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REVIEW

The history of phytolith research in Australasian archaeology and palaeoecology

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Abstract

Although phytolith research has come of age in archaeology and palaeoecology internationally, it has remained relatively marginalised from mainstream practice in Australasia. The region's initial isolation from international scientific communities and uniqueness of its vegetation communities, has led to an exclusive set of challenges and interruptions in phytolith research. Examining a history of Australasian phytolith research presents the opportunity to recognise developments that have made phytoliths a powerful tool in reconstructing past environments and human uses of plants. Phytolith research arrived early in Australia (1903), after a convoluted journey from Germany (1835–1895) and Europe (1895–1943), but phytoliths were initially misidentified as sponge spicules (1931–1959). Formal understanding of phytoliths and their applications began in Australasia during the late 1950s, continuing throughout the 1960s and 1970s (1959–1980). After a brief hiatus, the modern period of phytolith analyses in Australasian archaeological and palaeoenvironmental research began in the 1980s (1984–1992), focusing on investigating the deep past. Advancements continued into the 1990s and early 2000s. Wallis and Hart declared in 2003 that Australian phytolith research had finally come of age, but more a fitting description would be that it had peaked. Since then phytolith research in Australasia slowed down considerably (2005-present). Local phytolith reference collections for Australasian flora, critical for identifying ancient phytoliths, are essentially no longer produced.

Keywords Plant silica · Archaeobotany · Palaeoethnobotany · Palaeoenvironment · Vegetation · Prehistory

Introduction

The importance of plants to humans throughout time cannot be overestimated (Mooney and Martín-Seijo 2021). Evidence for dynamic human-environmental legacies are preserved in archaeological and palaeoenvironmental records in the form of macro-botanical and micro-botanical remains, such as wood charcoal, non-woody charred plant remains, starches, residues, pollen grains and phytoliths (biogenic plant silica). Investigating past human–environment interactions is the shared interest of archaeobotantists and palaeoecologists, who use macro-botanical and micro-botanical traces as proxies for cultural plant-use and vegetation dynamics. Phytoliths are among the most robust and abundant microfossils recovered from sedimentary deposits, often preserved when other proxies are absent (Piperno 2006; Hodson 2016). Despite a large increase in phytolith studies over the past three decades, phytolith analyses are still an underutilised method, especially when compared to other proxy methods such as pollen analysis (Parker et al. 2004).

Phytoliths are of great significance for archaeology and palaeoecology. Living plants absorb monosilicic acid ($Si(OH_4)$) from the soil, a by-product of the weathering of rocks and the dissolution of biologically deposited silica in the environment. Monosilicic acid is transported via the

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vascular system to different plant organs, where it polymerises to form solid opaline silica (SiO_2) deposits called phytoliths that often reflect the size and shape of the specific intracellular and extracellular locations where they are formed (Baker 1959a; Jones et al. 1963; Piperno 1988; Sangster et al. 2001). Many plants produce phytoliths with characteristic, repeated three-dimensional shapes and sizes (morphotypes) that are often genetically and physiologically controlled, making them, taxonomically significant (Fig. 1). Even though phytolith morphotypes can be highly variable in size (usually ~ 1–100 µm), depending on the source plant and plant part producing the phytoliths (Piperno 2006; Carter 2007), phytolith morphotypes that are diagnostic of plant taxa are a powerful tool in charting past vegetation change and human-plant interactions.

Globally, phytolith analysis has come of age in archaeology and palaeoecology. Over its nearly two-hundred-year history, four main stages of international phytolith research have been recognised by Dolores Piperno (2006), a leading phytolith analyst: 1) The discovery and exploratory stage (1835–1895); 2) The botanical phase of research (1895–1936); 3) The period of ecological research (1955–1975), and; 4) the modern period of archaeological and palaeoenvironmental research (1975-present). Australasian phytolith research has followed its own distinct trajectory, experiencing an exclusive set of challenges due to its initial isolation from international scientific communities and the uniqueness of its vegetation communities. By presenting the history of Australasian phytolith research we will explain why Australasia's trajectory differs from international phytolith research efforts.

