laboratory taphonomic factor affecting starch extraction from soils and their survival afterwards. For these purposes, we have differentiated three starch taphonomical stages or classes:

1. clearly well-preserved starch (CWP);
2. clearly damaged starch (CD), which consists of those specimens that still bear the main characteristics of starch identification (birefringence and Maltese cross) but have lost the others; and
3. doubtful starch (D), consisting of those specimens that have lost most of their characteristics but still have at least one of them.

Figure 6. Silica phytolith identifiable specimens. The number of specimens is shown on the vertical scale.
Test descriptions

Test 1
Sample: archaeological sediments.
Controlled factor: time in slides.
We made two scanning comparisons of the same slide, prepared following the complete protocol described earlier, mounted with immersion oil and counted at (a) UC Berkeley (using a Nikon Eclipse microscope, transmitted light, cross-polarised light, 200 x magnification), and (b) UN Tucumán, six months later (using a Zeiss Axioscope, transmitted light, cross-polarised light, 200 x magnification).

As mentioned above, this test was performed in order to understand why many of the starch granules initially found in our soil samples (processed using the complete protocol) disappeared with time.

Test 2
Sample: archaeological sediments.
Controlled factor: time in final silts.
Starch was scanned in new slides prepared with the same dry, stored, extracted samples (complete protocol), but now mounted in water for better starch scanning. As we had a further portion of the dry silt (floated) sample, we prepared new slides to see if in dry samples ZnI₂ might have also destroyed starch granules after some time.

Test 3
Sample: archaeological sediments.
Controlled factors: time and occurrence in final and pre-final silts.
Starch was scanned in new slides made with the previous dry, stored, extracted samples, but not floated in ZnI₂ (pre-final silt). These samples were mounted in water. Owing to the possibility that starch was being directly damaged by ZnI₂, slides were prepared with the pre-final silt (that is to say, samples that were not floated in heavy liquid yet), in order to focus on starch observation and preservation, during the same time period.

Test 4
Sample: modern commercial starch.
Controlled factors: ZnI₂, temperature and humidity.
Starch was scanned from samples floated in ZnI₂. For this test we took four modern commercial starchy products (dry corn, ripe corn, quinoa flours and potato starch). These products were chosen because all of them present at least some starch that is damaged due to the cultural food manipulative process (see Babot this volume).

(a) Equal weights (2g) of each product were placed in a test tube with ZnI₂ solution prepared at a density of 1.7, following Barton et al. (1998). In this case, the starch/ZnI₂ solution was not rinsed. Three slides of the specimens derived from each product were prepared and observed under the microscope as follows:
   - directly in the solution;
   - dried under environmental laboratory conditions (12°C) and mounted in immersion oil;
   - dried under a 75 W common lamp, at a distance of 20cm, and mounted in immersion oil.
All samples were checked after time periods of 0, 24, 36 and 48 hours.

(b) Equal weights (2g) of each product were placed in a test tube with ZnI₂ solution prepared at a density of 2.8 (as in our current multiple microfossil extraction), centrifuged at low
speed (900rpm for 10 minutes), and then rinsed at high speed (2700rpm for 5 minutes). Two slides of the specimens derived from each product were prepared and watched under the microscope as follows:
- directly in the solution;
- dried under environmental laboratory conditions (12°C) and mounted in immersion oil.
All samples were checked after time periods of 0, 24, 36 and 48 hours.

Results (Figs 7 and 8)

Test 1 (a) and (b)
The results clearly showed the disappearance of most of the starch granules from the slides in all three preservation categories.

Test 2
The results show, again, that starch in the three taphonomic classes is detectable when the sample is dry and it has not previously been scanned under the light (temperature) of the microscope.\(^2\) After some comparisons with modern *Chenopodium* sp. starch, we added the category ‘D tiny’ as similar starch-like clusters had appeared in two of the samples (Fig. 9).\(^3\) These were not seen in the previous permanent slides of Test 1, owing to the low expertise bias.

Test 3
We found both well preserved and dubious starch, but microfossils in the ‘dark’ slides were so heaped that it was very difficult to scan them; the same reason that made us move to the flotation step for better phytolith recovery and observation (see Fig. 4). Other non-biogenic silica particles also seemed to obscure the possibility of starch observation.

Test 4
This test, conducted using modern Andean starchy products, showed very interesting results.
(a) The ZnI\(_2\)/starch solution (1.7 density) showed a different behaviour in each of the three slides:
(1) When the solution was observed immediately, no damage at all either in quantity\(^4\) or in quality, was seen, even after 24, 36 and 48 storage hours.
(2) In the slide dried at environmental conditions, some aggregation occurred and some starch disappeared (Fig. 10), while 24 hours later only potato and quinoa starch remained in clusters and no maize was found.
(3) In the slide dried under artificial light, starch completely disappeared.
(b) The ZnI\(_2\)/starch solution (2.3 density), once rinsed, also showed a different behaviour in the prepared slides.
(1) When the solution was observed immediately, an aggregation process occurred and some starch disappeared in the viscous substance that was formed (Fig. 11). Once dehydrated though, starch seemed to be in perfect condition.

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\(^2\) The differences in number within (a) slides might be considered to be an over-representation due to the low expertise bias during the first scanning experience.
\(^3\) This result matches perfectly the site environmental conditions, adequate for chenopods.
\(^4\) We counted the starch in a quarter of the 20× ocular. Modern samples contain so many starch granules that we considered that a general, qualitative category (many, some, none) was enough for this purpose.
Figure 7. Tests 1(a) and 1(b), 2 and 3 results (archaeological sediments). Key: CWP = Clear well-preserved starch; CD = clear damage starch; D = dubious starch.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Test 1: time comparison on floated ZnCl₂, mounted in immersion oil</th>
<th>Test 2: floated in ZnCl₂ mounted in water (new slide)</th>
<th>Test 3: processed but not floated, mounted in water</th>
<th>Sample context precedence</th>
</tr>
</thead>
<tbody>
<tr>
<td>A164 (a) January 2001 (UC Berkeley)</td>
<td>3 (dubious) No starch at all</td>
<td>lots of D (tiny, as Chenopods cf.)</td>
<td>lots of D (tiny, as Chenopods cf.)</td>
<td>Morro Relincho productive field, E. XVII (prof. 38 cm)</td>
</tr>
<tr>
<td>C70 (clear + dubious)</td>
<td>10 2 CD 3 CWP 2 D</td>
<td>lots of D (tiny, as Chenopods cf.)</td>
<td>No starch at all</td>
<td>Morro Relincho productive field, E. X (prof. 30 cm)</td>
</tr>
<tr>
<td>A366 (clear + dubious)</td>
<td>11 1 CWP 2 CD 8 D</td>
<td>lots of D (tiny, as Chenopods cf.)</td>
<td>No starch at all</td>
<td>El Alto El Boson domestic space, E. 82 (prof. 50 cm)</td>
</tr>
<tr>
<td>A377 (clear + dubious)</td>
<td>17 3 D 1 D</td>
<td>1 CD 1 D</td>
<td>lots of D (tiny, as Chenopods cf.)</td>
<td>El Alto El Boson productive field, E. 104 (prof. 15 cm)</td>
</tr>
<tr>
<td>A379 (clear + dubious)</td>
<td>28 No starch at all</td>
<td>No sample remaining</td>
<td>1 CD 1 D</td>
<td>El Alto El Boson productive field, E. 104 (prof. 45 cm)</td>
</tr>
<tr>
<td>A400 (clear + dubious)</td>
<td>10 No starch at all</td>
<td>2 D</td>
<td>lots of D (tiny, as Chenopods cf.)</td>
<td>El Alto El Boson agricultural terrace, E. 19 (prof. 40 cm)</td>
</tr>
<tr>
<td>V68 (clear)</td>
<td>2 No starch at all</td>
<td>4 CWP 12 D</td>
<td>No starch at all</td>
<td>Los Viscos shelter, corral episode L12A (prof. 13 cm)</td>
</tr>
<tr>
<td>V81 (dubious)</td>
<td>3 (dubious) 1 CWP 4 CD</td>
<td>No starch at all</td>
<td>No starch at all</td>
<td>Los Viscos shelter, food refuse episode L12A (prof. 17 cm)</td>
</tr>
<tr>
<td>V90 No starch at all</td>
<td>No starch at all</td>
<td>1 CD 2 D 2 CWP 1 D</td>
<td>Los Viscos shelter, food refuse episode L12C (prof. 19 cm)</td>
<td></td>
</tr>
<tr>
<td>V405 (clear + dubious)</td>
<td>29 1 CWP 4 CD</td>
<td>5 CWP 1 D</td>
<td>Los Viscos shelter, food refuse episode (bottom) L13A* (prof. 21 cm)</td>
<td></td>
</tr>
</tbody>
</table>

1 At UC Berkeley the CWP, CD, D categories were not used while counting, so it’s not possible to reproduce them exactly now. Also what is now under consideration as tiny Chenopodium cf. starch, was not recognised at that time.
<table>
<thead>
<tr>
<th>Test 4</th>
<th>dry maize mild flour (lagua de maíz)</th>
<th>ripe maize mild flour (lagua de choclo)</th>
<th>quinoa mild flour (lagua de quinoa)</th>
<th>potato starch (almidón de papa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starch and H₂O solution (for comparison)</td>
<td>Mounted directly in water or immersion oil</td>
<td>Lots of starch (CWP and CD)</td>
<td>Lots of starch (CWP and CD)</td>
<td>Lots of starch (CWP and CD)</td>
</tr>
<tr>
<td>a) Zn₁₂ at density 1.7, not rinsed in H₂O</td>
<td>(1) Mounted directly in water</td>
<td>Lots of starch (CWP and CD)</td>
<td>Lots of starch (CWP and CD)</td>
<td>Lots of starch (CWP and CD)</td>
</tr>
<tr>
<td></td>
<td>(2) Dry (at environmental conditions) and mounted in immersion oil</td>
<td>Some aggregation of starch in clumps, and some disappearance</td>
<td>Some aggregation of starch in clumps, and some disappearance</td>
<td>Some aggregation of starch in clumps, and some disappearance</td>
</tr>
<tr>
<td></td>
<td>(3) Dry (under a light) and mounted in immersion oil</td>
<td>All disappeared</td>
<td>All disappeared</td>
<td>All disappeared</td>
</tr>
<tr>
<td>b) Zn₁₂ at density 2.8, then rinsed in H₂O</td>
<td>(1) Mounted directly in water</td>
<td>Some gelatinised starch in clumps</td>
<td>Few gelatinised starch in clumps</td>
<td>Very few and very damaged starch, not clustered</td>
</tr>
<tr>
<td></td>
<td>(2) Dry (at environmental conditions) and mounted in immersion oil (same as the soil extraction protocol)</td>
<td>Lots of starch (CWP and CD)</td>
<td>Lots of starch (CWP and CD)</td>
<td>Lots of starch (CWP and CD)</td>
</tr>
</tbody>
</table>

Figure 8. Test 4 results (modern starchy samples).
(2) In the slide dried at environmental conditions we observed no damage either in quantity or in quality of starch even when the slide was observed again after 24, 36 and 48 hours (Fig. 12).

It is worth noting that potato and maize starch showed differences in the type of damage caused by both processes. In Test 4(a) potato starch was stronger than maize, while in Test 4(b) the opposite situation was observed.

Also, all samples were checked in their liquid solution (at 1.7 and 2.3 densities) after 24, 36 and 48 hours, and were found to be in perfect condition quantitatively and qualitatively. This point clearly and definitively shows that while in ZnI₂ solution, starch is perfectly preserved, even after 48 hours soaking.

While the chemical processes involved in these situations are under research, for the purposes of our taphonomical questions this experience has been enough to show that the procedure using ZnI₂ as heavy liquid for microfossil extraction does not damage starch, calcium oxalates or carbonates. It is during the processes of hydration, dehydration and heat combination that at least part of the starch disappears, as in nature. Having this in mind, we believe that there is a possibility that the important difference between Tests 1(a) and 1(b) is that the slide was exposed under the microscope light for about six hours⁵ (see also Therin 1994:44). This possibility is further supported if we compare the slight difference between Tests 1(a) and 2 (in spite of the experience bias), based on the same silt preparation (the same six months passing), but one hydrated with immersion oil and exposed under the microscope light for at least six hours, and the other just dried under laboratory environmental conditions and then stored.

We also performed the iodine staining test for starch identification on some samples with the following results. Sample A400 in Test 2 showed damaged starch, although the staining results were not clearly positive. Sample V90, which had clearly non-damaged starch, was also ambiguously stained (Fig. 9); the colour change was not to dark brown (chenopods) or blue (maize and potato) as in modern samples, but turned to very light brown. The same can be said of the tiny starch granules as Chenopodium cf. ones of an archaeological sample (Fig. 10).

Therin (1994) has also dealt with the problems of staining in the case where the physical or chemical structure of granules is altered, which is definitively the case in our study.

**Discussion**

Therin (1994) drew attention to some of the taphonomic factors altering starch in some experiments conducted using zinc bromide (ZnBr₂) and cesium chloride solution (CsCl). Here

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⁵ Four hours is the standard time involved in searching and counting spherulites, starch, cellulose and calcium oxalates, and two more hours are needed to scan and count phytoliths in plain light.
we discuss them in relation to the use of ZnI₂. Both salts have a very close anion, which is supposed to behave similarly for these cases.

While Therin (1994:44) considered that ‘Damaged starch grains present within the sediment have less chance of surviving the extraction procedure than intact starch’, we have found both cases of damaged and well-preserved starch grains in modern samples test, as well as in the archaeological tests.

While Therin (1994:44) found that ‘ZnBr₂ causes the almost complete destruction of all the starch grains present in a period of 30 minutes’, we found that ZnI₂ does not destroy starch itself. Rather, it is the combination of water and heat that destroys it in slides.

Therin (1994:44) also quotes Banks et al. (1975), ‘Due to a smaller surface area, smaller starch grains are less susceptible to gelatinisation and degradation’ and agrees that ‘This means that smaller grains have a greater chance of surviving the extraction process’, and that ‘starch grains ... are more likely to be damaged due to their age’ (Therin 1994:46). Even if we are not able to prove this, it seems quite possible according to our observations.

Finally, we believe that the protocol for extraction from soils had itself some weaknesses concerning starch recovery, such as those involved in the high temperature used to stabilise the weight of the samples (although the starch might have survived it in our study because the soils used were very dry), and the inadequate density of the heavy liquid preparation, aimed especially at silica microfossils. Still, some starch is preserved anyway, and we have chosen a compromise solution for getting the whole variety of microfossils in one slide (Korstanje in press).

Conclusions

As a result of this research, we are now able to safely assign those archaeological micro-remains previously identified only as probable starch to the starch group, in spite of their intense morphological alteration. Our results also suggest that we can count incomplete (‘damaged’) starch from artefacts and soils as such, knowing that careful and controlled laboratory protocols may not be responsible for those alterations but that natural processes may be.

If ZnI₂ is to be considered an agent of destruction, it must be that it behaves so owing to a harmful combination of humidity and heat during slide preparation and scanning. ZnI₂ itself damages starch only when it is not well rinsed, and only once it gets dry. As floating the samples still seems to be necessary for starch observation (as shown in Fig. 4), we can only say for now that counts should be done immediately after the slide is prepared.

Starch ‘disappearance’ from the slides after some time has also been observed in archaeological samples from artefacts, where no flotation step was involved (Babot pers. comm.). This may indicate, again, that it is the exposure to the microscope light that may cause such ‘disappearance’.

Although it is not possible for analysts to exactly replicate Test 1, it was the positive evidence of starch disappearance which made us become interested in these taphonomic problems. That is why we include Tests 1 and 2; to show what the problem was in microfossil extractions. If the final reason for starch granule disappearance is, as we think, the large exposures to microscope light in a liquid mounting media, then we cannot suggest any way to avoid this destruction, as heat in a humid media is one of the natural ways starch is damaged, besides bacteria, etc. The disturbing factor is not necessarily the time that passed from the first to the second scan (six months), but the time we spent scanning the slides using the microscope light. We can conserve the extract in a vial for longer in an appropriate media, but
for the slides themselves we should take the precaution of taking photographs immediately if we are going to scan them for a long time, to confirm results before starch is destroyed.

Finally, it may also be the case that the surviving starch is somehow silicified (see Kealhofer et al. 1999). If so, the conditions and process of silicification of starch granules needs further research.

Acknowledgements

My very special thanks to Christine Hastorf for the opportunity to train at Berkeley’s laboratories, and to James Coil for introducing me into ‘hands-on’ phytolith-starch issues, as well as challenging me on laboratory creative possibilities. Also to Laura del Puerto, Hugo Inda and Jordi Juan Tresserras, for all the wisdom and help during these phyto-years. To Mariana Mondini for her contagious enthusiasm on exploring taphonomic issues, and to Guillermo Korstanje for his help on the chemical connotations of the tests performed — my thanks also. The final responsibility for this paper is mine.

References


Coil, J., M.A. Korstanje, S. Archer and C. Hastorf. in press. Laboratory goals and considerations for multiple microfossil extraction in archaeology. *Journal of Archaeological Science*.


The survival of starch residue in a subtropical environment

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Keywords
starch, residue analysis, grinding stones, taphonomy, China, subtropical environment, preservation

Abstract
An experiment on starch preservation in subtropical Hong Kong was carried out in the spring of 1999 in order to investigate the survival of different plant starch in different conditions. Sixteen small stones were used to replicate prehistoric food preparation processes using four plant species. These ‘artefacts’ were then exposed to three different simulated archaeological conditions. Results indicate that starch grain preservation was reduced significantly when left in an open situation condition, and survived better in a buried or sheltered situation condition. Meanwhile, an analysis conducted on grinding stones found in an open archaeological site in South China in 2000 did not recover any starch grains. It is argued that artefacts found in all open archaeological sites should also be subjected to starch analysis, and more attention should be given to artefacts found in caves and rock shelters in southern China in any future studies.

Introduction
Starch analysis has become an important approach in prehistoric archaeology, particularly for investigating the subsistence strategies of prehistoric populations. Starch residue has been identified on surfaces of prehistoric grinding tools in Australia (e.g. Veth 1997) and in the Pacific, the latter dated to as early as 28,000 years ago (Loy et al. 1992). The results indicate that plant roots such as yam and taro might have been important food resources for the prehistoric population in the subtropical and tropical areas. These plants do not produce large quantities of phytoliths, but contain hundreds of thousands of starch grains (Zhang 1998). Hence, starch residue analysis can provide useful data when applied to archaeological research in subtropical and tropical areas.

Southern China is one such subtropical area. To date, our knowledge of the prehistoric subsistence strategies in this region is very limited. In recent years, a multi-disciplinary approach (including starch analysis) has been applied to archaeological studies in this region.
However, the mechanisms of starch residue preservation are still unclear (Fullagar et al. 1998). Further, the climate and soil in Australia and the Pacific areas (where much of the starch-related research has been carried out to date) differ from that in subtropical southern China, which is humid and hot, and where the soil is often acidic. Such conditions are particularly damaging to organic materials. Therefore, it will be an important part of southern Chinese archaeological research to determine whether starch can survive in various taphonomic conditions in this environment.

To investigate this issue, an experiment was carried out in Hong Kong in early 1999. The results from this experiment document how starch can survive in varying situations, and how starch from different plants may have different survival rates when subjected to different taphonomic conditions.