Phytolith studies, and broadly the study of past plant remains, has remained relatively marginalised within mainstream archaeological practice in Australasia (defined as the region comprising Australia, New Zealand, New Guinea and neighbouring Indo-Pacific Islands), largely because early researchers were unconvinced of the longevity and antiquity of plant preservation in sediments. This belief was largely due to the aridity and humidity of the region with its own unique climates, soils, and vegetation (Bowdery 1984, 1989, 1996; Hart 1992; Wallis and Hart 2003; Denham et al. 2009, 2022). Phytoliths and other plant fossils were deemed unworthy of collection or further study, a view that only began to be challenged in the last 40 years. Investigating plant remains within archaeological contexts still often remains an afterthought, not typically included in the planning of fieldwork, and only considered post-facto or post-excavation (Denham et al. 2009, 2022; Dilkes-Hall et al. 2019). Undoubtedly, the lack of evidence for past plant use and vegetation shaped the now archaic attitudes held by early 20th century investigators regarding the apparent paucity of complex human-plant interactions occurring in Australasia's deep past (Lourandos and Ross 1994; Jones 1999; Ulm 2013). With knowledge of phytoliths dating back to the 1800s, their application to archaeological and palaeoenvironmental investigations should not have been considered radical. Recent advancements (Figs. 2–3) have demonstrated the great potential of phytoliths for providing high-resolution natural and cultural landscape reconstructions. While two reviews have already been published outlining the

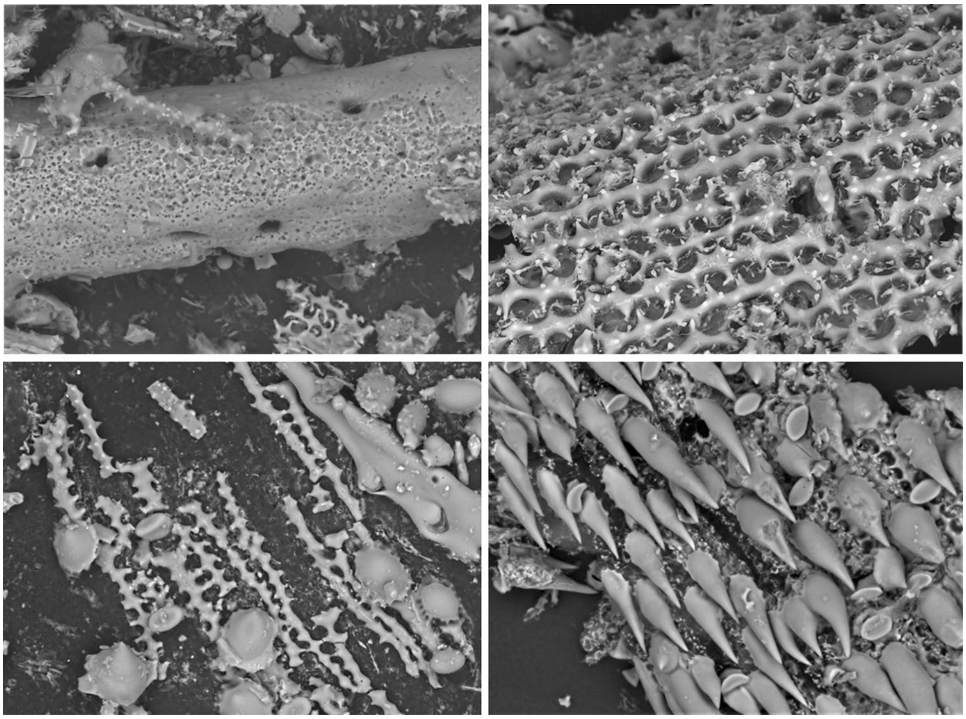
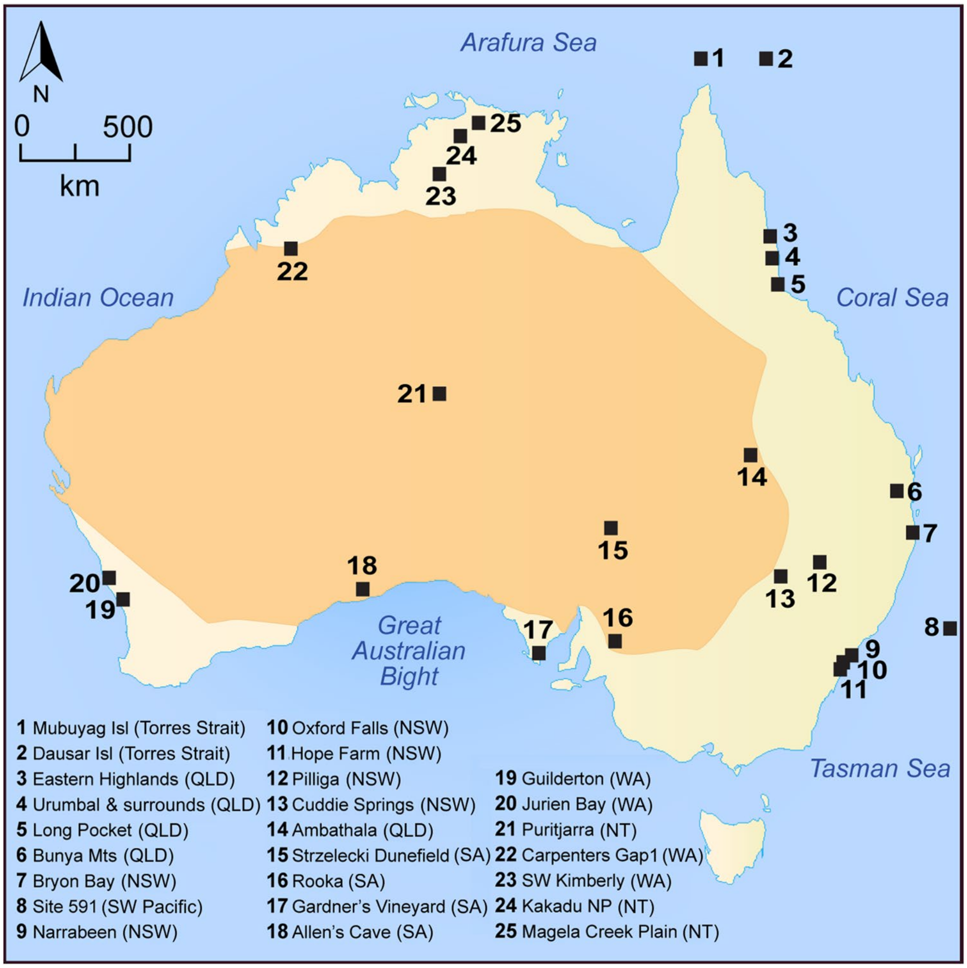


Fig. 1 Scanning Electron Micrographs (SEM) of articulated epidermal ELONGATE DENDRITIC phytolith cells diagnostic of Poaceae (grass) inflorescence. Sample obtained from the lemma (part of the husk enclosing the grain) of modern *Hordeum vulgare* plant tissue (image not to scale)

Fig. 2 Overview of significant Australian sites and localities where major contemporary phytolith studies have been conducted (since 1984 to present). Orange zone = Australia's arid/semi-arid zone