Materials and methods

In Australia and the Pacific, starch residues are often found on the surface of grinding tools (e.g. Fullagar et al. 1998). To investigate starch preservation, it would therefore be ideal to use grinding slabs as samples. Samples in this experiment, however, were observed using a high-power microscope, and it was found to be impossible to place grinding stones on the working station of the microscope. Therefore, small stone pieces were used as test samples instead. The rock samples used in this experiment were sandstone and granite (Fig. 1), as grinding slabs found in archaeological assemblages in southern China are often made of these materials. For example, grinding stones made of similar materials have been discovered in the Dingsishan and Zengpiyan assemblages in the Guangxi Municipality, southern China (Lu 2001).

Four plant species were selected for the experiment: foxtail millet (Setaria sativa), rice (Oryza sativa), yam (Diosorea spp.) and taro (Colocasia spp.). Foxtail millet and rice were initially domesticated in the prehistoric Yellow and Yangzi Valleys, respectively. The progenitors of these two cultivars (the green foxtail [Setaria viridis] and wild rice [Oryza rufipogon]) are found widely in southern China today, as are wild yam and taro. All these plants could have been staple food for the prehistoric gatherers in southern China and so were considered suitable for the purposes of this experiment. As wild species could not be located in Hong Kong, domesticated species were used instead.

All stone samples were washed thoroughly under running water using a toothbrush to clean the stone surface. After cleaning, each stone sample was designated a number for recording and two observation circles were randomly marked on each stone surface (Fig. 1).
Each observation point was examined using an Olympus metallurgical microscope\(^1\) with a magnification of 400 × to ensure that there were no remaining plant residues.

Each stone sample was then used to grind material from a single plant species for approximately five minutes, and was then observed under the same microscope using the same magnification as previously. Unfortunately, three samples were broken during the plant processing. The remaining 13 samples were observed to have starch grains covering the entire surface of the observation circles after grinding (Figs. 3[a] and 4[a]). The estimated quantity of starch grains within each observation point was recorded and photographed (Fig. 5).

The samples were then divided into three groups and subjected to three different conditions simulating the taphonomic conditions of archaeological artefacts. Each group consists of samples bearing starch from the four plants (Table 1). The first group was buried about 5 cm beneath the surface of red sandy soil (Fig. 2). This was to simulate the taphonomic condition in which artefacts discarded were quickly buried either by nature or human activities, then subjected to weathering activities (such as rain, strong sunshine and heat, as well as biological elements such as insects in the soil) but would have been protected from wind action. The second group was left on the ground surface without any cover, simulating the condition of open archaeological sites, where samples would be subjected unprotected in any manner to all weathering and biological elements. The last group of samples was positioned under the shelter of a building. This was to simulate conditions encountered in a rock shelter or cave context, where artefacts might have been partially sheltered from wind, and completely sheltered from sunshine and rain, but still subjected to biological elements such as insects.

The pH value of the soil used for this experiment was determined to be 7 (neutral). After the samples were buried or left, a climatic diary was kept to record the

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\(^1\) A microscope with cross-polarised light would be ideal for this experiment; however, such equipment was not available when this experiment was conducted (in 1999).
Table 1. Starch survival rates after 71 days.

<table>
<thead>
<tr>
<th>SAMPLE NO.</th>
<th>OBSERVATION CIRCLE NO.</th>
<th>PLANT SPECIES</th>
<th>BURIAL CONDITIONS</th>
<th>COVERING % ON 18/03</th>
<th>COVERING % ON 28/05</th>
<th>REDUCED BY %</th>
<th>SURVIVAL %</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>Taro</td>
<td>buried</td>
<td>85</td>
<td>67</td>
<td>21.2</td>
<td>78.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>94</td>
<td>78</td>
<td>17.0</td>
<td>83.0</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>Rice</td>
<td>buried</td>
<td>93</td>
<td>79</td>
<td>15.1</td>
<td>84.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>91</td>
<td>69</td>
<td>24.2</td>
<td>75.8</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>Yam</td>
<td>buried</td>
<td>98</td>
<td>69</td>
<td>29.6</td>
<td>70.4</td>
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<td></td>
<td>2</td>
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<td>96</td>
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<td>39.6</td>
<td>60.4</td>
</tr>
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<td>53.7</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>86</td>
<td>75</td>
<td>12.8</td>
<td>87.2</td>
</tr>
<tr>
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<td>1</td>
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<td>buried</td>
<td>92</td>
<td>81</td>
<td>12.0</td>
<td>88.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>66</td>
<td>43</td>
<td>34.8</td>
<td>65.2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Taro</td>
<td>open</td>
<td>97</td>
<td>28</td>
<td>71.1</td>
<td>28.9</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>96</td>
<td>62</td>
<td>35.4</td>
<td>64.6</td>
</tr>
<tr>
<td>7</td>
<td>1</td>
<td>Yam</td>
<td>open</td>
<td>63</td>
<td>1</td>
<td>98.4</td>
<td>1.6</td>
</tr>
<tr>
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<td></td>
<td></td>
<td>95</td>
<td>17</td>
<td>82.1</td>
<td>17.9</td>
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<tr>
<td>13</td>
<td>1</td>
<td>Rice</td>
<td>open</td>
<td>38</td>
<td>14</td>
<td>63.2</td>
<td>36.8</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>34</td>
<td>16</td>
<td>52.9</td>
<td>47.1</td>
</tr>
<tr>
<td>16</td>
<td>1</td>
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<td>87</td>
<td>43</td>
<td>50.6</td>
<td>49.4</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Taro</td>
<td>sheltered</td>
<td>72</td>
<td>71</td>
<td>1.4</td>
<td>98.6</td>
</tr>
<tr>
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<td>2</td>
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<td></td>
<td>87</td>
<td>73</td>
<td>16.1</td>
<td>83.9</td>
</tr>
<tr>
<td>9</td>
<td>1</td>
<td>Foxtail millet</td>
<td>sheltered</td>
<td>47</td>
<td>32</td>
<td>31.9</td>
<td>68.1</td>
</tr>
<tr>
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<td></td>
<td>98</td>
<td>73</td>
<td>25.5</td>
<td>74.5</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>Yam</td>
<td>sheltered</td>
<td>43</td>
<td>35</td>
<td>18.6</td>
<td>81.4</td>
</tr>
<tr>
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<td>89</td>
<td>67</td>
<td>24.7</td>
<td>75.3</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>Rice</td>
<td>sheltered</td>
<td>97</td>
<td>78</td>
<td>19.6</td>
<td>80.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td></td>
<td></td>
<td>89</td>
<td>71</td>
<td>20.2</td>
<td>79.8</td>
</tr>
</tbody>
</table>

Figure 4. Observation circle No. 2 on Sample No. 7 with yam and placed in an open condition. (a)(left) Starch observed on 18/03/1999 (400× magnification); (b)(right) Starch observed on 26/05/1999 (400× magnification).

rain, wind and sunshine conditions, etc. as elements possibly affecting the preservation of the starch grains.

All samples were left for 71 days from 18 March to 27 May 1999, and were collected and observed under the same microscope at 400× magnification on 28 May. The quantity of starch grains on the surface within each observation circle on 18 March and 28 May was estimated and compared. The quantitative estimation was conducted by making a transparency marked with 100 squares of equal size, then placing this transparency on the
The survival of starch residue in a subtropical environment

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Figure 5. Illustration of the use of a marked transparency to estimate starch residue quantity.

Table 2. Statistical analysis of starch survival in different conditions.

<table>
<thead>
<tr>
<th>BURIAL CONDITIONS</th>
<th>Open</th>
<th>Buried</th>
<th>Sheltered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (survival %)</td>
<td>35.17</td>
<td>74.75</td>
<td>80.24</td>
</tr>
<tr>
<td>Standard error</td>
<td>7.99</td>
<td>3.78</td>
<td>3.16</td>
</tr>
<tr>
<td>Median (survival %)</td>
<td>36.84</td>
<td>77.32</td>
<td>80.09</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>21.14</td>
<td>11.94</td>
<td>8.93</td>
</tr>
<tr>
<td>Sample variance</td>
<td>446.95</td>
<td>142.52</td>
<td>79.70</td>
</tr>
<tr>
<td>Range</td>
<td>63.00</td>
<td>34.38</td>
<td>30.53</td>
</tr>
<tr>
<td>Minimum survival %</td>
<td>1.60</td>
<td>53.66</td>
<td>68.09</td>
</tr>
<tr>
<td>Maximum survival %</td>
<td>64.60</td>
<td>88.04</td>
<td>98.61</td>
</tr>
<tr>
<td>Observation circle count</td>
<td>7</td>
<td>10</td>
<td>8</td>
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</table>

Table 3. Starch survival rates of different plants.

<table>
<thead>
<tr>
<th>CONDITIONS</th>
<th>PLANT</th>
<th>SURVIVAL RATE %</th>
<th>PLANT</th>
<th>SURVIVAL RATE %</th>
<th>PLANT</th>
<th>SURVIVAL RATE %</th>
<th>PLANT</th>
<th>SURVIVAL RATE %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>Taro 1</td>
<td>28.90</td>
<td>Yam 1</td>
<td>1.60</td>
<td>Rice 1</td>
<td>36.80</td>
<td>Millet 1</td>
<td>49.4</td>
</tr>
<tr>
<td></td>
<td>Taro 2</td>
<td>64.60</td>
<td>Yam 2</td>
<td>17.90</td>
<td>Rice 2</td>
<td>47.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>46.75</td>
<td></td>
<td>9.75</td>
<td></td>
<td>41.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried</td>
<td>Taro 1</td>
<td>78.80</td>
<td>Yam 1</td>
<td>70.40</td>
<td>Rice 1</td>
<td>84.90</td>
<td>Millet 1</td>
<td>88.0</td>
</tr>
<tr>
<td></td>
<td>Taro 2</td>
<td>83.00</td>
<td>Yam 2</td>
<td>60.40</td>
<td>Rice 2</td>
<td>75.80</td>
<td>Millet 2</td>
<td>65.2</td>
</tr>
<tr>
<td></td>
<td>Taro 1</td>
<td>53.70</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Taro 2</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>75.68</td>
<td></td>
<td>65.40</td>
<td></td>
<td>80.35</td>
<td></td>
<td>76.6</td>
</tr>
<tr>
<td>Sheltered</td>
<td>Taro 1</td>
<td>98.60</td>
<td>Yam 1</td>
<td>81.40</td>
<td>Rice 1</td>
<td>80.40</td>
<td>Millet 1</td>
<td>68.1</td>
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<td></td>
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<td>75.30</td>
<td>Rice 2</td>
<td>79.80</td>
<td>Millet 2</td>
<td>74.5</td>
</tr>
<tr>
<td>Average</td>
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<td></td>
<td>78.35</td>
<td></td>
<td>80.10</td>
<td></td>
<td>71.3</td>
</tr>
</tbody>
</table>

surface of the microphotos, and counting the area covered by starch grains at the beginning and the end of the experiment (Fig. 5). Results were recorded (Table 1), compared and analysed statistically (Tables 2 and 3).

Results

Before conducting this experiment, a number of assumptions were made. Firstly, it was assumed that the survival rate of starch in open conditions would be the lowest, as the starch would be fully exposed to all weathering and biological elements. Secondly, in a sheltered condition the starch survival rate was expected to be higher, as the impact of weathering would be reduced. Owing to the uncertainty involved with buried samples, no assumption was made as to how soil moisture and soil fauna would affect the starch preservation.

A summary of the climatic data recorded during the experimental period is provided in Table 4. During the 71 days, the temperatures ranged from 12.7 to 31.5°C, and the humidity from 31% to 98%. Strong winds of force 5 to 6 were recorded on three days. There were 32 days with rain during the experimental period, and the total precipitation was 343.3mm. Within the
The state of the art in phytolith and starch research in the Australian–Pacific–Asian regions

Table 4. Climatic conditions during the experimental period from the 18 March to 27 May 1999.

<table>
<thead>
<tr>
<th>CLIMATIC VARIABLE</th>
<th>Lowest Temperature (°C)</th>
<th>Highest Temperature (°C)</th>
<th>Lowest Humidity (%)</th>
<th>Highest Humidity (%)</th>
<th>Rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>21.96</td>
<td>26.42</td>
<td>70</td>
<td>90</td>
<td>10.73</td>
</tr>
<tr>
<td>Standard error</td>
<td>0.36</td>
<td>0.38</td>
<td>1</td>
<td>1</td>
<td>3.38</td>
</tr>
<tr>
<td>Median</td>
<td>22.30</td>
<td>26.90</td>
<td>71</td>
<td>92</td>
<td>2.65</td>
</tr>
<tr>
<td>Mode</td>
<td>21.10</td>
<td>28.50</td>
<td>75</td>
<td>96</td>
<td>0.10</td>
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<tr>
<td>Standard deviation</td>
<td>3.04</td>
<td>3.24</td>
<td>10</td>
<td>5</td>
<td>19.11</td>
</tr>
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<td>9.26</td>
<td>10.48</td>
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<td>0</td>
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<tr>
<td>Range</td>
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<td>15.10</td>
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</tr>
<tr>
<td>Minimum</td>
<td>12.70</td>
<td>16.40</td>
<td>31</td>
<td>74</td>
<td>0.10</td>
</tr>
<tr>
<td>Maximum</td>
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<td>31.50</td>
<td>89</td>
<td>98</td>
<td>81.50</td>
</tr>
<tr>
<td>Sum</td>
<td>1559.10</td>
<td>1876.10</td>
<td>49.7</td>
<td>64.24</td>
<td>343.30</td>
</tr>
<tr>
<td>Count (days)</td>
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<td>71</td>
<td>71</td>
<td>71</td>
<td>32</td>
</tr>
</tbody>
</table>

32 raining days, four days with heavy rainfall (28.1, 46.9, 58.9 to 81.5mm per day) were recorded.

The experiment appears to validate the aforementioned assumptions, and the main findings are summarised as follows:

- A large percentage of starch grains survived under sheltered conditions. For example, the quantity of starch on observation circle No. 2 of Sample No. 1 changed very little during the 71 days. The starch grains shrank slightly but still covered almost the entire surface of the sample (Fig. 3[b]). On average, more than 80% of starch grains were preserved in the sheltered conditions (Table 2).

- The quantity of starch grains was reduced significantly in the open conditions. Starch within the observation circle No. 1 of Sample No. 7 had almost completely disappeared after 71 days, and was also reduced significantly within observation circle No. 2. The surface of the second observation circle had been almost fully covered by starch grains at the beginning of the experiment (Fig. 4[a]), but only a small quantity was still visible after 71 days (Fig. 4[b]). On average, only 35.17% of the starch survived in an open condition (Table 2). The difference between open and sheltered conditions varied by more than 200%.

- Starch grains on stone artefacts buried in the soil survived very well. Average quantitative survival rates of starch grain in the buried condition was 74.75% (median = 77.32%) (Table 2). This is quite close to the result from the sheltered condition (which shows a mean value of 80.24% and a median of 80.09%), but is substantially different from the results obtained in the open contexts (Table 2).

- Another objective of this experiment was to investigate whether starch of different plants would have different survival rates. The survival rates of different plants, as well as the same plant on the same sample surface, vary (Table 3). For example, on the surface of Sample No. 7, only 1.6% of the original yam grains within observation circle No. 1 survived after the experiment, yet 17.9% of the same plant starch survived at observation circle No. 2 (Table 1). Significant differences in terms of survival rates were also observed on other samples bearing other plant starch (Table 3).
Discussion

This experiment documents the belief that the preservation of starch grains varies under different (simulated) archaeological conditions. It had been assumed that starch grains would have survived considerably better in a sheltered situation than in an open situation, since in the latter strong winds might have blown the starch grains away and heavy rainfall could have washed off the starch grains. Originally, it had been planned to observe the starch grains after each day of heavy rain and/or strong wind; but this plan could not be carried out due to the limited access to microscope facilities. The results of this experiment, however, seem to indicate that strong wind and/or heavy rainfall have a strong impact on the preservation of starch left in open conditions, but have limited impact on starch on artefacts buried in the soil or in otherwise sheltered environments. In the open buried situation rain could still have penetrated through the soil and reached the surface of the samples. It is possible, however, that the flowing movement of the rain, which should have been the major force carrying starch grains away, was significantly reduced when the rain moved through the soil; consequently, more starch grains were preserved. This hypothesis will be tested in a future experiment.

In respect to the survival rates of different plants, starch grains from taro and rice seem to have a higher average survival rate than those from yam and foxtail millet in open and sheltered conditions, although the survival rate of foxtail millet is also quite high in a buried condition (Table 3). As the populations of this experiment are quite small, this preliminary result cannot be viewed as a pattern. Further experiments are required to address this issue.

This experiment ran for only 71 days, which is by no means comparable to the time that archaeological artefacts are buried in the soil or left for thousands of years. This preliminary result still indicates that starch can be preserved on the surface of stone artefacts, and would be preserved better in a covered condition.

Encouraged by the experimental results, an attempt to extract archaeological starch residues was conducted on 12 grinding stones from the Dingsishan assemblage, southern China. The pH value of the soil at the site is between 6.5 and 7. The extraction followed the protocol of van der Meer (1998), and the samples were observed using an Olympus biological microscope with cross-polarised light at 500 x magnification. Disappointingly, no starch grains were found on the artefact surfaces, although phytoliths and charcoal particles were present (Lu 2001).

The results of the archaeological extraction attempts should not be taken as evidence for assuming starch grains do not survive on artefacts in open sites, and it is advocated that artefacts found in open sites be examined for starch grains. On the other hand, the outcome of this experiment indicates that starch analysis would most profitably be applied to artefacts found in caves and rock shelters in southern China. Accordingly, samples from grinding stones and other stone artefacts found in the Zengpiyan Cave in southern China have recently been collected and will be processed in the near future. It is hoped that by applying starch analysis, more data can be gathered on the prehistoric subsistence strategies and natural resources in southern China.

Acknowledgements

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Phytolith analysis of Ipomoea batatas (kumara) and Lagenaria siceraria (gourd) in New Zealand: A method of providing direct evidence of prehistoric farming in ancient Polynesia

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Keywords
gourd, kumara, Ipomoea batatas, Lagenaria siceraria, New Zealand, Pacific, Polynesia, phytoliths, prehistoric agriculture

Abstract

Lack of direct evidence of Ipomoea batatas (also referred to as kumara or sweet potato) in association with datable material is an impediment to resolving the conflicting hypotheses regarding the transport of this cultivar to and through Polynesia. Presented herein are the results from a successful blind test of soils from experimental garden plots situated close to two archaeological sites. Also provided is evidence of phytoliths from modern vegetable matter. The results indicate that phytolith analysis of Ipomoea batatas and Lagenaria siceraria (gourd), either as stand-alone data or in association with other proxy evidence, will contribute towards resolving some of the fundamental questions regarding prehistoric Polynesian agriculture.

Introduction

This paper is a research-in-progress report presented as a workshop topic at the State of the Art in Phytolith and Starch Research in the Australian–Pacific–Asian Regions conference held in Canberra, August 2001.