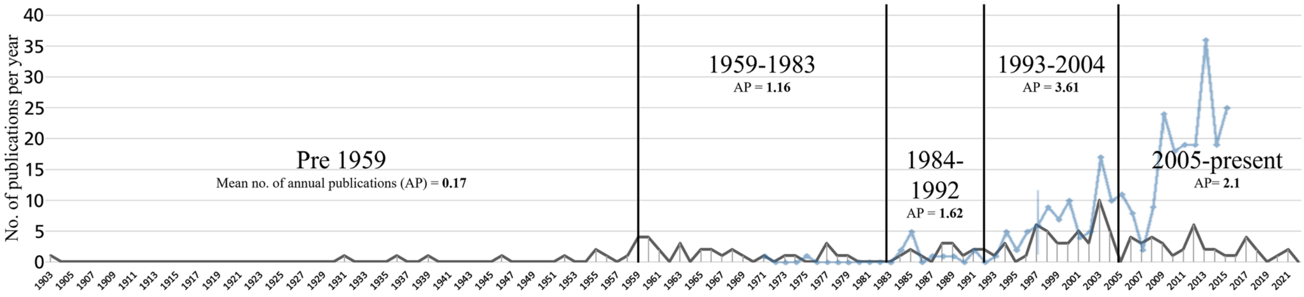


Fig. 3 Overview of major Australasian phytolith research publications. Note the rise 1992–2004, decline in 2005 and sporadic nature of publications in recent years. Blue line = Comparative international study by Hart (2016) of major phytolith studies in journal publications (1971–2015)

development of phytolith research in Australia (Bowdery 1989; Wallis and Hart 2003), the most recent review was published nearly 20 years ago. This paper traces the history of Australasian phytolith research, with particular attention given to investigations of the Australian continent from its origins in Europe, detailing how we have reached our current understanding of phytolith production in Australasian plants and sediments. Significant Australian-based phytolith research of New Zealand, New Guinea and neighbouring Indo-Pacific Islands, with shared floral taxa and ecological similarities, relevant to this shared history are also integrated into this discussion.

Discovery: Germany (1835–1895)

Germany established itself as the early centre of phytolith research, where phytoliths were first formally observed and explored in plants and soils. The first report on phytoliths in modern plants was published by German botanist, Gustavus Adolphus Struve, in 1835. Interestingly, this was only a year before pollen grains were first recorded in pre-Quaternary sediments. German microbiologist and one of the early leaders of phytolith research, Christian Gottfried Ehrenberg, coined the term ‘Phytolitharia’ after ‘plant stones’ in Greek. Ehrenberg observed phytoliths in soil samples worldwide, developing the first classification systems for phytoliths (Piperno 2006; Madella and Zurro 2007).

Ehrenberg became well-known and sought after for interpreting phytolith assemblages, collaborating with some of the great scientists of the time. Charles Darwin was an early collector of phytoliths, sampling the fine powder deposited on the sails of his ship, HMS Beagle, off the coast of the Cape Verde Islands. The samples were given to Ehrenberg for analysis and found to contain phytoliths (Ehrenberg 1841, 1854). Largely due to Ehrenberg, phytolith research began gaining recognition throughout Europe for its applications (Piperno 2006; Madella and Zurro 2007).

Botanical exploration: Europe (1895–1943)

Following its start in Germany, phytolith research dispersed throughout Europe, entering a botanical exploration phase when phytoliths became widely recognised as being derived from plant tissues. There was an eruption of botanical research on Kieselkörper (‘silica bodies’; another term for phytoliths) which examined silica production, taxonomy and morphology in Poaceae, Urticaceae, and various dicotyledons (Piperno 2006). There was also keen interest in the phytoliths of ‘exotic’ plants from outside Europe in this period, such as Arecaceae (palms), Musaceae (bananas), Zingiberaceae (gingers), Orchidaceae (orchids), and Polypodiopsida/Polypodiophyta (ferns) (Fig. 4) (Wiesner 1914). This investigative work enabled researchers to identify which plant families do and do not produce silica structures, and provide detailed notes and illustrations of findings. Importantly, some phytolith morphologies were found to be sufficiently characteristic to differentiate between plant families (Piperno 2006).

During this time, leading European botanical institutions actively promoted the widespread collection of ‘exotic’ plants worldwide, continuing well into the 20th century. Many Australasian plants (and animals) were transported from their natural habitats, especially in tropical regions, back to Old-World institutes to be studied, a practice that was innately tied to violence and imperialism (Blais and Markovits 2019).