Ipomoea batatas (kumara or sweet potato), in prehistory as in the present day, is an important economic plant and its presence in pre-European New Zealand (Fig. 1) raises a
number of fundamental questions, such as how did it reach Polynesia, by what means was it transported and when did this happen? A number of hypotheses have been postulated to answer these questions, ranging from an Asian origin spreading along the west-to-east migration routes during the early settlement of Oceania, to a South American origin transported by Polynesians, Amerindians or early European explorers. The South American origin of *Ipomoea batatas* was confirmed by Yen (1974). He went on to postulate that this plant was introduced into central eastern Polynesia during the prehistoric period from where it spread to the extremes of the Polynesian triangle during migration. The colonial expansion of the Spanish and Portuguese during the 15th and 16th centuries later spread *Ipomoea batatas* to island South-East Asia and on to New Guinea (Hather and Kirch 1991). Historic evidence from the 18th-century European voyagers Cook and Rogevéen confirm the cultivation of *Ipomoea batatas* in Easter Island, Tahiti,
New Zealand and Hawaii. Direct evidence, however, is very limited. Rosendahl and Yen (1971) described a carbonised tuber from Hawaii. Davidson (1987) interpreted pits found in New Zealand with *Ipomoea batatas* storage. More recently, an interdisciplinary study on Mangaia Island in the Cook Islands found a number of carbonised *Ipomoea batatas* specimens in sediments dated between about AD 1000 and 1600 (Hather and Kirch 1991).

To investigate the questions raised above it is necessary to find fossil traces of *Ipomoea* and other associated introduced plants, such as gourd (*Lagenaria siceraria*), in association with datable material. Pollen from *Ipomoea batatas* appears to be unsuitable because of its scarcity of flowers and by the fact that it is cultivated vegetatively (Horrocks et al. 2000). Phytoliths, silica microfossils formed in the cells of living plants, are an alternative microfossil with which it may be possible to trace the migration of *Ipomoea* cultivation. A literature search found no references relating to observations of phytoliths in *Ipomoea*. In 1998, however, Carter (unpublished data) extracted phytoliths from *Ipomoea* leaves. After extraction, small (5–15 µm) spherical smooth phytoliths were observed under light and scanning electron microscopes (SEM) and found to be distinctive (Figs. 2A and B).

Subsequently, Horrocks et al. (2000) analysed sediments from stone mounds at Pouerua, Northland, for phytoliths and pollen. They suggest the spherical smooth phytoliths found in these sediments originate from a pre-European sweet potato variety known as *rekamaria*. Gordon (2000) also recovered spherical smooth phytoliths (Fig. 2C) from a surface soil sample taken from an area of a northwest facing hillside on Banks Peninsula, which was found to be a humanly modified soil (a large amount of fine greywacke pebbles having been added to the soil).

This paper presents the results of a blind test carried out to determine whether phytolith assemblages extracted from soils and sediments can verify that *Ipomoea* and *Lagenaria* (hereafter referred to as kumara and gourd, respectively) were grown in those soils. Seven soils were sampled in and around experimental garden plots. The plots are part of an continuing experiment conducted by Te Papa (Museum of New Zealand, Wellington, New Zealand) archaeologists to monitor the growth of old (possibly prehistoric) varieties of kumara and gourd in gardens developed on sites close to known archaeological sites. In addition, kumara and gourd leaves were processed to provide phytoliths from plants growing at these sites.

**Blind Test**

Seven soils were provided for phytolith analysis. The only information revealed to the researcher was that the samples were labeled A to G, four deriving from one site and the other three from a different location. The researcher was told that the sites were at Robin Hood Bay and Whatarangi in New Zealand (Fig. 1). The researcher was also told that one site in each area had been used to grow kumara and/or gourd, but not which samples had come from which site. Phytoliths were to be extracted from these soils. On the basis of the phytolith assemblages found, a judgment was to be made as to which sites were most likely to have come from the sites growing kumara and/or gourd. After the presentation of a report of results and assessment of which soils were judged to be growing kumara and gourd, Te Papa archaeologists released details (Table 1) showing which soils had actually been used to grow these plants.
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Figure 2. Photomicrographs of Ipomoea phytoliths extracted from plant material, garden topsoils and archaeological sediments. A and B = modern kumara; C = archaeological sediment (Banks Peninsula; courtesy H. Gordon); D = H2 39 Hutihuti (Robin Hood Bay); E = Rekama rua (Robin Hood Bay); F and I = Tapanui (Robin Hood Bay); G and H = Tapanui (Whatarangi); J to N = garden soil (Robin Hood Bay). Arrows indicate kumara phytoliths. Scale bar = 10μm for all images except C, where it = 1μm.
Table 1. Information released after blind test, disclosing the linkage between the experimental soils, region, area, history and use of garden.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>SAMPLE</th>
<th>SITE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Robin Hood Bay</td>
<td>A</td>
<td>Mound 18</td>
<td>In part of garden (second season).</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>Mound 48</td>
<td>In part of garden (first season).</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td>At edge of garden where tops were dumped after first season.</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td></td>
<td>25m west of garden.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Note gourds have not been grown at the Robin Hood Bay site as part of this experiment.</td>
</tr>
<tr>
<td>Whatarangi</td>
<td>E</td>
<td>Mound 25</td>
<td>Kumara garden (first season).</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td></td>
<td>SW corner of garden where gourd was rampant and kumara struggling.</td>
</tr>
<tr>
<td></td>
<td>G</td>
<td></td>
<td>Outside of experiment garden, about 3m to the north, but close to archaeological features.</td>
</tr>
</tbody>
</table>

Table 2. Kumara-type phytoliths: Photo notation, phytolith origin, origin to plant or sediment and sample location used in blind test.

<table>
<thead>
<tr>
<th>FIGURE 2 PHOTO</th>
<th>PHYTOLITH ORIGIN</th>
<th>PLANT OR SEDIMENT</th>
<th>SAMPLE LOCATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>modern kumara leaf</td>
<td>plant</td>
<td>Hawkes Bay</td>
</tr>
<tr>
<td>B</td>
<td>modern kumara leaf</td>
<td>plant</td>
<td>Hawkes Bay</td>
</tr>
<tr>
<td>C</td>
<td>archaeological sediment</td>
<td>archaeological sediment</td>
<td>Banks Peninsula</td>
</tr>
<tr>
<td>D</td>
<td>H2 39 Hutihuti</td>
<td>plant</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>E</td>
<td>Rekama rua</td>
<td>plant</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>F</td>
<td>Tapanui</td>
<td>plant</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>G</td>
<td>Tapanui</td>
<td>plant</td>
<td>Whatarangi</td>
</tr>
<tr>
<td>H</td>
<td>Tapanui</td>
<td>plant</td>
<td>Whatarangi</td>
</tr>
<tr>
<td>I</td>
<td>Tapanui</td>
<td>plant</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>J</td>
<td>Sample A</td>
<td>Sample A</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>K</td>
<td>Sample A</td>
<td>Sample A</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>L</td>
<td>Sample A</td>
<td>Sample A</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>M</td>
<td>Sample A</td>
<td>Sample A</td>
<td>Robin Hood Bay</td>
</tr>
<tr>
<td>N</td>
<td>Sample A</td>
<td>Sample A</td>
<td>Robin Hood Bay</td>
</tr>
</tbody>
</table>

Site Descriptions

Robin Hood Bay (NZMS 260-P27 995830): The garden is located just inland of a very extensive archaeological garden site that is illustrated and described in Brailsford (1981). It is towards the inland edge of an almost flat river terrace, about 200m in from the beach, with a northeasterly aspect. The soil consists of a schistose pale-yellow clay loam over river and beach gravels. The vegetation consists of pasture of introduced grass and weeds with some exotic trees on the edge of the river terrace inland of the garden.

Whatarangi (NZMS 260-S28 948676): The garden is situated on a flat and narrow, shingle-covered coastal platform between a Pleistocene terrace and the beach in eastern Palliser Bay. It is situated about 100m inland from the beach, on the inland side of a prominent post-Pleistocene raised beach ridge. The soil is a greywacke-derived, dark-brown coarse sandy silt. The vegetation consists of pasture of introduced grass and weeds.

Phytolith extraction techniques

The method of phytolith extraction described here is similar to methods described by Piperno (1988) and Hart (1988). Initially, the organic component was removed by heating in 27% hydrogen peroxide. After washing to remove hydrogen peroxide, the residue was wet sieved at 250µm and the coarser material discarded. Ultrasonic treatment was used to break down...
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Figure 3. Phytolith frequency diagram of Samples A to G. Grass forms to left, fern forms in the centre and tree/shrub forms and Nikau, Broad Point, hair cell (gourd type) and spherical-K (kumara type) to the right. Spherical K = kumara-type phytoliths; Spherical L = large (>40µm) spherical phytoliths; Spherical V = spherical verrucose phytoliths.

the organic and clay complexes to release phytoliths. Clay-sized particles <5µm were removed by settling and any remaining organic material was removed by digestion in Schulzes Solution (Traverse 1988). The phytoliths were then floated off from the other silicates using a sodium polytungstate solution diluted to a specific gravity of 2.3. Phytoliths were mounted with Canada Balsam on glass slides for visual examination. After processing, the phytolith residuals were mounted and 300 phytolith forms counted per slide. The numbers were converted to percentages, grouped into trees, ferns and grasses and plotted as a frequency diagram (Fig. 3). It should be noted that the term ‘grass’ in this study is used in the broader sense and includes members of the Gramineae, Juncaceae, Cyperaceae, Typhaceae and Restionaceae families.

The modern plant material was ashed in a muffle furnace at 500°C, the residual matter was washed in 10% HCl and rinsed in distilled water before mounting on microscope slides.

Phytolith identification and analysis

The phytolith classification used is that developed by Kondo et al. (1994). Judgment was made as to the origin of phytolith types by comparing these with phytoliths from a personal reference collection, and with those described by Kondo et al. (1994). Particular attention was given to the kumara- and gourd-type phytoliths extracted from the soils of the blind test.
These were compared with phytoliths extracted from kumara and gourd samples provided for this study and others from earlier research (Figs. 2 and 4; Table 2) (Carter unpub. data; Gordon 2000) and previous published work (Piperno 1988: Plate 10).

Results

The results of the analysis of the seven soils of the blind test are shown on a percentage frequency diagram (Fig. 3). Microphotographs of examples of phytoliths of kumara and gourd extracted from the blind test soils are shown in Figures 2 and 4. There are fundamental differences in the phytolith assemblages extracted from the Robin Hood Bay and Whatarangi soils as shown in Figure 3. The Robin Hood Bay soils have greater percentages of tree and shrub phytoliths, whereas grass phytolith forms dominate the Whatarangi soils.

Robin Hood Bay samples

Samples A and C recorded the highest percentages of kumara-type phytoliths (Fig. 3) with 19% and 18%, respectively. Sample D recorded 13% and Sample B had the lowest percentage of 7%.

Gourd-type phytoliths were found in very low numbers in Sample C, which recorded 1%.

Whatarangi samples

The samples from Whatarangi recorded lower percentages of kumara-type phytoliths than those from Robin Hood Bay. Sample E recorded 1%, Sample F, 4% and Sample G, 3%.

Gourd-type phytoliths were also found in very low numbers from one Whatarangi site, with Sample F recording 1%.

Phytoliths extracted from modern plant material

A small number of phytolith forms were extracted from four fresh samples of kumara leaves. Some were of an irregular blocky form while others were of a tracheid form. The most diagnostic phytoliths (which were the focus of this study) were the smooth spherical forms (Figs. 2E-I). These range in size from 5 to 15µm and have very smooth surfaces. This smooth surface is in most cases blemished by a ring of small grooves and/or pits running around the middle of the sphere (Figs. 2A and B). Additionally, hair-cell phytoliths were extracted from one gourd sample (Fig. 4A).

Discussion

The high percentages of tree and shrub phytolith forms which dominate the assemblages from the Robin Hood Bay samples are probably remnants from the previously cleared coastal forest (Wardle 1991). The kumara-type phytoliths extracted from samples in this study are very similar to those phytoliths extracted from modern plant material (Fig. 2). Higher percentages of kumara-type phytoliths in the two Robin Hood Bay Samples A and C are a good indication that these soils were used for growing kumara. The kumara-type phytoliths in Samples B and D pose a problem. It is possible that they represent ‘background noise’ from other vegetation. Small, smooth, spherical phytoliths were extracted from Nothofagus truncata by Kondo et al. (1994: Plate 10). However, the presence of nikau palm (Rhapalostylis sapida) in the assemblage and proximity of the Robin Hood site to the sea effectively rule Nothofagus out of contention as a source for these phytolith forms in these assemblages (Wardle 1991). The alternative and
The most favoured hypothesis is that these smooth spherical phytolith forms are all derived from kumara planted or discarded at these sites some time in the past.

Grass forms dominate the phytolith assemblages from the Whatarangi soils, suggesting a grassy landscape with a small amount of trees and shrubs. This is very like the environment today, where grass dominates the coastal flats with a few trees and shrubs in the gullies. The marked contrast with the Robin Hood Bay site phytolith assemblage is probably the result of the more exposed nature of the Whatarangi site at Palliser Bay. It is probable that high winds caused the loss of the sandy soil and phytoliths after coastal forest clearance (McKinnon et al. 1997: Plate 13). Therefore, the phytolith assemblage from the Whatarangi site represents only post-clearance vegetation.

The percentages of kumara-type phytoliths in the Whataran gi samples are lower than those from the Robin Hood Bay site. Notwithstanding the low percentages, Sample F, with the
The highest percentage of kumara-type phytoliths in the Whatarangi samples, was used for growing kumara. The presence of kumara-type phytoliths in soils E and G could represent background noise from other vegetation. It is more probable, however, that aeolian processes have removed phytoliths representing the original coastal forest and the small spherical phytolith forms represent kumara planted or discarded at these sites some time in the past.

The smooth spherical phytolith referred to as a kumara-type phytolith found in Samples A to G cannot be unambiguously identified as being derived from kumara vegetable matter. However, because of the higher percentages of these forms and the similarity with the phytoliths extracted from modern plant material, this is a more plausible hypothesis than derivation from trees and/or shrubs or some other unknown vegetation. Examination of the kumara-type phytoliths under a SEM may help to resolve this problem.

The identification of gourd-type phytoliths (hair-cell forms) is less ambiguous than spherical kumara-type phytoliths. Only two of the seven samples (C and F) recorded the presence of hair-cell phytoliths, which compare well with the segmented hair-cell phytoliths extracted from the fresh plant material (Fig. 4) and with gourd phytoliths described by Piperno (1988). On the basis of their presence in Samples C and F and their similarity with phytoliths extracted from fresh gourd plant material, it is probable that gourd was grown in these two soils in the past. The presence of segmented hair-cell phytoliths in Whatarangi Sample F confirms that gourd was grown during the last growing season. The presence of gourd-type phytoliths in Sample C suggests that at some time in the past gourd was probably grown or disposed of in that soil.

In conclusion, the results of this successful blind test provide evidence that phytolith analysis, either as stand-alone data or in association with other proxy evidence, can contribute towards resolving some of the fundamental questions regarding prehistoric Polynesian agriculture. Future work should include the phytolith and starch analysis of yam, taro, ti-pore and paper mulberry. Thought should also be given to the possibility of the extraction of DNA signatures from carbon remains found occluded within any phytoliths as a means of positively identifying the phytoliths to species of origin.

Acknowledgements

I thank Janet Davidson from Te Papa for suggesting the blind test and providing samples for the experiment. I thank Hamish Gordon for allowing access to material from his Honours dissertation and Bruce McFadgen from the Department for Conservation for encouragement in pursuing this research. I would like also to thank Doreen Bowdery and James Coil for their constructive suggestions.
References

The search for El Niño/Southern Oscillation in archaeological sites: Recent phytolith analysis at Jugali-ya rock shelter, Wardaman Country, Australia

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Keywords
northern Australia, Holocene, ENSO, phytoliths, climatic variability, technological change, stone artefacts, vegetation change

Abstract

This paper presents preliminary results from a phytolith analysis undertaken on sediments from a rock shelter located in Wardaman Country, on the edge of the semi-arid zone in northern Australia. This research aims at understanding the nature of technological developments and shifts in land-use patterns in the context of changing climatic and environmental conditions during the Holocene. The study of phytoliths seeks to elucidate the sequence of local vegetation and, by inference, environmental changes that have taken place at Jugali-ya rock shelter during the past >4000 years. The study also explores the possibility that increasing inter-annual variability in rainfall associated with the onset of ENSO conditions between c. 3000 and 5000 years ago may have been one factor giving rise to environmental and cultural changes about this time. Initial results from Jugali-ya rock shelter indicate climatic deterioration beginning before c. 4000 years ago, with the replacement of palms and other tree species by predominantly grass species about 3000 BP.
Introduction

A number of archaeologists have recently drawn attention to short-term environmental oscillations (i.e. inter-annual and decadal time-scales) as a significant factor requiring further consideration in the explanation of Holocene cultural change. This trend also mirrors recent international research (Bridgemann 1983; Bryson 1994; Fagan 1999; Finney 1985; Jones et al. 1999; Potts 1996a, 1996b; Sandweiss 1986, 1996; Sandweiss et al. 1996, 1997, 1999).

In particular, Australian researchers (Anderson et al. in prep.; Hiscock in press; Rowland 1999a, 1999b; Sim 1998) have begun to draw attention to the potential impacts of El Niño/Southern Oscillation (ENSO) related climatic variability on human technology, demography, settlement and subsistence patterns in the past 3000 to 5000 years in Australia and New Guinea. For example, Hiscock (in press) has tentatively linked the proliferation of backed artefacts in the mid-Holocene to a possible increase in aridity and environmental variability triggered by the onset of an ENSO-dominated climatic pattern about 4000 to 5000 years ago. Hiscock (1994, in press) points to the advantages such maintainable and reliable tool kits may have offered mobile groups in exploiting riskier and less predictable environments after this time.

Rowland (1999a, 1999b) has provided an extensive review of evidence for long- and short-term climatic oscillations in the Australasian region. Like Hiscock, he suggests climate change and variability as possible factors leading to dietary changes among prehistoric groups occupying the coasts of Tasmania, New South Wales, Queensland and New Zealand at various times in the mid- and late Holocene.

Anderson et al. (in prep.) have reviewed arguments for and against the possible human responses to climate change and variability in the mid-Holocene in Australia and New Guinea. These include the introduction of new stone tool technologies, new forms of plant processing, changes in mobility and occupational intensity, demographic fluctuation, colonisation of new environments, population increase and the emergence in New Guinea of wetland gardening as a possible means of managing agricultural water throughout periods of climatic instability. Anderson et al. argue that while various ideas relating climatic variability to extensive cultural changes in the Holocene are plausible, there is a need for greater modelling of palaeodemographic processes and trends at regional and local scales to better understand the various cultural responses to increased uncertainty about access to or control over critical resources in the past 5000 years.

The present study looks for possible connections between periods of potential Holocene environmental change and fluctuation and cultural changes in Wardaman Country (Fig. 1). Recent developments in the theory of lithic production and design provide a basis from which to investigate technological changes as possible reflections of changing settlement and subsistence practices in the Holocene period. By examining Holocene archaeological and phytolith records, it is possible to test hypotheses about the changing way in which people provisioned themselves with tools and raw materials for making tools against the record of environmental changes. The use of phytoliths to explore the nature and timing of local environmental changes may provide an independent test of hypotheses advanced to explain changes in residential mobility and economy derived from an investigation of Holocene technological changes. The study of phytoliths from Jugali-ya rock shelter is therefore an attempt to link multiple lines of evidence to build stronger hypotheses than those based on a single line of evidence alone.

In considering potential environmental impacts on technology and land-use in Wardaman Country, we do not downplay the potential role of socio-political and demographic factors in bringing about significant societal changes in the past, nor the potential influences of
The search for El Niño/Southern Oscillation in archaeological sites
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15°30' S

Key
- Land above 250m ASL
- Excavated rock shelter

Figure 1. Location of Wardaman Country and the excavated rock shelters mentioned in the text.

external cultural contacts. Rather, we are exploring climatic change as one of many potential factors contributing to cultural changes in the mid- to late Holocene. This study represents a first and very preliminary step in modelling the role of environmental and cultural factors in shaping changes in the archaeological record of the study region in the past 10,000 years.

Holocene changes in technological provisioning in Wardaman Country

To provide a backdrop for the results of the phytolith analysis, the timing and nature of technological changes that have taken place in Wardaman Country in about the past >8000 years are summarised for four stratified rock shelter sites excavated and analysed (Jugali-ya, Gordol-ya, Nimji [Ingaladdi] and Garnawala 2; see Fig. 1 [Clarkson 2001, 2002; Clarkson and David 1995; Cundy 1990]). Results reveal a pattern of directional changes in the organisation of stone artefact production and transport which may be seen as changes in the way raw materials were provisioned, curated and maintained over time. By provisioning, we mean the strategies people used to manage raw materials in order to satisfy the need for tools given different levels of uncertainty over scheduling and resource availability (Kuhn 1995).

The regional sequence in Wardaman Country may be broadly characterised as a change from the provisioning of sites with raw material, as reflected in on-site core reduction early in the sequence (Fig. 2a), to the increased provisioning of people with highly standardised retouched tool kits (Fig. 2c) (Clarkson 2002). Accompanying this trend is a significant decrease in the weight of retouched artefacts after 4000 BP (t-test for mean weight changes pre- and post-3000 BP: $t = -2.78$, df = 20, $p = 0.011$) (Fig. 2b) and a sudden increase in the transport of high-quality exotic raw materials (cherts and chalcedonies) between 4000 and 2000 BP (Fig. 2d).
Figure 2. General trends in stone artefact production and provisioning in the past >8000 years in Wardaman Country, summarised from four sequences. Excepting weight, trends are calculated as percentages of the assemblage per unit time. Trends have been smoothed using moving averages of two units. Median is used in place of mean and standard deviation as populations are heavily skewed.

Figure 3. Retouched implements manufactured in Wardaman Country since c. 2800 BP. Arrows indicate the location of burin blows. Not to scale.
The specific reasons behind this transition require further investigation, but we offer the view that these changes may indicate (among other explanations) an increase in residential mobility through time. Increasing mobility places constraints on the amount people can carry and, as a consequence, hafted, portable, multifunctional tool kits may have provided specific advantages to mobile hunter-gatherer groups (Bamforth 1986; Bleed 1986; Hiscock 1994, in press; Kuhn 1995; Torrence 1983, 1989). In Wardaman Country, these mid- to late Holocene tool kits primarily take the form of bifacial points, burrens, tulas and burins, which probably formed components of composite tools (Fig. 3). These standardised retouched implements first appear in Wardaman Country about 2800 years ago (Attenbrow et al. 1995; Cundy 1990; Mulvaney 1976).

In considering explanations for these changes in provisioning, it is worth examining the sequence of Holocene environmental changes to identify trends or periods of aridity and/or greater climatic variability that may have given rise to increased levels of economic risk and/or greater residential mobility. It must be stated, however, that it is not variability itself that creates risk for hunter-gatherers, but reduced predictability of conditions (Hiscock 1994), as people can plan for, and even take advantage of, predictable variation (such as under a monsoon system). It is with the purpose of identifying periods of heightened variability (and perhaps reduced predictability) that we now review recent palaeoenvironmental research conducted in northern Australia.

**ENSO and Holocene climate change in northern Australia**

Generally, the early Holocene in Australia is characterised as a period of increased precipitation (i.e. up to 50% wetter in northern Australia than in modern times), with a mid-Holocene optimum (that is, somewhere between 5000 and 3500 BP depending on exact location) of warmer and wetter conditions (Gagan et al. 1994, 1998, in press; Kershaw 1983, 1995; Kershaw and Nix 1989; McGlone et al. 1992). The mid- to late Holocene is thought to have been a period of increasing aridity, although exactly when the onset of increased aridity occurs is not well documented and appears to vary with location. For instance, a number of studies point to a later onset of arid conditions in northern Australia than occurred in more southern latitudes (McGlone et al. 1992; Shulmeister and Lees 1995). Further, studies of north coastal cheniers are interpreted as indicating decreased wet season precipitation from 2800 to 1600 BP (Lees 1992a, 1992b; Lees et al. 1990, 1992), whereas a pollen record from Groote Eylandt indicates a marked decline in precipitation between 4000 and 3500 BP (Shulmeister and Lees 1995), with increased rainfall during the past 1000 years (Fig. 4). Shulmeister and Lees (1992) also argue that tropical monsoonal rainfall is likely to have become more variable within 1000 years of sea-level stabilisation. These general
trends toward increased aridity and heightened variability in the mid-Holocene are supported by records of flood deposits in the Kimberley (Gillieson et al. 1991) and by other indicators from sites in Australia and the circum-Pacific region after c. 3000 BP (Brookfield and Allen 1989; Hope and Golson 1995; Kershaw 1995; McGlone et al. 1992; McPhail and Hope 1985; Singh and Luly 1991; Whetton et al. 1990).

Within these longer-term trends, the ENSO phenomenon has exerted a strong influence on climatic patterns in tropical and eastern Australia for some time (Jones 1996; Jones et al. 1996; McGlone et al. 1992; Shulmeister and Lees 1995). The term ENSO refers to inter-annual reversals in ocean-atmosphere interactions of the Walker Circulation System that operates in the Indo-Pacific region (Allan et al. 1996; Enfield 1989; Trenberth 1996; Webster and Palmer 1997). ENSO embraces two distinct phases that tend to oscillate between two extremes — El Niño and La Niña — and occurs as a consequence of ‘see-saw like’ reversals in sea-level pressure, ocean currents, sea-surface temperatures and trade winds between the south-eastern tropical Pacific and the Australian-Indonesian region (Diaz and Markgraf 1992:9). The state of the system is monitored by the Southern Oscillation Index (SOI), which is the ratio of sea-level pressures between Tahiti and Darwin.

During El Niño events there is a weakening of sea-level pressure gradients in the south-eastern tropical Pacific, accompanied by a decrease in the strength of trade winds. This results in a weakening of the cool oceanic upwelling along the western coast of South America, in turn causing sea-surface temperatures to rise. Warmer sea-surface temperatures give rise to increased evaporation and heating of the troposphere, resulting in increased convection and rainfall over the coast of Ecuador and Peru, over parts of the Andean cordillera and, to a lesser extent, the southern United States and central Chile (Allan et al. 1996; Diaz and Markgraf 1992:10; Enfield 1992:97). El Niño events often coincide with drought in many parts of Australia, southern Africa, northern India, Sahelian Africa, Indonesia and South-East Asia (Allan et al. 1996:22; Enfield 1992:97).

In contrast, La Niña events represent an intensification of the ‘normal’ ocean-atmosphere circulation pattern, and have impacts that are generally opposite to those of El Niño (Allan et al. 1996:22).

The structure and duration of ENSO events are highly variable, but El Niño phases typically last between 12 to 18 months and tend to recur every three to seven years. Quasi-cyclical changes in intensity at decadal and greater time-scales have also been noted (Anderson 1992; Kerr 1998, 1999; Trenberth and Hoar 1996).

Today, ENSO constitutes the largest single source of interannual climatic variability on a global scale, especially within the dynamical core of the Indo-Pacific region (Allan et al. 1996; Diaz and Markgraf 1992; Glantz 1991; Glantz et al. 1987, 1991; Rowland 1999a). In recent times, ENSO events have had wide-ranging and often severe impacts on terrestrial and marine ecosystems. The worst of these (for example the 1957–58, 1972–73, 1982–83, 1987–88 and 1997–98 ENSO events) have also caused considerable economic hardship and many deaths in some countries through increased periods of drought, frosts, bushfires, cyclones, high temperatures, severe winds and storms (Allan et al. 1996:3; Anderson et al. in prep.; Bourke 1998; Diaz and Kiladis 1992; Glantz 1996; Glantz et al. 1991; Handler and Andsager 1994; Nicholls 1992).

Based on a review of long-term palaeoenvironmental proxy climate indicators, McGlone et al. (1992) have suggested that the ENSO phenomenon may have intensified in the past 3000 to 5000 years. Shulmeister and Lees (1995) also argue for the onset of Walker Circulation-dominated climate with ENSO-scale variability embedded in the system after c. 4000 BP. Evidence also exists from a number of locations world-wide that the impacts of mid- to late Holocene climatic oscillations may have been far greater than any events recorded.
in the late historical period (although this is not necessarily surprising or significant in itself) (Ely et al. 1993; Graumlich 1993; Hughes and Brown 1992; Knox 1993; Rowland 1999a, 1999b).

ENSO-related climatic oscillations no doubt had significant impacts on prehistoric human groups through their effects on the long- and short-term availability, stability and structuring of economic resources. However, until medium- to fine-grained palaeoenvironmental sequences can be developed and matched to archaeological sequences of comparable resolution for the Australasian region, links between Holocene climatic oscillations and human responses (however plausible) remain speculative (Rowland 1999a:34).

Unfortunately, compared with other regions of Australia, in northern arid and semi-arid Australia there are few sites with good palaeoenvironmental data. This is perhaps owing to a combination of poor preservation of pollen and organics in the latter regions and a lack of suitable depositional sites such as swamps and lakes, but may equally relate to a dearth of relevant research projects. Consequently, models of palaeoenvironmental change in arid and semi-arid northern Australia are often extrapolated from records recovered elsewhere in a manner that is not always appropriate.

Currently there are no inter-annual records of ENSO events for the wider Australasian region beyond about 1500 years ago, and medium resolution records are also scarce beyond this time (McGlone et al. 1992:444). It is therefore worth exploring the possibility of obtaining such records by whatever means possible. Phytoliths provide one avenue that has the capability to provide a record of fluctuating vegetation and, by extrapolation, climate from a range of site types in a range of environments.

Since northern arid and semi-arid environments are currently under-represented in Australian palaeoenvironmental studies, yet are also those likely to register changes brought about by ENSO-driven climatic variability, phytolith studies may be of great value in understanding changes in natural and cultural systems during the Holocene period. This study therefore explores the potential of phytoliths found in archaeological sediments to provide a low to medium resolution proxy indicator of climatic change in northern Australia (see also Bowdery 1998; Carter and Lian 2000; Wallis 2000, 2001). In this case we do not mean the level of resolution that may be obtained from undisturbed lake sediments, corals, ice cores or tree-ring data; although we do entertain the possibility of tracking variability at century-long or even shorter intervals within sites that have accumulated rapidly with little post-depositional disturbance. We intend to not only explore longer-term environmental change, but the possibility of using phytoliths to detect the sorts of variations that might be attributable to shifts in the positivity or negativity of the Southern Oscillation Index or, in other words, long periods characterised by either El Niño or La Niña regimes (McGlone et al. 1992).

The test case study: Jugali-ya rock shelter

The site and environment

Jugali-ya rock shelter is located in a shallow gorge which forms the junction between a high sandstone escarpment to the west and undulating limestone plains to the east (Fig. 5). The shelter is located approximately 80m from a permanent waterhole and would have been an attractive location for various human activities in the past (Fig. 6).

The vegetation on the escarpment surrounding the gorge is a low, open snappy gum woodland with curly spinifex, while a taller woodland and grassland dominates the plains to the east. Spinifex, bloodwood and pandanus occur on the rocky slopes immediately outside the site, but vine thicket, weeping paperbarks and pandanus groves occur deeper within the gorge fringing the narrow permanent waterholes.
Jugali-ya is a small rock shelter with a soft sandy floor (Fig. 7), formed from the overhang of a large boulder that has fallen from the cliff immediately above the site. A single 1 x 1m test pit was excavated in the centre of the shelter floor directly in front of a rock art panel depicting dingoes and anthropomorphs. The site was excavated in 37 spits to a total depth of 130cm, revealing seven stratigraphic units (Fig. 8). Sediments changed from reddish-brown sandy loam at the top to a brown sandy loam with massive sandstone rubble at the bottom, and maintained a fairly constant pH of about 6 throughout.

Four radiocarbon dates have been obtained for the top 55cm of the site. The scarcity of charcoal at greater depth makes further conventional dating below this point impracticable. Analysis of the sorted remains reveals major changes in site contents through time, with four groups of materials showing changes at roughly the same depths (Fig. 9).

**Phytolith analysis**

It is considered that the phytolith assemblage within the site derives primarily from the in situ decay of plant materials deposited by people, with some windblown input of (mostly)
grass phytoliths from the immediate surrounds and possibly in situ decay of macropod faecal pellets (which are present in the upper levels of the site) (see Wallis 2000). The interpretation of phytoliths from archaeological sites in terms of vegetation change is complicated due to the nature of accumulation, whereby economically useful plants will be positively selected for, making it highly unlikely that the assemblage will reflect a holistic view of the surrounding vegetation. Having said this, we proceed with the assumption that people will exploit any useful plants available in the immediate site environs and therefore that the appearance or disappearance of phytoliths in the record will reflect the availability of those plants within the local area. We cannot, however, completely rule out the possibility that some phytoliths may have entered the site through long-distance transport from significantly different environmental contexts.

Phytolith samples were extracted from 20 × 5g samples spaced throughout the stratigraphic sequence using a standard heavy liquid extraction technique (following Bowdery 1998). As can be seen in Figure 9, phytoliths were present in all samples examined,
albeit in very low quantities. Phytoliths represent less than 0.5% by dry weight of the original, complete 5g sediment sampled, comparable with modern sediments taken from sand-dunes in the Kimberley region, but only one-tenth the quantity of phytoliths recovered from phytolith-rich, modern vine thicket sediments (Wallis 2000).

Despite their overall low quantities, there were sufficient phytoliths present to undertake counts of 300, a figure which gives a reasonable estimate of types and their relative abundance. Shown in Figure 10 are selected phytolith morphotypes that can be confidently assigned to the broad plant types of grasses and trees. No microscopic particles of charcoal were observed during counting, while diatoms and sponge spicules were observed only in minimal quantities in isolated spits.

Figure 10. Phytolith sequence compiled from 20 samples from Jugali-ya rock shelter.
As evident in the lower levels of the site, tree phytoliths dominate the assemblage, which then decline in abundance after 4000 to 3000 BP (note that these patterns are apparent whether plotted as absolute counts or percentages, so are not merely an artefact of the analysis). Palms can be distinguished easily as spheres with echinate ornamentation, a type that decreases in abundance through time before dropping out of the record entirely by c. 3000 BP. Psilate spheres (some of which also probably derive from palms, but also from other identified tree species) are another tree marker which show a similar pattern to the palm phytoliths. Verrucate spheres (possibly from the dry vine thicket members of Ulmaceae) are also more prevalent in the lower and middle parts of the sequence, dropping out in the upper levels; however, they do persist for a period after the loss of the other trees.

Within the types representative of grasses, the reverse pattern is apparent, these being restricted in the lower levels of the site and increasing quite markedly in the last few hundred years of the sequence. Unfortunately, the grasses are dominated by Panicoid types, a sub-family which incorporates a substantial range of genera that collectively can tolerate a wide range of environmental conditions, making it difficult to elucidate further their significance. Bulliform cells (representing grasses grown in wet habitats) seem to be more common in the lower and middle levels of the sequence, their frequency declining slightly later than that of the trees and palms.

Also of interest at Jugali-ya in terms of fluctuating numbers through time are starch grains, shown in the final column of Figure 10. No attempts have yet been made to identify the starch grains, however, this issue will be addressed in the continuing analysis.

Although somewhat broad in nature, the phytolith record at Jugali-ya does appear to record a significant decline in trees during the mid- to late Holocene, which may be most simply interpreted as a response to decreased surface water availability. Interestingly, in the last 1000 years of the sequence we do not see any evidence of climatic amelioration such as has been proposed on the basis of other palaeoenvironmental records. Unfortunately, sedimentation for the part of the Jugali-ya sequence in which the most significant vegetation changes seem to occur is highly compressed, making it difficult to accurately pinpoint the timing of these changes. It is hoped that by expanding the study to include other sites in the region with Holocene sequences and faster sedimentation rates, we may be better able to resolve such chronological issues. At present, there are at least three other rock shelters (Gordol-ya, Garawala 2 and Ingaladdi) that we consider suitable for future analyses. It remains to be determined through the analysis of these additional sites whether the patterning of phytoliths at Jugali-ya represents regional trends or is site specific.

Discussion and conclusions

The low to medium resolution nature of the phytolith record at Jugali-ya mitigates against fine-grained detection of climatic variability as a driving force behind the vegetation changes at Jugali-ya. We are therefore still able only to speculate at this time about whether a trend toward greater aridity about 3000 to 4000 BP was indeed driven by increasing frequency or duration of El Niño events, or what impact these may have had on the organisation of settlement and subsistence systems in Wardaman Country at this time. This preliminary analysis of phytoliths from Jugali-ya rock shelter nevertheless provides a step in the right direction toward linking Holocene cultural and environmental changes in northern Australia.

1 Definitions of ornamentation terms (i.e. psilate, verrucate and echinate) are provided in Bowdery et al. 2001.
If Rowland (1999a, 1999b), Hiscock (in press) and Anderson et al.’s (in prep.) calls for a reappraisal of the potential role of climatic variability in shaping Holocene cultural changes are to be heeded, paired sequences that match palaeoenvironmental and cultural data, such as that found at Jugali-ya, must be examined at local and regional scales. Modelling human responses to fluctuations operating at a variety of temporal scales will require detailed consideration of multiple lines of evidence. These include changes in stone artefact provisioning as an estimate of changing land-use and mobility, changes in discard and deposition rates, site establishment rates and occupational intensity as proxy indicators of demographic change, and changes in faunal and floral assemblages, foraging range and diet breadth as a guide to changing subsistence practices.

Examination of the medium resolution environmental records obtainable from archaeological sites should also give high priority to the consideration of indicators of climatic variability as well as directional change. Clearly, analysis of archaeological sites with broad temporal units will not allow detection of the interannual (or even decadal) variability in precipitation that characterises ENSO. However, botanical remains in archaeological sites may still register shifts in the positivity or negativity of the Southern Oscillation of the sort that give rise to El Niño or La Niña phases, even if it is not possible to directly discern changes in the amplitude of that variation. McGlone et al. (1992) argue that pollen records showing anomalous combinations of plant assemblages indicating increased moisture and increased drought, as well as increased fire frequency and the expansion of disturbance favoured taxa, can be used as guides to shifts in the amplitude of ENSO events in medium resolution sequences. There may also be potential to develop such indicators for use in phytolith research.

Future research will be aimed at exploring these issues in greater depth, and at determining the nature of the interconnections between multiple lines of evidence of the sort proposed above. We hope to expand the phytolith analysis to include several other rock shelters in the region with deep deposits that span the past 10,000 years and contain an abundance of stone artefacts. Broadening the project to include new sites should aid in the modelling of human responses to climatic changes throughout the Holocene at local and regional scales.