The first archaeological phytolith applications were impressively realised during this early period in Europe. Netolitzky (1900, 1914, 1929) and Schellenberg (1908) identified phytoliths of key economic Poaceae species such wheat, barley and millet in ceramics and ash piles in Europe and Turkey. The onset of World War II unfortunately halted most botanical research on phytoliths just as they were becoming increasingly utilised throughout Germany and Europe. Few German publications are found after 1936 and many important older publications were exclusively written in German. Hence, foundational German and European publications were not widely available to the English-speaking world until their rediscovery and translations in the 1950s (Piperno 2006).

Mistaken identity: the early arrival of phytoliths in Australia (1903–1959)

Researchers working in Australia have a long history of studying the silica properties of plants, however, research made a convoluted journey to recognise these as phytoliths and realise their potential for archaeology and

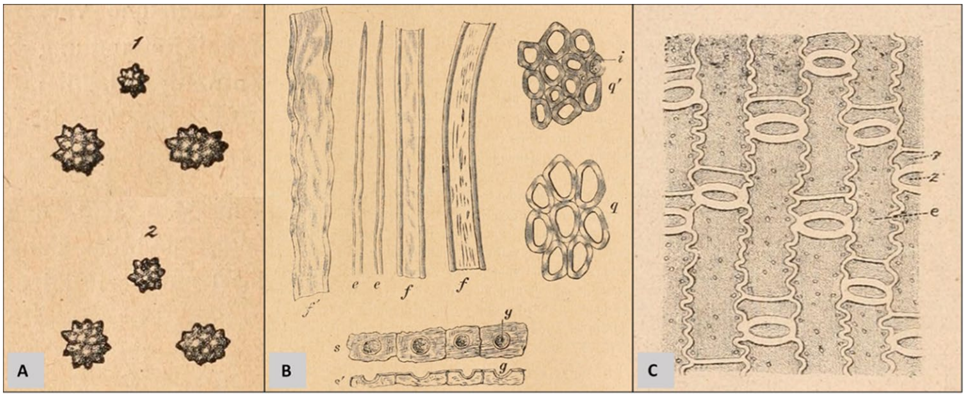


Fig. 4 ‘Kieselkörper’ illustrations from Julis Wiesner’s (1838–1916) Die Rohstoffe des Pflanzenreichs: Versuch einer technischen Rohstofflehre des Pflanzenreiches (1914, pp 60, 285, 332). **A** Arecaceae from Africa (1) and Brazil (2); **B** *Musa* (Musaceae); **C** *Stipa* (Poaceae)

palaeoecology. Knowledge of plant-derived silica arrived in the early 20th century, with Chapman and Grayson (1903) reporting silica elements in Australian wind-borne dust from Victoria. However, plant silica research remained relatively dormant for several decades before developing into two distinctive research schools, one in forestry and agronomy, and the other in earth science. Forestry and agronomy researchers such as Hely and Hallsworth (1947) and Amos (1952) investigated silica content in Australian and New Zealand Poaceae and woody plants in terms of livestock nutrition and economic exploitation. Earth science researchers began noting the presence of phytoliths in various Australian soil contexts but mistakenly identified these as ‘sponge spicules’ (structural elements of sponges). This incorrect identification was initially made by Carroll (1933) and would be repeated for at least 25 years in various publications (Leeper et al. 1936; Nicholls 1939; Brewer 1955, 1956; Leeper 1955). The presence of sponge spicules was interpreted to confirm the past existence of many freshwater lakes in southern Australia, or alternatively the result of extremely high wind activity (Baker and Leeper 1958; Baker 1959a).

The re-emergence of European phytolith research began with English scientist Frank Smithson (1956, 1958), who observed plant silica particles in Australian soils. Smithson (1956, 1958) initially often conflated phytoliths with other microfossils, such as ‘diatoms’ (microalgae), similar to early research in Australia. Phytolith misidentification was likely caused by English speakers’ limited access to earlier foundational German and European phytolith research. Smithson was fortunately heavily inspired by Russian soil scientists such as Oosov (1943) who researched the role of phytoliths in soils (Piperno 2006). The English-speaking world became reacquainted with phytoliths through research by Smithson and collaborators (Smithson 1956, 1958; Parry and Smithson 1958a, b). However, confusion surrounding plant silica remained uncorrected in Australia.