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The search for El Niño/Southern Oscillation in archaeological sites
Clarkson and Wallis

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Evidence for maize processing on 2000-year-old obsidian artefacts from Copán, Honduras

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starch, Zea mays, Copán, obsidian, residues, use-wear

Abstract

Ancient starch granules recovered from stone artefacts are receiving increasing attention from archaeologists because they can reveal aspects of subsistence not accessible through other means. This study reports the identification of Zea mays starch granules on 2000-year-old obsidian artefacts from the Maya site of Copán, western Honduras. The observation of maize processing residues and use-wear on these artefacts provides evidence for a previously unrecognised use of obsidian in Mesoamerica. Furthermore, the results reflect the importance of the in situ study of organic residues and raise the possibility of establishing seasonality from residue analyses.

Introduction

Explorations of ancient plant-related subsistence activities and resources constitute key areas of archaeological investigation. Traditionally, such studies have focussed on the identification of carbonised plant macro-remains (see Pearsall 2000) and with assigning artefact function through ethnographic analogy. More recently, the application of sediment analysis and microscopic investigation to organic residues adhering to artefact surfaces has become increasingly important to reconstructing ancient subsistence regimes. As starch-rich plants form a crucial component of many diets, the study of starch grains provides one such avenue for reconstruction. Here I report the identification of maize (Zea mays) starch grains on 2000-year-old obsidian artefacts from a domestic setting at the Maya site of Copán, Honduras. Concurrent use-wear analysis and microscopic inspection of sediment adhering to the artefacts show that the starch grains result from their use on maize and not from their...
deposition through taphonomic processes. This result indicates a use for obsidian not previously noted in the Mayan area.

Starch residue analysis

The analysis of ancient starch grains on stone artefacts is a relatively new but expanding field (Barton et al. 1998; Fullagar et al. 1996; Hall et al. 1989). In the past decade a variety of lithic types and geographically diverse areas have been included in residue analyses which have recovered starches. For example, Loy et al. (1992) found *Colocasia* and *Alocasia* taro starch on a collection of small, irregular stone artefacts from a 28,000-year-old cave site in the northern Solomon Islands. Starch grains on obsidian artefacts from Bitokara in Papua New Guinea provided evidence for taro as well as yam processing (Fullagar et al. 1998). The Bitokara study was particularly important in that ethnographic observations in this region related the dominant use of obsidian to tasks involving the human body, such as surgery, rather than to plant processing. In Australia, grinding and pounding stones at Cuddie Springs and Jinmium rock shelter exhibited starch residues (Field and Fullagar 1998), while Piperno and colleagues (Piperno and Holst 1998; Piperno et al. 2000) discovered starches of the root crops manioc, yam and arrowroot on milling stones up to 7000 years old from tropical forests in Panama. Perry (2001) details the finding of manioc, maize and other starches on Venezuelan stone artefacts, while Juan-Tresserras (1992, 1998) and others have analysed European archaeological seed starches. Starch grains representing at least three tuber sources have even been observed on Oldowan stone tools up to two million years old from Sterkfontein Cave, South Africa (Loy et al. 1999).

The range of site types (open, forest, rock shelter and cave) and lithic types (obsidian, sandstone and others) studied, as well as the great antiquity of some of the artefacts, indicate that starch grains can not only survive but, importantly, retain their diagnostic characteristics under a variety of conditions. While grass-seed processing was noted in addition to starch residues on the Cuddie Springs artefacts (Field and Fullagar 1998), and maize starch was present on some Panamanian grindstones (Piperno et al. 2000), starch types from root and tuber crops predominate in the literature. The recovery of maize starch from Mesoamerican obsidian artefacts is therefore an important addition to the literature.

The Copán study site

Copán is located in a narrow river valley in western Honduras, on the south-east periphery of the Maya area (Fig. 1). The site was first occupied some time before 1000 BC (Fash 1986) and reached its peak during the Late Classic Coner ceramic phase at AD 600–800 (Webster et al. 2000). Ethnographic observations in the Copán Valley in the 19th and early 20th centuries (e.g. Stephens 1841; Popenoe 1919:128; Wisdom 1940:98) emphasised the importance of maize to the diet, while palaeoethnobotanical research confirmed the central significance of maize alongside beans (*Phaseolus* sp.), squash (*Cucurbita* sp.) and the palm *Acrocomia mexicana* in ancient Copán (Lentz 1991). Furthermore, dietary studies based on bone chemistry and stable isotopes (Reed 1997, 1998) reveal that the ancient Maya population of Copán ‘exhibits the most terrestrial, maize-heavy dietary signature’ (Webster et al. 2000:133) of all Mesoamerican populations for which such studies have been undertaken. Less direct evidence in the form of grinding stones including *manos* and *metates*, ethnographically associated with maize milling in the region (Wisdom 1940:88-9), is also abundant in Copán’s archaeological record (Spink 1988).
Artefact analyses

The artefacts analysed in the current study were recovered from inside and surrounding a shallow pit feature excavated in 1997 in Copán’s El Bosque ward (Hall and Viel 1998), immediately to the south-west of the main Acropolis (Fig. 2). A calibrated 14C date of 100 BC to AD 30 (Hall and Viel 1998) was returned for charcoal associated with the pit, placing it within the Late Formative period in Copán’s chronology (Viel and Hall 1998). The feature forms part of an inferred long-term domestic context including an earthen platform, collapsed house, earth ovens/kilns, pits and burials, as well as ceramic types not found elsewhere in Copán (Hall and Viel 1998, in press). Archaeological evidence also suggests that the pit may have been rapidly filled with mainly lithic debris swept from around a domestic area (Haslam 1999). With the exception of one retouched obsidian blade, the stone artefacts consisted of non-modified flakes which appear to have been expediently utilised without the need for extensive re-shaping (Fig. 3). No artefacts were washed or cleaned after excavation.
The state of the art in phytolith and starch research in the Australian-Pacific-Asian regions

and all handling was with starch-free gloves. The artefacts were also individually bagged. In all, 150 artefacts, including 109 obsidian flakes (Table 1), were analysed under low and high magnification using an Olympus BHM incident light metallographic microscope, with use-wear and organic residue analyses undertaken concurrently to ensure maximum confidence with respect to assigning artefact function.

All residues were analysed in situ on the artefact surface before removal with ultrapure water to microscope slides (see Loy 1994, n.d.). The presence of starch grains was confirmed while the residue was still attached to the artefact through the occurrence of a diagnostic rotating birefringence cross under cross-polarised light. The identification of starch prior to transferring the residue to a slide allowed for use-wear assessment of the associated tool edge, and therefore judgement as to the authenticity of the residue. Those residues associated with used edges were considered as being use-related rather than present due to taphonomic processes. Identification of *Zea mays* starch grains was done via a comparative reference collection using grain size, shape and the presence of distinct grain-size classes (Piperno and Holst 1998). The preliminary nature of the study precluded the gathering of an exhaustive reference collection and no observed starches other than maize were able to be identified to any taxonomic level.

**Results**

Starch residues were found on obsidian, chert and chalcedony artefacts. Only those results obtained from obsidian artefacts are considered here, for two reasons. Firstly, obsidian represents an important lithic material at Copán — estimates of obsidian composition of artefact assemblages at Copán range as high as 90% to nearly 100%, despite the local availability of chert nodules (Aoyama 1995; Mallory 1986:153). Secondly, obsidian is not usually considered to be associated with maize processing at Copán. Concentrating on the obsidian results, therefore, goes beyond simply confirming ethnographically observed maize-processing and obsidian-use activities, and emphasises the potential for residue analyses to add to our knowledge of ancient activities within the domestic sphere.

Of the 109 obsidian flakes, 15 showed unequivocal evidence of maize processing (Figs. 4 and 5). All 15 cases included use-wear consistent with a slicing, chopping or scraping
action; maize starch grains associated with the used edge(s); and in some cases cellulose residue similar to that of the maize kernel pericarp. Transmitted light microscopy confirmed the identification of the starch grains as *Zea mays*. Two artefacts (#126 and #146) displayed evidence of having been used to process fresh maize cobs, with quantities of maize starch attached to the artefact surface by a dried liquid residue (Fig. 6) with reactions to brightfield, darkfield and cross-polarised lighting conditions identical to those given by freshly cut maize residues. One of the residues also possessed attached plant epidermal tissue identical to that of a maize kernel.

In addition to the unequivocal residues, maize starch granules were noted complexed with sediments adhering to a number of the 109 obsidian artefacts, which acted as a control for the presence of taphonomic or post-depositional starch residues. While it was not possible to obtain bulk soil samples for analysis as part of this preliminary study, microscopic examination of the adhering soil proved to be sufficient for assessing the likelihood of non-use related starches being present. In order to be certain of task-associations, starch grains in adhering soils were not treated as being use-related, owing to the possibility that the starch was present in the soil rather than associated with the use of the flake. Exact numbers of artefacts with starch in adhering soil were not recorded at the time of the analysis, as this issue was peripheral to the aims of the project.

**Discussion**

Three themes emerge from this study. The first involves the finding of maize-processing residues and use-wear on obsidian artefacts, the second concerns the *in situ* analysis of organic residues,
and the third raises the possibility of establishing seasonality from residue analyses. Currently in Mesoamerica, maize processing is implicitly taken to be associated with grindstones alone, largely because this is the picture presented through ethnography (e.g. Tozzer 1941; Wisdom 1940:88-9). Hayden (1987:183) notes that the cutting of vegetables and fruits is a common requirement in contemporary Maya households, although he is quick to point out a number of reasons why he would 'hesitate to infer the use of stone tools for such functions', among them the fact that some Maya communities today make almost no use of knives in the kitchen. He then posits that perhaps unmodified obsidian flakes may have acted as a kitchen knife in the past, but that these tools 'probably were used primarily, and infrequently, for cutting meat'. In contrast, Lewenstein (1987:194) in her use-wear study of the lithic artefacts of Cerros, Belize, noted that 'the apparent dearth of kitchen knives in modern Mayan households does not serve as an appropriate analogue for cutting tool frequency in the residential contexts at Cerros ... In Prehispanic times at Cerros ... substantial numbers of slicing/cutting tools provide the best indicator of a domestic locus'. Although somewhat limited in scale, the present study also revealed slicing and cutting with chipped stone tools to have been common tasks undertaken at the Copán domestic locus.

It is becoming increasingly apparent as the fields of use-wear and residue analysis grow, that expedient use of lithic artefacts regardless of 'formal' characteristics was quite common in the past (see Gero 1991:165–6). Obsidian serves as an efficient tool for cutting soft materials without the need for edge strengthening through retouch. As this study shows, obsidian flakes were used to process maize in antiquity at Copán, although ethnographies have not recorded such a practice. The point to be made from these results, therefore, is a warning that while ethnographic analogy acts as a useful and informative guide to the past, it is still only a guide, and cannot predict all past behaviours.

The second theme addressed by this study concerns the nature of residue analyses of obsidian. Hurcombe (1992:96) states, 'It is clear both from understanding the theory and from previous work on obsidian, that microscopic techniques using surface alterations and residues are the only means by which a specific use-material can be identified for obsidian tools.' In my opinion, emphasis should also be placed on obsidian as one of the best lithic materials for the *in situ* analysis of residues. Unlike many lithic types, the often smooth surfaces of the stone allow for a relatively clear view of organic deposits and the accompanying mechanical fractures and scratches that constitute use-wear. While it may not always be possible to do so, analysing all microscopic aspects of an artefact's function simultaneously is preferable to the removal of residues from their artefactual 'context' (Loy 1993). This is especially true in a study such as the one reported here, where the basic unit of measurement was the artefact itself.

Finally, there is the tantalising possibility that the evidence for processing fresh maize could lead to an estimate of the time of year that two of the artefacts were used. The common Maya practice is to leave maize cobs attached to the stalk to dry in the field at the end of the growing season (Smyth 1991:15; Vogt 1970:51; Wisdom 1940; see also Sheets 1992:77 for an archaeological example from Ceren, El Salvador). This action results in cobs that can be stored either husked or dehusked, with the hard, dry kernels available for later use throughout the year. Depending on specific agricultural circumstances, there would likely have been a period of only a few months each year in which freshly harvested maize would have been available for consumption. Among the Chorti speakers of eastern Guatemala and western Honduras, including Copán, spring maize or *elote* (the ear of tender corn) was available only in the spring and early summer, and was eaten mostly during July and August (Wisdom 1940:92). At the very least, therefore, the use of two of the obsidian artefacts can be narrowed to the time of the maize harvest, a result which opens the door to a range of further investigations of site use.
Conclusions

This study of organic residues on obsidian artefacts is presented more as a means of opening up the possibilities of residue analysis within the Mesoamerican context than as a definitive study of ancient Mayan lithics. It is hoped that continued research in this field will add to and perhaps even challenge these results, furthering our knowledge of ancient Maya domestic activity not only at Copán but at other Mayan centres. In addition, these findings show that the investigation of starch residues in areas with a high dependency on starchy food crops may lead to a much greater understanding of past subsistence and domestic activities in general.

Acknowledgements

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References


Pollen and phytolith records from primitive paddy fields during the Neolithic at Caoxieshan, Taihu Plain, southern China

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Keywords
pollen, phytoliths, rice, paddy field, Early Neolithic, Majiabang, Caoxieshan, Taihu Plain, southern China

Abstract

Pollen and phytolith analyses were carried out at the Caoxieshan site in Suzhou, Jiangsu, southern China. The results indicate that \textit{Oryza} (rice) phytoliths and pollen are common in the Neolithic cultural layers at this site. The evidence strongly suggests that cultivated rice (including \textit{Oryza japonica} and \textit{O. indica}) was grown locally during the Neolithic. Based on the archaeopalynological and phytolith records, together with the archaeological excavation, two distinct phases of paddy field development have been recognised during the early Majiabang. The first phase (Early MJBPF-1) is characterised as warm and humid with arable farming pursued in open lowland contexts which were well situated to take advantage of water for irrigation. The second phase (Early MJBPF-2) is considered to be more arid, giving rise to more specialised irrigation, including mouth, well, ditch and furrow systems.

Introduction

Phytolith analysis was first used in archaeological research in the early 1970s and is now widely applied (Kealhofer and Piperno 1998; Piperno 1988; Rovner 1971). Phytolith analysis of archaeological sediments can reflect the patterns of plant selection and utilisation by humans. Phytolith and pollen analyses can help archaeologists interpret the function of archaeological features, although fossil pollen is often poorly preserved. In archaeological sites, phytoliths are generally abundant. Phytoliths and pollen analyses are powerful methods for detecting the
relationships between human activity and environmental change. This paper presents the preliminary results of phytolith and pollen analyses from the Caoxieshan site and provides evidence for paddy field development during the Neolithic.

Natural environment and archaeological context

The Caoxieshan site (31°22′N, 120°47′E) lies in the middle of the Taihu Plain (Fig. 1). The annual average temperature is 14.9–16.2°C, with an average January temperature in the range of –1.0 to 2.5°C. Annual precipitation varies from 1000 to 1400mm. The study area is situated on the southern margin of a northern subtropical evergreen deciduous broad-leaf mixed forest (Wu 1980). As a consequence of human activity, this original vegetation is rarely seen except on the hills in the northern part of the study area where there is northern subtropical mixed deciduous broad-leaf and evergreen forest. Characteristic tree taxa include Quercus variabilis, Q. acutissima, Q. fabri, Q. glandulifera, Liquidambar formosana, Platycarya strobilacea, Dalbergia hupeana and Pistacia chinensis and broad-leaf evergreen taxa such as Castanopsis sclerophylla, Cyclobalanopsis glauca and Ilex chinensis. Introduced trees include Salix matsudana, S. babylonica, Populus canadensis, Euonymus bungeanus, Ulmus pumila, Morus alba and Bischofia javanica. The main cereal crops in the region are rice and wheat.

Initially two excavation seasons were carried out at the site, one each during 1972 and 1973. A total of 1037.8m² was excavated, in which 10 cultural layers were recorded. The total depth of the profile is between 1.94 and 2.10m thick, and cultural phases (Li et al. 1996) at the Caoxieshan site can be seen in Table 1. Layers 10-4, approximately 100cm in thickness, are argued to be Neolithic in age (Table 1; Fig. 2), since radiocarbon dating of sediments from Layers 10 and 7, respectively, gave ages of 6275±205 (dendrological calibration) and 5200±50 BP (AMS). Layers 1 to 3 are of a more recent age.

![Figure 1. Detailed map showing the location of the Caoxieshan site, Jiangsu Province.](image-url)
Table 1. Summary of the main stratigraphic and cultural layers at Caoxieshan, also including details of where samples were taken for pollen and phytolith analyses.

<table>
<thead>
<tr>
<th>LAYER NO.</th>
<th>STRATIGRAPHY</th>
<th>DEPTH BELOW SURFACE (m)</th>
<th>SAMPLE NO.</th>
<th>CULTURAL PHASES</th>
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<td>1a</td>
<td>Modern cultivation layer, greyish clay</td>
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<td>Modern</td>
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<tr>
<td>1b</td>
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<td>Modern</td>
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<td>Greyish clay mixed with iron-manganese nodules</td>
<td>0.57</td>
<td>P3</td>
<td>Ming-Qing Dynasty (MQD)</td>
</tr>
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<td>Greyish clay mixed with brownish-yellow clay</td>
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<td>P4</td>
<td>Song Dynasty (SD)</td>
</tr>
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<td>Greyish clay</td>
<td>0.81</td>
<td>P5</td>
<td>Songhe (SZ)</td>
</tr>
<tr>
<td>7</td>
<td>Greyish clay mixed with brownish-yellow clay, AMS 14C 5200±50 BP</td>
<td>1.13</td>
<td>P7</td>
<td>Neolithic Majia bang (MJB)</td>
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<td>Greyish-yellow silty clay</td>
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<td>P10</td>
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<td>Majia bang (MJB)</td>
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<td>Natural layer</td>
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<td>1.86</td>
<td>P16 (S13)</td>
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</table>

Figure 2. Profile of 94WCIV, Caoxieshan site, showing sampling points (after Li et al. 1996).

Between 1992 and 1995 an extensive second series of excavations was carried out by a joint Chinese-Japanese research team exploring the Neolithic paddy fields. The earliest Majia bang cultural layers include many open pits, such as those designated as S13, S' and S15 on Figure 2. The pits are always found in the lowland areas and vary in shape from rectangular with rounded corners, to elliptical or irregular. Based on their archaeological and stratigraphic relationships, these pits have been interpreted as representing paddy fields. According to the cultural remains from different archaeological layers, there are two types of paddy fields in the profile of Trench 94WCIV during the early Majia bang phase (used in this
study). These can be distinguished as either Type I (Early MJBPF-1 phase [i.e. S13]), which are thought to be natural pits adjacent to natural ditches; or Type II (Early MJBPF-2 phase [i.e. S', S15]), which are clearly artificial pits, with mouth, ditch and furrow features apparent.

As shown on Figure 2, in Trench 94WCIV, 16 samples from cultural layers (P1 to P16) and one sample from a natural layer (P17) were collected for pollen and phytolith analysis. As will be described below, pollen and phytolith analyses from cultural layers, especially pits during the Majiabang phase, support the interpretation of these features as primitive paddy fields.

Laboratory methods

Pollen samples were processed using standard pollen extraction techniques (Faegri and Iversen 1989). Except for a few samples where pollen was rare or absent, a minimum of 200 pollen grains was counted for each sample.

Samples were prepared for phytolith extraction by removing organic matter with $\text{H}_2\text{O}_2$ and deflocculating with $\text{NaHCO}_3$. After deflocculation, samples were subjected to ultrasonic treatment and repeatedly washed with water until pH neutral. Finally, biogenic silica including phytoliths and diatoms were extracted by heavy liquid flotation in zinc bromide (specific gravity 2.3). Approximately 250 phytoliths were counted in each sample microscopically investigated at 400× magnification, except sample P17 which had poor phytolith preservation.

Results and discussions

Archaeopalynological record

Pollen was common in samples P17, P15 to P12 and P3 to P1 (Fig. 3.; Table 2). In samples P16, P11 and P10, pollen was only sporadically recorded. In samples P9 to P4, no pollen was present, but charcoal was abundant.

The archaeopalynological record at Caoxieshan consists mainly of NAP (non-aboreal pollen) (approximately 44.9% to 97.6%; Table 2). Among the NAP, Gramineae (approximately 19.8% to 66.9%) and aquatic taxa (including Typha, Potamogetonaceae, Sparganium, Nymphaea, Alisma, Myriophyllum and Ceropteris) dominate (Fig. 4). In samples P1 to P3 and P12 to P15,
### Table 2. Pollen and spores statistics of samples from Trench 94WCIV profile at Caoxieshan. Code: AF = absolute frequency; RF = relative frequency, i.e. % of total.

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<td>23</td>
<td>430</td>
<td>290</td>
<td>420</td>
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</table>

terra australis 19
the Gramineae pollen (diameter >40µm, Fig. 4) is considered to be derived from Oryza (Sun et al. 1981; Wang et al. 1996). The aboreal pollen (AP) values in the pollen assemblage are low (approximately 2.4% to 30%), and are composed mainly of Pinus, evergreen Quercus, Quercus, Castanea and Pterocarya.

In sample P17 (from the natural layer), NAP (81.9%) predominates with AP accounting for only 18.1%. NAP is dominated by aquatic taxa (40.9%) (mainly Typha, 31.9%; Potamogetonaceae, 7.9%) and Gramineae (30.4%). Oryza pollen is not present. AP types mainly include Pterocarya (3.1%), Pinus (2.6%), evergreen Quercus (2.2%) and Quercus (1.8%). Subtropical-tropical taxa, such as Altingia, Corylopsis, Euphorbiaceae, Sapindaceae and Myrtaceae, occur occasionally in the natural layer.

Elsewhere in the Taihu Plain, high-resolution pollen sequences from lake cores and peat profiles reveal that the regional vegetation was characterised by evergreen and deciduous broad-leaf forest (Cyclobalanopsis, Castanopsis, Castanea, Betula, Alnus, Liquidambar, Pterocarya and Pinus) between 8500 and 3000 BP (Han et al. 2000; Liu et al. 1992, 1996; Xu et al. 1996). This corresponds broadly with what is regarded as the Holocene thermal maximum in China (Shi 1992). During the thermal maximum, the vegetation zone shifted northwards, lake levels and sea levels rose and the annual average temperature was higher than at present. Under these favourable climatic conditions, Neolithic culture in the study area flourished and agriculture developed.

The pollen results indicate that in the period before the cultural layers began accumulating, aquatic plants (mainly Typha and Potamogetonaceae) flourished in the lowland, and only fragments of forest were present in the nearby highland.

In the earliest Majiabang cultural layers, pit samples (from S13, S' and S15) are characterised by NAP (>90%); AP is less than 10%. Among the NAP, Gramineae (approximately 38.8% to 74.1%) dominates, with Oryza pollen increasing remarkably. The aquatic taxa (mainly Typha, approximately 5.7% to 28.6%, and Potamogetonaceae, 0.95% to 12.8%) is still abundant. Potamogetonaceae pollen sharply declines from 12.8% during the Early MJBPF-1 phase (S13), to 1.2% during the Early MJBPF-2 phase (S15). In samples P3 to P1, NAP is dominated by Gramineae and Artemisia. Aquatic taxa is less important. AP value increases and ferns appear.

According to Behre (1981, 1990), primary anthropogenic pollen indicators derive from cultivated plants and particularly cereals. Secondary anthropogenic indicators include NAP and especially the pollen of ruderals and weeds associated with arable activity, i.e. plants not intentionally favoured by humans. Thus, the archaeopalynological results from the Majiabang phase at Caoxieshan, especially the occurrence of Oryza pollen and predominance of NAP, show an open environment strongly influenced by human activity.

The presence of Oryza pollen reveals rice cultivation was practised. Aquatic plants are defined as those adapted to living in waterlogged soil or partly or wholly submerged in water. Typha is most common in waterlogged soil while Potamogetonaceae is often submerged in water, or has floating leaves with stomata through which gases can be exchanged as in land plants (Blackmore 1984). In the Early MJBPF-1 phase, the high percentage of Potamogetonaceae pollen suggests the lowlands area had plenty of water. The pit was well situated to take advantage of water for use in a primitive, small-scale irrigation system and the natural lowlands were suitable for ancient agricultural practices. In the Early MJBPF-2 phase, the aquatic pollen consists mainly of Typha. Potamogetonaceae pollen is less than 2%. The sharp decrease of Potamogetonaceae suggests water levels declined (from submerged to merely waterlogged). The adjacent body of water shrank during the Early MJBPF-2 phase. Archaeological evidence suggests ditches were constructed to create an artificial irrigation system during the Early MJBPF-2 phase. Thus, it appears that declining water resources brought about the change of paddy field type. The pollen data support the archaeological
Figure 4. Main pollen and spores recorded at Caoxieshan (all enlarged 650× unless stated otherwise). 1 = Podocarpus; 2 and 3 = Pinus; 4, 5, 6 and 11 = evergreen Quercus; 7 and 8 = Pterocarya; 9 = Carpinus; 10 and 12 = Quercus; 13 and 32 = Cyperaceae; 14 = Tiliaceae; 15 and 16 = Ulmaceae; 17 and 18 = Typha; 19 = Nymphoides (400×); 20 = Sparganiaceae; 21 = Gramineae; 22 and 24 = Compositae; 23 = Pyrrosia; 25 = Artemisia; 26 = Pteris; 27 = Myriophyllum; 28 and 31 = Chenopodium; 29 = Alisma; 30 = Potamogetonaceae; 33 = Polygonum; 34, 35 and 37 = Oryza; 36 = Liliaceae (400×).
interpretation that the pits during the Majiabang are the remains of primitive paddy fields. During the Early MJBPF-1 phase, the ancient people capitalised on the waterlogged land for paddy fields; in the Early MJBPF-2 phase, primitive rice cultivation was influenced by the declining water level and primitive irrigation agriculture begins.

Although paddy fields have not been discovered from later cultural layers, the Oryza pollen record from the Song Dynasty and younger phases indicates rice cultivation developed progressively.

**Phytolith record**

Phytoliths, mainly derived from grasses, are abundant in samples from Caoxieshan (Figs. 3 and 5; Table 3). Distinctive phytolith types derived from Oryza, e.g. fan-shaped bulliforms and the bilobates, are common throughout the cultural layers (Fig. 5). The Oryza bulliform is typically fan-shaped with fishscale-like ornamentation on the top and two lateral protrusions. These are regarded as the criteria for identification of phytoliths associated with cultivated rice (Fujiwara 1993; Pearsall et al. 1995; Zhao et al. 1998; Zhao and Piperno 2000). The bilobate phytoliths, with concave ends and the long axis of the individual phytoliths running parallel to each other and perpendicular to the leaf vein, are also characteristic of the tribe Oryza (Fig. 5: 8, 10, 11 and 25). As shown in Figure 3, bilobate and bulliform-shaped phytoliths, which occur mainly in warm and humid environments, dominated most cultural layers at Caoxieshan, although a substantial change is evident during the early Neolithic period.

It is supposed that the cultivated rice (Oryza sativa, including O. indica and O. japonica) originated from common wild rice (O. rufipogon). The morphological differences between O. indica and O. japonica are so small that they are difficult to distinguish on the basis of macroscopic features. They can, however, be distinguished easily by phytolith morphological criteria (Sato et al. 1990). Based on the mean ratio of the length of the lower part (a) to the upper part (b) in Oryza fan-shaped bulliforms, there are two types of Oryza present at Caoxieshan during the Neolithic (one with a ratio <1, the other >1 [Fig. 5]). This indicates that a mixture of O. japonica with O. indica was grown locally during the Neolithic at the site, which supports other evidence from the archaeological excavations (Li et al. 1996).

China is one of the places of origin of cultivated rice in Asia. There are several centres of diversity for Chinese cultivated rice, including the middle and lower reaches of the Yangtze River, southern China and mid-Yangtze Valley and the upper Huai River region (Di 1957; Liu 1975; Yan 1989; You 1986; Wang et al. 1996). Rice phytolith and carbonised rice grains during the Neolithic at Hemudu (Natural History Section, Zhejiang Provincial Museum 1978; Zhen and You 1994) and Luojiagao (Luojiagao Archaeological Excavation Team 1981) in Zhejiang; Songze (Shanghai Cultural Relics Management Committee 1962) in Shanghai; Longnan (Tang 1992) and Caoxieshan in Jiangsu, indicate O. japonica with O. indica relate mainly to the lower reaches of the Yangtze River.

Phytoliths from the Early MJBPF-1 phase (P16 and P15) are dominated by smooth-elongates (29.6%) from long cells and square-rectangular forms (17.8%), bulliforms (14.6%) (including Oryza bulliforms representing 3.7%); epidermis short-cell phytoliths (including bilobates, saddles and crosses) account for 13.5% and elongates are less than 10% of the assemblage. Phytoliths during the Early MJBPF-2 phase (P14 to P12) are characterised by a dominance of short-cell phytoliths (50.8%) and smooth elongates (21.8%); Oryza bilobates and tribe Oryza are common; elongates (13.8%) increase and square-rectangular forms (2.8%) and bulliforms are less important (2.7%).

Phytolith assemblages often mirror changes in the parent vegetation. Epidermis short cell phytoliths have restricted distributions within the Gramineae. Bilobate and cross shapes occur mainly in the Panicoideae or tall grass subfamily and in some bamboos; saddle shapes
Figure 5. Phytolith types recorded at Caoxieshan (all enlarged 650x unless stated otherwise). 1, 2 and 26 = Oryza-type bulliform (b/a>1); 3 and 6 = point shape; 4 and 5 = Oryza-type bulliform (b/a<1); 7 = diatom; 8, 10, 11 and 25 = bilobate characteristic of the tribe Oryza; 9, 12 and 23 = elongate; 13, 15, 17 and 18 = bilobate (1,200x); 14 = Festucoid type; 16 and 20 = saddle shaped (1,200x); 19 = polylobate; 21 = cross type (1,200x); 22 = trilobate; 24 = square-rectangular bulliform; 27 = bulliform.
Table 3. Phytolith statistics of samples from Trench 94WCIV at Caoxieshan. Code: \(^*\) = characteristic of the tribe Oryza; AF = absolute frequency; RF = relative frequency, i.e. \% of total.

<table>
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<th>P-16</th>
<th>P-15</th>
<th>P-14</th>
<th>P-13</th>
<th>P-12</th>
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<th>P-9</th>
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<th>P-5</th>
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occur abundantly in the *Eragrastoideae* and in many bamboos. In the *Eragrastoideae*, bilobates are uncommon, and cross shapes are not produced (Piperno 1988). The parent plants of epidermis short-cell phytoliths are dominant in semi-arid to arid warm regions (Twiss 1992). Based on phytolith distribution from modern surface soil in China (Wang and Lu 1993), the bulliform and bamboo saddle-shaped phytoliths are found mainly in southern China (subtropical-tropical climate zone), while elongate phytoliths are found in cold arid conditions.

As discussed above, based on the phytolith data during the early Majiabang, the increase in epidermis short-cell phytoliths (e.g. bilobate, saddle, cross) and epidermis long-cell phytoliths (e.g. elongates) shows a relatively warm arid condition during the Early MJBPF-2 phase. The evidence suggests the grass subfamilies and quantities have varied, with the *Eragrastoideae, Panicoideae* and *Chloridoideae* much more abundant during the Early MJBPF-2 phase. *Oryza* phytoliths come mainly from motor-cell fan-shaped bulliforms during the Early MJBPF-1 phase; while during the Early MJBPF-2 phase, they derive primarily from short-cell bilobates and *Oryza* tribe bilobates.

*Oryza* phytoliths are common throughout the other cultural layers at the site, demonstrating the continuing significance of rice agriculture in this region.

Compared with the archaeopalynological records, the sharp decrease of *Potamogetonaceae* during the Early MJBPF-2 phase suggests a shift to a more arid environment in which *Eragrastoideae, Panicoideae* and *Chloridoideae* taxa flourished. As stated above, though the climate during the Majiabang phase was warm and humid, the conditions during the Early MJBPF-2 period were relatively arid in relation to those of the Early MJBPF-1 phase.

**Conclusions**

The archaeopalynological and phytolith results provide evidence for rice cultivation during the Neolithic at Caoxieshan. The occurrence of *Oryza* pollen and phytoliths, together with the dominance of NAP, suggest an open environment strongly influenced by human activity. Based on archaeological excavations, the development of paddy fields may be divided into two phases during the early Majiabang. In the earliest phase (Early MJBPF-1), the climate was warm and humid and the paddy fields were well situated in an open lowland with enough water for irrigation; in the later phase (Early MJBPF-2), there is evidence for an artificial irrigation system encompassing mouth, well, ditch and furrow features. The phytolith data suggest this change in agricultural regime relates to the development of a more arid climate.

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References


The banana phytolith as a direct marker of early agriculture: A review of the evidence

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Keywords
Musa, morphology, tropical agriculture, phytoliths

Abstract

The banana is probably one of the oldest cultivated plants in the tropics. Archaeological traces of the crop could significantly contribute to the general reconstruction of domestication and initial agriculture. Since the crop does not leave classical traces of its existence in the past, such as wood, seeds and pollen, its phytoliths and starch grains appear to be the only reliable material evidence available to researchers at present. Musa phytoliths in archaeological context have been reported for Papua New Guinea (Wilson 1985; Bowdery 1999), Laos and Peninsular Malaysia (Bowdery 1999), Easter Island (Scott-Cummings 1998; Vrydaghs et al. in press), India (Fuller and Madella 2001) and Africa (Doutreleponent et al. 1996; Mbida et al. 2001). Their interpretation should rely on the genetic and phytogeographical backgrounds of the banana. An African finding illustrates this suggestion (Mbida et al. 2001). It is concluded that each instance of archaeological detection of a Musa phytolith in regions where native wild relatives do not exist is direct evidence of tropical agriculture.
Speculations on a very old history

The banana is a staple food for millions of people in the tropics. In many areas, the crop and some of its wild relatives are also the source of fibres, fodder, medicines and alcoholic beverages. The domestication of bananas probably started on wild diploids \((Musa acuminata)\) of AA genome) in and around New Guinea (Simmonds 1962). It led to the generation of the ‘edible AA’; perhaps originally used for fibre and medicines, but not for the fruit. The fruits eventually acquired parthenocarpy and became attractive. The second step in the domestication involved intraspecific hybridisation or interspecific hybridisation with \(M. balbisiana\) (of BB genome), a species originally endemic to a restricted zone of mainland South-East Asia and widespread through human migrations. Hybridisations were followed by somatic mutations, with pronounced parthenocarpy and nearly complete seed sterility as the end result (Simmonds 1966).

The current taxonomy for edible bananas was invented in the 1950s (Simmonds and Shepherd 1955) and has amply proved to be the most feasible one. It is based on the theory that the two species \(M. acuminata\) and \(M. balbisiana\) generated the edible bananas, with or without inter-crossing; hence the genomic qualifications: AA, AAA, AB, AAB, ABB and perhaps BBB.

Three groups of banana cultivars are of particular importance to tropical prehistory. They belong to quite distinct and restricted genetic categories, respectively ‘edible-AA’, AAB-Plantain (or African Plantain) and AAB-Maia maoli, Popoulu and Iholena (or Pacific Plantain), but show an extreme morphological diversity of between 50 and 100 cultivars. There exist no indigenous wild bananas in the areas where the two plantain groups show the highest diversity, the African rainforest and Polynesia to the East and North of Samoa. Consequently, the plantains must have been introduced there by people, and the diversity can only have been generated through somatic mutations over a long period, given the relatively rare occurrence of such mutations (De Langhe and de Maret 1999; De Langhe et al. 1996). Most of the edible diploids in New Guinea are highly seed sterile, which points to a long period of their domestication and subsequent diversification (Simmonds 1966). These three groups would represent the oldest stock of edible bananas. They are deeply rooted in the culture and may have been cultivated for millennia. A speculative reconstruction of their history was recently offered by De Langhe and de Maret (1999). Briefly, according to the hypothesis, moving people brought into contact the first domesticated diploids of \(M. acuminata\) from the New Guinea–Philippines area with \(M. balbisiana\). Interspecific crosses generated two basic AAB stock; the original African versus Pacific plantains. This event would have occurred at about 3500 BP. Subsequently, one human group moved eastwards and brought the Pacific plantains to Polynesia, while another group moved westwards and may have been instrumental in the introduction of the other AAB-plantain stock to Africa. The latter package was introduced to Latin America, most probably by the slave trade.

Beyond the speculations

Such a hypothesis calls for direct material evidence of bananas in the past. The unfortunate situation of the banana in this respect is well known; the plant does not produce wood and the edible forms generally lack pollen and seed. Starch grains and phytoliths appear to be the only potential vestiges of the edible forms. The first historical record of ancient banana cultivation based on phytolith analysis was from sediments extracted at Kuk, a Papua New Guinea site in the Upper Wahgi Valley near Mt Hagen, and identified by Wilson (1985) from the phytolith
literature and a reference collection. A discriminant analysis using three variables was carried out on the archaeological material and Wilson’s reference phytoliths. More recently, Lentfer (2001:19) found Musaeae phytoliths in sediments from the Kundil’s section of Kuk.

Papua New Guinea is in the large area of primary Musa diversity. Two sections of genus Australimusa, with the Fe’i bananas as edible variant, and Eumusa with the species Musa schizocarpa, M. acuminate subspecies banksii, and M. balbisiana. The natural status in PNG of the latter species is questioned, however (Argent 1976). Before one can firmly state if banana was cultivated at the Kuk site for the stratum involved there is the problem of sorting out to what species or group of cultivars the Kuk phytoliths belong. The Wilson paper seems to indicate that they would at least not have come from an Australimusa plant.

The African configuration is a rather simple one. No wild Musa have ever been reported in the natural state on the continent. The genus Ensete, however, grows over the whole of eastern tropical Africa, from Ethiopia in the north to Swaziland-Natal in the south, and its habitat extends far to the west on both sides of the rainforest, down to Angola and Nigeria and even further. The east African highlands are the homeland of Ensete ventricosum, while E. gilletii is characteristic of the humid plains and lowlands in western Africa. As a result, Musa phytoliths in an African archaeological context would directly prove the existence of edible banana cultivation, and hence some form of agriculture, provided these phytoliths are verified to be distinct from those of Ensete.