The research of Australian geologist George Baker (1908–1975) corrected the misidentification of phytoliths as sponge spicules in Australia. Baker, a scientist at the Commonwealth Scientific and Industrial Research Organisation (CSIRO), was introduced to Smithson during a visit to University College of Wales and learned about phytolith from him (Wallis and Hart 2003). Baker subsequently reinterpreted Australian sponge spicule assemblages as phytoliths, finally explaining their widespread occurrence in the Australian landscape (Baker and Leeper 1958; Baker 1959a). This meeting between Baker and Smithson bridged much of the initial isolation between Australia and international phytolith researchers. Australian researchers then began applying this knowledge of phytoliths to the unique geology, botany and pedology, and eventually the archaeology and palaeoecology, of Australia and nearby regions.

Formal phytolith research: fundamental studies in Australia and globally (1959–1980)

Fundamental phytolith research was undertaken in Australia in the late 1950s, with broad, global research relevance (Rovner 1983). Researchers from a wide range of earth science disciplines produced a suite of ecological, agricultural, botanical and pedological studies investigating silica development in Australian plants and soils during this period (Table 1). Most of these environmental studies do not directly apply phytolith analyses to ancient assemblages but explore methods and produce results often allied with archaeology and palaeoecology (Wallis and Hart 2003). This research typically focused on understanding silica production and distribution in modern plants and soils, an essential foundation for later phytolith applications.

Baker became the leading phytolith analyst in Australia during this period, a true pioneer in phytolith science in demonstrating the longevity of phytolith preservation to Australian and international peers (Wallis and Hart 2003; Piperno 2006). Baker began classifying the silicification process in plant cell linings and walls and developing nomenclature for the variety of shapes and sizes of phytoliths, particularly for Eurasian species introduced to Australia (Baker and Leeper 1958; Baker 1959a, b, c, 1960a, b, c, 1961). One of Baker’s (1959b) most significant contributions was being the first internationally to analyse the phytoliths present in modern surface sediments samples to understand the correlation between vegetation dynamics and the phytoliths deposited into sediments. This formed the foundation of the comparative method (Piperno 2006; Wen et al. 2018), where phytolith assemblages from modern surface sediments are analysed and compared to phytolith assemblages from archaeological and palaeoenvironmental contexts. Baker (1959a, 1960a) identified the potential of using phytoliths in sediments from the Holocene, Pleistocene, Pliocene and earlier for archaeological and palaeoecological applications. Baker’s influence can be seen in various publications also implementing similar earth science phytolith applications.

Many studies during this period focused on researching how sheep ingest silica, embed phytoliths into their teeth and excreted phytoliths into soils (Baker et al. 1959, 1961; Jones and Handreck 1965b), and the specific silica uptake patterns of *Avena sterilis* (oat) and its unique silicified morphologies (Baker 1960c; Jones and Milne 1963; Jones et al. 1963; Jones and Handreck 1965a; Handreck and Jones 1967, 1968). Kamminga (1971, 1977, 1978, 1979), Costin and Polach (1973) and Bowler (1978) began considering and advocating for phytoliths by suggesting