Many theories have been advanced for the introduction of bananas to the African continent. The remotest dates commonly proposed for their introduction are still within the Christian era. However, on the basis of phytogeographical considerations, linguistic evidences, cultivar proliferation and mutation rates, it has recently been suggested that the plantains were the first to reach the African continent about 3000 years ago (De Langhe et al. 1996). The suggestion of such a remote date for the introduction of plantain has recently been supported for the first time by archaeological evidence from the site of Nkang (in Cameroon, 100km north of Yaounde). Archaeozoological, carpological, charcoal and general phytolith analyses establish that the site was located at the time within walking distances of various facies of forests (Mbida et al. 2000). Musaceae phytoliths were recovered from two contexts: at two horizons of pit F9 (Horizons 1b and 7) and in residues adhering to the inner face of a vessel found in pit F7NF (Mbida et al. 2001). The archaeological context of the finding is well dated. C\(^4\) dates from charcoals indicated a site occupation between 2580 BP and 2170 BP. The dates obtained for pit F9 indicate a period between 2490 and 2400 BP (see Table 1). They all fit with those obtained from charcoals on the Nkang culturally related sites of Ndindan, Nkumetu, Obogogo, Okolo and Oliga (Mbida 1996).

Although Ensete does not thrive in the rainforest under natural circumstances, the plant could have been cultivated at the time, as is still the case in Ethiopia. A thorough comparative study of Musa versus Ensete phytoliths was in order. Indeed, previous comparative descriptions of Musaceae phytoliths did not provide distinctive morphological criteria (Wilson 1985) or elaborate on comparative morphological studies of Musa and Ensete phytoliths (Kealhofer and Piperno 1998; Piperno 1988; Runge 1996; Runge and Runge 1997; Tomlinson 1959, 1969).

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1 The banana cultivars important to the African prehistory are distributed in three groups: the African plantain (AF-AAB), the Eastern African Highlands (EA-AAA) and the Indian Ocean Complex (IOC). Although these groups present an important morphological diversity and a different geographical distribution, they belong to restricted genetic categories: edible-AA; AB, AAA, AAB and ABB.
The state of the art in phytolith and starch research in the Australian-Pacific-Asian regions

Table 1. Radiocarbon dates for Nkang and their calibration.

<table>
<thead>
<tr>
<th>STRUCTURE</th>
<th>LABORATORY CODE</th>
<th>C-14 DATE (YEARS BP)</th>
<th>CAL-BC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit 6</td>
<td>Lv-1940</td>
<td>2580±110</td>
<td>850-410</td>
</tr>
<tr>
<td>Pit 9</td>
<td>Lv-1944</td>
<td>2490±110</td>
<td>840-370</td>
</tr>
<tr>
<td>Pit 9</td>
<td>Lv-1943</td>
<td>2490±80</td>
<td>790-400</td>
</tr>
<tr>
<td>Pit 9</td>
<td>Lv-1942</td>
<td>2400±60</td>
<td>770-350</td>
</tr>
<tr>
<td>Pit 3</td>
<td>Lv-1939</td>
<td>2420±70</td>
<td>770-350</td>
</tr>
<tr>
<td>Pit 7bis</td>
<td>Lv-1941</td>
<td>2340±70</td>
<td>800-150</td>
</tr>
<tr>
<td>Pit 13</td>
<td>Lv-1945</td>
<td>2310±90</td>
<td>800-100</td>
</tr>
<tr>
<td>Pit 14</td>
<td>Lv-1946</td>
<td>2170±80</td>
<td>390-AD 1</td>
</tr>
</tbody>
</table>

Various *Musa* and *Ensete* tissues from the KU Leuven University, where an international germplasm collection is maintained *in vitro* under slow growing conditions (Van den Houwe et al. 1995), were treated for phytolith extraction using dry ashing and wet oxidation methods (Piperno 1988: 126, method 4). The studied collection included at least one specimen of each of the banana groups traditionally cultivated in Africa which belong to restricted genetic categories: edible- AA; AB, AAA, AAB and ABB (see Table 2). Several organs were investigated; leaves, pseudostems and fruits. Phytoliths were found only in leaves and fruits. Attention was focussed on the leaf phytoliths since only these presented morphological analogies with the archaeological material. All reference samples were studied by optical microscopy (LM) at 400× magnification as well as by Scanning Electron Microscope (SEM) (Mbida et al. 2001). Referring to the specific topic of this research (i.e. morphological criteria allowing to distinguish the *Musa* phytolith from the *Ensete* phytolith), a cursory microscopic observation showed no striking differences between the phytoliths extracted from the different *Musa* accessions. Considering the actual geographical distribution of the African *Musa* cultivars (De Langhe et al. 1996), the specimen catalogued as ITC 0754, the popular plantain ‘Corne 1’ in Cameroon, was therefore selected for extensive morphological description.

Despite the fact that the morphology of silica bodies extracted from *Musa* (Figs. 1 and 3) and *Ensete* (Fig. 2) presents a similar overall structure — i.e. a more or less flat base surmounted by a ‘volcano-like’ elevation, with size ranging from 10 to 30µm in length — qualitative differences are evident on the phytolith elevation and base, as well as on the surface (see Table 3, Figs. 1 and 2 and Mbida et al. 2001). The LM revealed archaeological phytoliths from Nkang have concave slopes, protuberances on the basal part, a smooth rim without deep indentations and a smooth surface. This combination of features allows us to infer that they definitely belong to the genus *Musa*. Since the plantains were the only bananas grown in the rainforest before colonial times, the Nkang phytoliths almost certainly derive from plantain tissues.

The interpretation of this finding needs to consider several aspects. As already stated, no wild *Musa* have ever been reported in the natural state on the African continent. All the
The banana phytolith as a direct marker of early agriculture

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Figure 1. Illustration of the longitudinal and polar view of the *Musa* phytolith (from Mbida et al. 2001).

Figure 2. Illustration of the longitudinal and polar view of the *Ensete* phytolith (from Mbida et al. 2001).

Figure 3. Various views of the *Musa* phytolith (ITC 0754; 400×)

Table 3. Comparative table of the morphological characters observed in LM for the *Musa*, *Ensete* and archaeological phytoliths.

<table>
<thead>
<tr>
<th></th>
<th>MORPHOLOGY OF CONE-SHAPED PART</th>
<th>MORPHOLOGY OF BASAL PART</th>
<th>SCULPTURING</th>
</tr>
</thead>
<tbody>
<tr>
<td>slope</td>
<td>outline</td>
<td>truncature</td>
<td></td>
</tr>
<tr>
<td><strong>MUSA</strong></td>
<td>concave</td>
<td>saddle-like</td>
<td>thin; continuous or with 1 indentation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ENSETE</strong></td>
<td>convex</td>
<td>flat</td>
<td>rough; 1 to 3 crenulations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>saddle-like</td>
<td>thin; continuous</td>
</tr>
<tr>
<td><strong>ARCHAEOLOGICAL</strong></td>
<td>concave</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*terra australis* 19
African bananas present parthenocarpy, seed sterility and most of them, triploidy. Those characteristics can be explained only if the introduced *Musa* was already a domesticated plant. The Nkang finding establishes that plantain was cultivated in central Cameroon by the middle of the last millennium BC. Some form of agriculture must have been practised in western Africa at that remote time. Incidentally, and as the plantain has been the major staple crop in the rainforest for many centuries (Vansina 1990), its early presence in Cameroon could explain the increase in village density in the forest environment at this time and should improve our understanding of the early stages of Bantu expansion (de Maret 1996).

Neither native wild bananas nor *Ensete* sp. have been duly reported in tropical America. Except for a few cultivars in Colombia, Ecuador and Peru, all the AAB-Plantains are the ‘African plantains’. Their introduction should have occurred in post-Colombian times. The exceptions on the west of the South American continent are similar to cultivars of the AAB-Pacific Plantain subgroup. They could point to a pre-Colombian contact with Polynesia but they could have been recent introductions from Hawaii as well (Simmonds 1966). The case calls for direct evidence of the crop in the past, but tracking the evidence for *Musa* in South America requires ruling out possible morphological confusion with the *Heliconia* phytolith.

Observations in LM of phytoliths of *Heliconia* conducted by Piperno (1988), Pearsall (1998) and by two of the authors of the present paper (L. Vrydaghs and H. Doutrelepons pers. obs.) demonstrated that their morphology is significantly different from that of the *Musaceae*. The *Heliconia* phytolith is elongate elliptic to blocky, lacking the volcano shape of *Musaceae* phytoliths, but with a deep crater almost cutting the phytolith into two parts. Specimens with and without projections were observed (Pearsall 1998). In contrast with several findings of *Heliconia* phytoliths for prehistoric and colonial periods (Jones 1993; Pearsall 1994; Piperno 1988, 1991; L. Vrydaghs and H. Doutrelepons pers. obs. on archaeological material from Peru provided by L. Scott Cummings, Paleo Research Institute), a *Musa* phytolith has never been reported in an archaeological context. The thus investigated geographical areas (western Ecuador, Panama and Peru) and the different time periods thereby studied (Terminal Valvidia, 1550–1700 BC; Guadal Phase AD 250–450; Janu-Cuaque Phase 355 BC–AD 1532, for Ecuador and several dates about 2000 BP, 4750 BP and 6610 BP for central Pacific Panama) indeed seem to rule out the possibility of bananas having been introduced in pre-Colombian times.

Despite a number of archaeological and sedimentary phytolith studies having been conducted on sediments from the Hawaiian Islands, to date no *Musa* sp. phytoliths have been observed in such contexts (Pearsall and Trimble 1984; Scott-Cummings pers. comm.). Further, the only reports for the whole of Polynesia that have been able to confirm the presence of *Musa* sp. phytoliths are those from Easter Island (Scott-Cummings 1998; Vrydaghs et al. in press.). Nevertheless, it should be noted that as yet very few phytolith studies have been carried out in the Polynesian region, and yet even fewer that have been specifically focussed on the issues of banana cultivation.

**Conclusions**

Since the First European Meeting on Phytolith Research (Madrid 1996, see Doutrelepons et al. 1996), there have been several reports of archaeological *Musa* phytoliths in various contexts (open air habitats, rock shelters, garden pits and in pot jar and residues) for historical times.

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2 The *Heliconia* phytolith has never been found in Argentinean archaeological deposits while three species (*Heliconia brasiliensis*, *H. hirsuta* and *H. subulata*) are reported for northern Argentina (A. Zucol pers. comm.).
and prehistoric periods as old as 9000 BP (Bowdery 1999; Fuller and Madella 2001; Scott-Cummings 1998; Bowdery 1999; Fuller and Madella 2001; Vrydaghs et al. in press).

The first identification of *Musa* phytoliths of great antiquity in humid Africa demonstrates that agriculture began much earlier than previously assumed in that zone. In Polynesia to the east and north of Samoa and in Latin America, the same approach could be productive. However, the rising expectations of the performances of archaeological *Musa* phytolith research should take into account the complex ethno-botanical, genetic and phytogeographical backgrounds of the crop, as illustrated by the interpretation of the African finding. The problem of the evaluation of the prehistoric significance of the detected phytoliths can be rapidly overcome in regions where no wild relatives of the crop exist in their natural state: the African continent, Latin America and the majority of the Polynesian islands. For all these areas, the identification of archaeological *Musa* phytoliths is direct evidence of early and recent tropical agriculture. For the areas where various wild and cultivated *Musa* plants should have coexisted for millennia, as is the case for Melanesia, the description of more reference material is required. Differentiation within *Eumusa* at the level of the phytoliths is probably feasible but should rely on strict and precise morphological criteria if they can be found, which is likely (C. Lentfer and D. Bowdery pers. comm.) but has not as yet been systematically ascertained nor applied.

**Acknowledgements**

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**References**


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Integrating biological data: Phytoliths and starch grains, health and diet, at Real Alto, Ecuador

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Keywords
dietary reconstruction, multiple indicator approach, Zea mays, phytoliths, starch, Real Alto site, Valdivia Period

Abstract

Understanding what people ate in prehistory is fundamental for understanding how past populations survived and prospered. However, few published applications of dietary reconstruction have produced convincing results, because few have integrated multiple biological indicators. In this paper I describe an approach for integrating different kinds of biological and archaeological data to reconstruct diet. The key to success is to evaluate multiple lines of evidence critically, to verify one indicator by one or more different ones, and to synthesise multiple lines of evidence into a cohesive picture of diet and health. I illustrate the power of the approach by considering the question, how important was maize in diet at the Early Formative Real Alto site? Finally, I present new phytolith and starch evidence relevant to understanding the role of maize in the onset of settled village life in coastal Ecuador.

Introduction

The goals of this paper are to describe an approach for integrating archaeological dietary data; to illustrate the power of the approach by considering the Real Alto case; and to present new phytolith and starch evidence on the role of maize in supporting settled village life in Ecuador.

Why is a new approach necessary? Understanding what people ate is fundamental for understanding how populations survived and prospered. Few studies produce convincing reconstructions of diet. For example, botanical and faunal data are rarely considered together. Isotope and trace element studies seldom include the results of studying the plants and animals that produced the observed chemical signatures. Use of data outside an author’s area of expertise is often uncritical or naive.
The key to success in dietary reconstruction, in my view, is to evaluate multiple lines of evidence critically, verifying one indicator by one or more other indicators, and synthesising multiple lines of evidence into a cohesive picture of diet and health. Central to the approach is an understanding of the roles of each type of data in dietary reconstruction, and evaluation of their strengths and weaknesses.

One way to look at the relationship among indicators of human diet and health is to array these along two dimensions: direct to indirect, and individual to community to extra-community (Fig. 1). Central to understanding past human diet and health are direct, individual indicators: trace elements and stable isotopes, which reflect lifetime consumption patterns of the individual; skeletal indicators of dietary insufficiency or disease processes; and coprolites (human faeces) and gut contents, which preserve remains of ingested foods. Indirect, household-level indicators include faunal and botanical macro-remains recovered from garbage middens and trash pits; and pollen, phytoliths and starch grains found in soil, on tools and in food residues. Dietary patterns of a community may be reflected in botanical remains recovered from non-site contents, such as lake cores and agricultural fields, or may be inferred from site location, site size or the presence of water control features.

Different dietary regimes should cause predictable differences in these indicators, and permit development of models of diet that can be used to interpret archaeological dietary

![Diagram of dietary indicators]

**Figure 1.** Relationships among dietary indicators (from Pearsall 2000).
Indicators. Figure 2 illustrates two such models, maize-based agriculture with terrestrial protein (a), and maize-based agriculture with marine protein (b). Note the differences in predicted values for carbon and nitrogen isotopes, the trace elements strontium (Sr), barium (Ba), magnesium (Mg) and zinc (Zn), levels of anaemia and enamel hypoplasias, and the richness of the animal portion of diet. In the discussion that follows, I will summarise how these and other indicators can be used to infer past diet and health.

## Dietary indicators

### Stable carbon and nitrogen isotopes

Isotopes are variants of the same element that differ in the number of neutrons. Because of this difference in atomic weight, stable isotopes of an element, such as C\(^{13}\) and C\(^{12}\) and N\(^{15}\) and N\(^{14}\), react at different rates in chemical reactions. This in turn results in differences in the ratios of stable isotopes in plants and air or water. This process of isotope ratio change is called fractionation (Hoefs 1987). The ratio of two elements (i.e. C\(^{13}/C^{12}\)) is expressed in delta (\(\Delta\)) values in parts per thousand relative to a standard. Differences in stable isotope ratios in plant tissues are passed up the food chain to the consumers of those plants, with additional fractionation occurring.

### Data trend from lower to higher value
- Unk: Unknown
- A: Absent
- L: Low
- I: Intermediate
- H: High

<table>
<thead>
<tr>
<th>Diet 5: Maize-based agriculture with terrestrial protein</th>
<th>Diet 6: Maize-based agriculture with marine protein</th>
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</thead>
<tbody>
<tr>
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<td>Carbon isotopes</td>
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<tr>
<td>Nitrogen isotopes</td>
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<tr>
<td>Sr</td>
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<tr>
<td>Ba</td>
<td>Ba</td>
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<tr>
<td>Mg</td>
<td>Mg</td>
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<tr>
<td>Zn</td>
<td>Zn</td>
</tr>
<tr>
<td>Caries</td>
<td>Caries</td>
</tr>
<tr>
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<tr>
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<tr>
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<tr>
<td>Richness of animal foods</td>
<td>Richness of animal foods</td>
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<tr>
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<tr>
<td>Sedentism</td>
<td>Sedentism</td>
</tr>
<tr>
<td>Landscape modification</td>
<td>Landscape modification</td>
</tr>
</tbody>
</table>

Figure 2. Two model diets incorporating maize use: Diet 5, maize and terrestrial protein; Diet 6, maize and marine protein (from Pearsall 2000).
Plants differ in carbon isotope ratios according to which pathway of photosynthesis is utilised, the C3, C4 or CAM pathway. Tissues of plants following the C3 pathway are depleted in C\(^{13}\) (delta values are more negative), while plants following the C4 pathway are enriched in this rare isotope of carbon (delta values are less negative). Enriched \(\Delta C^{13}\) values in maize, a C4 plant, are passed to consumers of maize, resulting in enriched \(\Delta C^{13}\) in human bones (Fig. 2). High consumption of marine foods also enriches \(\Delta C^{13}\), but not to the level of maize consumption.

Stable nitrogen isotope values separate plants, herbivores and carnivores: moving up the food chain \(\Delta N^{15}\) values are enriched (values are higher) at each level. In addition to these trophic level differences, there are also differences among nitrogen-fixing plants (e.g., legumes), other terrestrial plants and marine plants in \(\Delta N^{15}\) values, with nitrogen-fixing plants having lower \(\Delta N^{15}\) values than other terrestrial species, and marine plants having higher values. When \(\Delta C^{13}\) and \(\Delta N^{15}\) values are both determined for a human population, terrestrial C3 diets (depleted \(\Delta C^{13}\), depleted \(\Delta N^{15}\)), terrestrial C4 diets (enriched \(\Delta C^{13}\), depleted \(\Delta N^{15}\)), and marine-based diets (mid-range \(\Delta C^{13}\), enriched \(\Delta N^{15}\)) can be separated. Analysis of carbon and nitrogen stable isotope ratios of suspected 'menu' items permits more precise modelling of these relationships for dietary reconstruction.


**Trace elements**

Living matter, including our bodies, is made up mostly of hydrogen, carbon, nitrogen, oxygen and sulphur (the bulk elements), with sodium, magnesium, phosphorus, chlorine, potassium and calcium the next in concentration (macrominerals or minor elements). The rest of the elements are present in very low concentrations in tissues; these are the trace elements, some of which are essential for life (Mertz 1981).

Trace elements are incorporated into animal tissues through the intake of food and water. Concentrations of the alkaline earth metals strontium (Sr), barium (Ba) and magnesium (Mg) in plants reflect the concentrations of these elements in the substrate: soil, fresh water or seawater (Pate 1994). Herbivores discriminate against these elements in favour of calcium for forming bone tissues. Concentrations of trace elements in herbivore bones are thus lower than in the plants that herbivores consume. A similar discrimination occurs in carnivores, resulting in still lower concentrations of these trace elements in carnivore bones. Sr, Ba and Mg concentrations in bone therefore reflect trophic level. While these relationships are best understood for Sr, there is some consensus that Ba and Mg are also useful trophic level indicators (but see Ezzo 1994a).

There is less consensus that the essential trace element zinc (Zn) is useful for dietary reconstruction (Ezzo 1994b). The biochemistry of zinc absorption, transport and depletion are complex processes. Caution must be exercised in interpreting bone zinc levels since concentrations may differ between men and women, and may change over the life span. In general, however, animal flesh (including shellfish and fish) has higher levels of zinc than most plant foods (whole grains, legumes and nuts are exceptions). This permits trophic level separation using zinc: high concentrations in carnivores, low in herbivores (Kleping 1993).

In any trace element study of archaeological bone, it is essential that the degree to which diagenetic processes (postmortem alteration of trace element concentrations in bone) have affected the sample population be evaluated. Approaches to this are summarised in Pearsall (2000). In situations in which diagenetic processes are minimal, high levels of Sr, Ba
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and Mg, and low levels of Zn, suggest a diet high in plant foods, such as illustrated in Fig. 2. The ratio of Ba/Sr helps maximise the separation of marine and terrestrial components of diet, since barium occurs in very low concentrations in seawater.

Skeletal indicators of nutrition and health

Nonspecific indicators of stress in the human skeleton are associated with dietary change, especially the transition from hunting and gathering to agriculture (Larsen 1995). I focus in the models on dental indicators (caries, tooth loss, tooth wear), developmental indicators (enamel defects [hypoplasias] and Harris [transverse] lines), anaemia, and a measure of workload and activity (long-bone cross-sectional geometry), because these indicators show a somewhat consistent patterning with dietary change. The interplay of diet and disease is complex, however, and not all dietary deficiencies and disease states manifest in the skeleton. Determining that stress in an individual or population was diet-related must be done in the context of what was eaten (i.e. floral and faunal data), how foods were processed (i.e. artefacts and features), and what disease load the population faced, given site location (i.e. types of endemic disease, parasites) and living conditions (i.e. settlement type, population density, sanitation).

It is impossible to discuss in detail here how each of the skeletal indicators illustrated in Figure 2 patterns with diet; see Pearsall (2000) for further discussion. Dental caries (cavities) are familiar to most of us. The rate of caries, and eventual tooth loss, increases with increased consumption of sticky carbohydrate foods. High caries rates are often associated with heavy reliance on processed agricultural staples such as maize or tubers (Fig. 2), while it is typical for foragers to have no to few caries (Turner 1979).

Diet change, especially declining diet quality, has an impact on skeletal development. Defects in dental enamel are an indicator of stress often seen in prehistoric populations (Skinner and Goodman 1992). Enamel hypoplasias are linear depressions in tooth enamel where enamel-producing cells ceased production prematurely. There is a strong association between hypoplasias and malnutrition, although disease can also cause this developmental disturbance. Stress from disease or poor diet can also arrest growth in long bones. Arrest and resumption of growth produces Harris lines (Goodman 1984). Stressors do not have to be of long duration or magnitude to disrupt long-bone growth, making Harris lines useful indicators of seasonal stress. Since bone is remodelled (new bone added, old bone reabsorbed) continually over the lifetime, Harris lines can be obliterated. Sub-adults give a more accurate picture of the frequency and severity of growth-arresting stressors than do adults.

It is well documented that disease load increases in sedentary, agricultural populations relative to mobile foragers. This trend is indicated by increased rates of anaemia and parasitic infection in agricultural populations (Reinhard 1992; Stuart-Macadam 1992). The relationship between diet and skeletal indicators of anaemia is a complex one. For example, poor sanitation (high parasite load) rather than low dietary iron may lead to anaemia (Kent and Dunn 1993).

Figure 2 models skeletal indicators of populations highly dependent on maize agriculture. General trends include high rates of caries and tooth loss, frequent occurrences of enamel defects and low to moderate levels of interrupted long-bone growth (Harris lines) and high levels of anaemia and parasites. Modelling of Harris lines and enamel hypoplasias is based on agricultural populations being less impacted by seasonal stressors than by prolonged malnutrition from crop failure. Populations relying on marine protein are modelled as somewhat healthier, based on relative ease of access to fish and molluscs. With increased sedentism comes reduced robustness in many cases.
Botanical and faunal indicators of diet

Botanical macro-rema ins (charred, dried or waterlogged seeds, fruits, roots), faunal remains (bones, shells, feathers, fur), pollen, phytoliths and starch grains are important indirect indicators of diet that identify potential members of the food web, the ‘menu’ items for human populations. Botanical or faunal data recovered from coprolites or latrine samples provide direct dietary information.

As discussed in detail in Pearsall (2000), Lyman (1994), Reitz and Wing (1999) and other sources, botanical and faunal remains are subject to biases of deposition, preservation, recovery and identifiability that impact on their usefulness for understanding human subsistence behaviours. It can be challenging to distinguish among plant or animal taxa included in site deposits through natural processes and those that were brought to the site purposefully. Of the latter, consumption is only one of a number of possible uses that may be inferred from the presence of remains. The presence of food remains in contexts associated with food preparation, consumption or disposal can permit a convincing argument to be made that a taxon was a menu item. Such associations may be more difficult to make for pollen and phytoliths of wild plants, some of which form part of the ‘background’ microfossil assemblages of site soils. In this case, one looks for levels of occurrence elevated above the ‘normal’ background, for associations of microfossils and food preparation tools or cooking vessels, and for plants occurring outside their natural ranges.

If botanical and faunal data are robust enough to be quantified by frequency, ubiquity (percentage presence) or diversity measures, one can model the differences among diets focused on different mixes of wild, cultivated and domesticated plants, wild game, domesticated animals and fish and molluscs. The diets presented in Figure 2, for example, show the high levels of domesticated plants, declining dietary richness (reduced use of cultivated and wild plants), increase in weeds and commensals (animals associated with disturbance) in site deposits and off-site evidence for vegetation modification that are associated with intensive agriculture. The terrestrial diet factors in the keeping of domesticated animals; the relative contribution of marine and terrestrial faunas can be quantified in some instances by MNI (minimum numbers of individuals) or biomass calculations. In both the diets illustrated in Figure 2, populations are sedentary and landscapes have been modified to increase agricultural production (i.e. terraces, raised fields, irrigation canals or run-off water storage features).

Applying the approach: The Real Alto case

Using the approach described above, I developed eight model diets for the New World tropics, each of which is distinguishable on the basis of one or more dietary indicators (Pearsall 2000). Figure 3 illustrates two diets that contrast sharply with the maize-based diets illustrated earlier: foragers, primarily terrestrial protein, and foragers, primarily marine protein. Both forager diets model predominantly C3 plant foods in the diet. In the ideal case (excellent preservation and recovery) there would be many features that distinguish among the four model diets illustrated.

The archaeological reality can be quite different, of course. The approach that I suggest is the following: that the fit of an archaeological case to a dietary model be tested using one or more new lines of evidence suggested by the model. In other words, if existing evidence from analysis of macro-rema ins suggests maize was important in the diet (maize is ubiquitous; other dietary items relatively few; weeds are common) and site size and location imply sedentism and orientation to agricultural lands, then the model of maize agriculture...
Figure 3. Two model diets for foragers in C3 vegetation settings: Diet 1, gathered plant foods and terrestrial protein; Diet 2, gathered plant foods and marine protein (from Pearsall 2000).

predicts: enriched $\Delta^{13}C$ values, dominance of plant foods in diet (high Sr, Ba, Mg; low Zn), abundant caries, high rates of enamel hypoplasias and anaemia, low robustness, high parasite load and evidence for extensive vegetation clearing and increases in commensals.

In the section that follows, I will illustrate the application, and strength, of the approach using an actual archaeological case: the Real Alto site, south-west coastal Ecuador.

Real Alto: The issues and the site

The following are some of the issues that drive my continued research interests at Real Alto (Pearsall 1996): How ancient is maize? Were the inhabitants of Real Alto agriculturalists? Maize agriculturalists? Was maize domestic or ceremonial? What role did maize play in the florescence of Valdivia culture?

The Real Alto site is located in south-west Guayas Province, along a small intermittent river (Fig. 4). The site was initially excavated in 1974-75 by Donald W. Lathrap and associates (Lathrap et al. 1977), with later excavations by Damp (1979). The site dates to the Early Formative Valdivia Period of coastal Ecuador, and was occupied from Valdivia 1–7 (4500 BC to 2100 BC, cal.; Zeidler 1991). During the Valdivia 3 Period, dating to about 2800 BC cal., the site grew to its greatest extent: 12.4 ha, with two ceremonial mounds and two plaza areas (Figs. 5 and 6).

What did we learn about Real Alto through the analysis of materials in the 1970s and 1980s? My analysis of botanical macro-remains and phytoliths (Pearsall 1978, 1979), reviewed in Pearsall (2003), resulted in the identification of arrowroot (Maranta), achira (Canna), cotton,
jackbeans (*Canavalia*), maize, squash and gourd (cultivated and domesticated plants), and tree fruits, cactus fruits, sedge roots and rainy season annuals like *Trianthema* (wild plants). Unfortunately, preservation and recovery problems made it impossible to quantify the results. Analysis of fuel wood patterns indicated some impact on near-coastal environments: xerophytic tree species were selected as fuels.

Analysis of faunal remains by Byrd (1976, 1996) and Stahl (2003) resulted in the identification of fish from estuarine, mangrove and marine habitats (including sea catfish, grunt, drum and jack), mangrove molluscs (*Anadara tuberculosa*, *Cerithidea pulchra*) and non-fish vertebrates (including white tail and brocket deer, dog, fox and sea turtle), among other taxa. A diverse array of animal foods was available. While there are problems with quantifying the faunal data, marine and estuarine resources contributed substantially to the diet. Commensals were present on the site, but these data were not quantifiable.

Skeletal studies by Klepinger (1979) and Ubelaker (2003), and isotope analyses by van der Merwe and colleagues (van der Merwe et al. 1993) and Burleigh and Brothwell (1978), revealed the following: frequencies of dental caries in the range associated with agricultural populations; one human skeleton with a C3 isotope signature (no maize use), one dog skeleton with a C4 isotope signature (maize use implied), and low to intermediate stress indicators. In relationship to populations of the earlier, preceramic Vegas tradition, Real Alto villagers were less healthy.

Figure 7 is my model of early Valdivia diet based on the data summarised above. The low ΔC13 value reflects the human skeleton; if the dog was graphed, the value would be in the enriched, or maize, range. Is this maize agriculture or not? Isotope values are contradictory; stressors are low to intermediate; no off-site data on clearance are available. Caries rates are high, but there are no quantifiable botanical data to assess which of the available sticky carbohydrate sources (maize, arrowroot, *achira*, tree fruits) was causing this.

If we propose a fit of early Valdivia diet to the model for maize agriculture with marine protein (Fig. 2), then the following predictions arise: maize was commonly used (new measure: remains in many houses, on many artefacts, in dental calculus and tooth crevices); populations were dependent on agriculture (new measure: substantial land clearance;
Figure 6. Excavations at Real Alto: (a) the Real Alto site setting today. Wood charcoal remains indicate that a more forested environment existed in the past; (b) view across the inner plaza (area between the two mounds; Fig. 5) towards the Channel House mound; (c) and (d) excavations revealed rows of domestic structures. Note structure wall trenches (foreground and left, c) and floor excavations in progress (d).

increased construction of water catchment structures or *albarradas*; maize was a dietary staple, not, or not only, a ceremonial plant (new measure: maize in domestic contexts).

Results of new research: Testing the predictions

To date I have carried out three studies whose aims are to test predictions generated from the model presented above. The first was a study of maize phytolith occurrences in samples from floors of structures at Real Alto, reported in Pearsall (2000). Fourteen soil samples from six houses dating to the Valdivia 3 Period were reprocessed to extract phytoliths using an improved protocol (Zhao and Pearsall 1998). Cross-shaped phytoliths, produced predominantly in the leaves of maize and other panicoid grasses, which were recovered from floor deposits, were classified as maize or wild grass based on discriminant analysis. (For details of the development of the cross-body method for identifying maize and its application, see Pearsall 2000.) Classification of cross-bodies as maize is 85% correct using the discriminant function formulae. Maize cross-bodies were present in all houses (n = 6) and in 86% of individual soil samples (n = 14). These results support the prediction that maize should be commonly used in village households.

The other two studies, analysis of starch and phytolith residues on stone tools, are in progress. These studies will be based, ultimately, on analysis of 70 stone tools from four Valdivia 3 house floors. Preliminary results are available for ground stone tools from Structure 20 (Fig. 8). For the starch grain analysis, I consulted published protocols (Loy 1994; Piperno and Holst 1998; Therin et al. 1999) and also benefited from the work of Perry (2001). A four-stage sampling strategy was followed: tools were brushed gently of adhering soil (Sediment 1); crevices and work-surfaces were sampled by pipette (*in situ* samples); tools were washed in distilled water and the supernatant recovered (Sediment 2); and tools were sonicated and the supernatant recovered (Sediment 3). Direct mounts were made of a portion of all sediments, as well as the *in situ* samples, and then sediments were processed to concentrate the starch, then
The state of the art in phytolith and starch research in the Australian-Pacific-Asian regions

Carbon isotopes
Nitrogen isotopes
Ba/Sr
Sr
Ba
Mg
Zn
Caries
Tooth loss
Enamel hypoplasias
Harris lines
Anaemia
Robustness
Parasite load
Domesticated plants
Cultivated plants
Richness of plant foods
Weeds (on site)
Vegetation modif. (off site)
Domesticated animals
Tended animals
Richness of animal foods
Commensals (on site)
Marine/terrestrial
Sedentism
Landscape modification

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Figure 7. Model of Early to Middle Valdivia diet (from Pearseal 2000).

Maize starch grains were recovered on 76% of ground stone tools analysed from Structure 20 (n = 17 tools) (Fig. 9). Maize starch was abundant on two of these tools, with 15 grains observed in one slide mount for tool 3383-A (size range, 11.1-25.4 microns) and 21 grains on one slide mount for tool 3290-A (size range 12.7-27.0 microns). In addition, arrowroot starch grains (*Maranta arundinacea*) were observed on 24% of the tools. To this point, no starch grains of economic plants have been observed in soil adhering to the tools. These preliminary results indicate: that analysis of starch on tools is a productive approach; that maize was commonly processed by grinding, at least in the Structure 20 household; and that grinding stones were multi-purpose tools.

Figure 8. Two ground stone tools included in the study. On the left is tool FS 3415-A, from Structure 20-4-t (excavation unit) and on the right is tool FS 3331-A, from Structure 20-3-o.
Integrating biological data: Phytoliths and starch grains, health and diet, at Real Alto, Ecuador

Figure 9. Examples of starch grains and phytoliths recovered from Structure 20 tools and house floor sediments: (a) and (b) polarised and transmitted light photomicrographs of a maize starch granule (Granule 5) from the surface of tool FS 3294-B (S20-3-n); (c) another maize starch granule (Granule 3) from the same tool surface; (d) an arrowroot starch granule (Granule 2) from the same tool surface; (e) ruffle-top maize cob phytolith from floor sediments adhering to tool FS 3415-A (S20-4-t); (f) wavy-top maize cob phytolith from floor sediments, unit S20-3-b. MAIZE STARCH GRANULE CHARACTERISTICS: spherical with double outline, smooth surface, no visible lamellae, hilum centric and open, fissure linear or Y-shaped, extinction cross with straight, narrow arms. ARROWROOT STARCH GRANULE CHARACTERISTICS: ovate to clam-shell shape, smooth surface and outline, fine lamellae, hilum open and eccentric, fissure absent, extinction cross with bent, narrow arms. MAIZE COB PHYTOLITH CHARACTERISTICS: rondel (circular to oval) base longer than the body is high/tall, top (side opposite the base) is a single, undulating wave, formed by the convergence of the sides (wavy-top) or flat and ephemeral with ruffled or undulating edges (ruffle-top); tops distinctly not with spikes. The wavy-top is a maize species (Zea mays) diagnostic; the ruffle-top a Zea genus diagnostic (Pearsall et al. 2003).
described above, after flotation to recover starch. A shortened version of University of Missouri phytolith procedure (Zhao and Pearsall 1998) was followed. In addition to tallying the occurrence of maize cross-bodies, which are produced predominantly in leaves and husks, a new protocol for identifying maize using cob phytoliths was applied to these samples (Pearsall et al. 2003). Maize cob phytoliths were recovered from 7% of the tools (Sediment 3 samples, N = 14 tools); maize leaf phytoliths from 21%. Maize cob and leaf phytoliths were also present in soil adhering to several tools (Sediment 1 samples) and in house floor deposits. In addition to maize, phytoliths identified as achira and arrowroot were observed in Sediment 3 samples, and a number of unknown, yet well-preserved phytoliths were encountered. These results add another line of evidence for maize processing in the Structure 20 household, and support the finding that ‘grinding’ stones were multi-purpose plant processing tools.

To summarise the results of the new analyses, maize was commonly used at Real Alto. Maize cross-shaped phytoliths were identified in all Valdivia 3 house floors sampled; maize starch was recovered from many ground stone tools analysed from Structure 20; maize cob phytoliths and cross bodies were encountered on some tool surfaces and in soil adhering to tools from the same structure. I anticipate that when the stone tool analysis is completed, and all house floor samples are resampled for presence of cob phytoliths, the importance of maize in domestic cuisine will be established.

The Real Alto case also demonstrates that maize use during Valdivia 3 times was within the context of a diet of considerable richness. Root crops, jack beans, squash and wild plant and animal resources, especially fish and molluscs, were consumed. Health was good overall, but caries rates indicate a decline in dental health relative to the earlier Vegas culture. Consumption of processed maize, arrowroot and achira starch likely all contributed to this decline. The new data thus lend additional support to the agricultural basis of Valdivia 3 society, and enhanced fit to the model of maize agriculture with marine subsistence.

Conclusions

Integrating multiple lines of evidence provides insight into prehistoric diet. Dietary modelling reveals ways to test interpretations based on incomplete data. For the Real Alto case, residue analyses support the importance of maize in the diet of Valdivia 3 villagers and the agricultural basis of Valdivia society.

As discussed earlier, however, other avenues exist to explore the relationship of Real Alto villagers to maize and other crops. Future research plans include off-site coring to recover palaeoenvironmental sequences for the middle and late Holocene of south-west Guayas Province. This will permit us to assess the extent to which Valdivia peoples modified local vegetation, and may provide independent evidence for the changing importance of cultivated plants. Research is also under way to study starch and phytoliths caught and preserved in human dental calculus.

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Pearsall

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References


PHYTOLITH AND STARCH RESEARCH IN THE AUSTRALIAN-PACIFIC-ASIAN REGIONS publishes refereed papers from a conference held at The Australian National University in Canberra, 2001. In recent years, phytoliths, with their high potential for long-term preservation, and starch grains, found in archaeological sediments and residues with the potential to provide taxonomic identifications for a range of important economic plant species, are microfossils that have increasingly been the focus of Quaternary scientists. This volume reports new results and work in progress relating to the application of starch and phytolith analyses in archaeological, sedimentological and palaeoenvironmental contexts across a broad geographical region in the southern hemisphere. These papers will be of interest to those actively involved in similar microfossil research, as well as to general researchers in the fields of archaeology, ethnobotany, Quaternary studies and pedology wishing to keep up to date with developments in these emerging fields or who might have reason to incorporate such studies in future multi-disciplinary projects.

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