Table 1 Synthesis of significant Australasian phytolith research 1959–1980

Researchers, references	Research field	Specific region contributions	Specific taxon contributions
Baker (1959a, b, c, 1960a, b)	Soil science	VIC Australia	
Baker (1959c)	Phytolith nomenclature	Australia	
Baker (1960c)	Agronomy, botany, chemistry	Australia	*Avena sterilis* (oat)^{I}
Baker (1961)	Agronomy, botany, chemistry	San Fernando, Philippines	*Saccharum* sp. (sugarcane)^{N}
Baker et al. (1959, 1961)	Agronomy, botany, chemistry	Australia	Sheep (teeth)^{I}
Bamber and Lanyon (1960)	Agronomy, forestry	NSW Australia	Woody plants^{I,N}
Jones and Handreck (1963)	Agronomy, soil science	Australia	
Jones and Handreck (1965b)	Agronomy, soil science	Australia	Sheep (excrement)^{I}
Jones et al. (1966)	Botany, chemistry	Southwest Asia	Bambusoideae (bamboo)^{N}
Handreck and Jones (1967); Jones and Handreck (1969)	Agronomy, soil science	Australia	*Trifolium incarnatum* (Crimson clover)^{I}
Jones and Milne (1963); Jones et al. (1963); Jones and Handreck (1965a); Handreck and Jones (1968)	Agronomy, soil science	Australia	*Avena sterilis* (oat)^{I}
Norton (1966)	Botany	Wakefield, NSW Australia	Cyperaceae (sedge) incl. *Lepidosperma* sp.^{N}
Stace et al. (1968)	Soil science	Australia	
Kamminga (1971, 1977, 1978, 1979)	Archaeology (incl. use-wear and residue analyses)	Australia	
Costin and Polach (1973)	Geomorphology, palaeoecology	Black Mountain, ACT Australia	
Bowler (1978)	Geomorphology	Murray Basin, NSW Australia	
Scurfield et al. (1974)	Botany, chemistry	Australia, Melanesia, Southeast Asia	Woody plants incl. *Gynotroches axillaris*^{I,N}
Clifford and Watson (1977)	Botany	Eastern Australia	Poaceae^{I,N}

^{I} Introduced, ^{N} Native

This table and all succeeding tables are not comprehensive lists of Australasian phytolith research. Studies from regions surrounding Australia are included based on relevant intersecting native taxa and/or if research was led by Australian phytolith analysts

their presence in anthropogenic and geogenic contexts. Geomorphologists speculated on the characteristics of phytoliths and their role in Australia soil contexts (Costin and Polach 1973; Bowler 1978), suggesting the need for more modern studies. Majority of modern phytoliths studies during this time focused on the phytoliths produced by Eurasian economic crops, which have only been present for a brief moment in long history of vegetation and land use on the Australian continent and nearby regions.

Many key Eurasian crop plants and associated weeds were introduced to Australia during the colonial period. Phytoliths of introduced Eurasian plants serve as chronological markers of European settlement and associated environmental change in Australia and surrounding localities (Lentfer et al. 1997; Denham et al. 2009). The phytoliths in introduced Eurasian species are markedly different from those in native taxa. Native taxa form key vegetation communities which dominated Australasian landscapes throughout prehistory and continue to do so. Phytolith research had yet to be applied to Australasia's deep past, despite progress along these lines made by the international phytolith community during this time.

International phytolith researchers, particularly in the Americas, began seriously examining phytolith production and morphologies in a wide range of modern plant taxa, allowing analysts to answer important palaeobotanical and palaeoecological questions. Rovner's (1971) formative study, increased global awareness of phytolith analyses, cementing its place in Quaternary literature and advocating for its potential in archaeology and palaeoecology. Classification systems for differentiating plant families were produced by investigating and comparing phytolith patterns in modern plants and ancient sediments, particularly prehistoric deposits of the Pleistocene and Holocene (Piperno 2006). Twiss et al. (1969) and Pearsall (1978) created phytolith discrimination systems that are still extensively used today as an independent means of studying prehistoric plant use, domestication and the environment (Piperno 2006).

In direct contrast, at this time Australasian research had not yet applied phytoliths to deep time records. Wallis and Hart (2003) analysed Australian phytolith research publications from 1971 to 1980 and categorised this as a period of decline with a nearly five year pause in publications, but asserted 1981–1990 was a period of revitalisation, when phytolith research began to be seriously applied to prehistoric landscapes in Australasia. This decline period coincides with the passing of George Baker in 1975 (Gill and Segnit 1976).

Entering the deep past: the modern period of Australasian archaeological and palaeoenvironmental research (1984–1992)

The lack of interest in the plant-use and vegetation of Australasia's deep past was in part a relic of colonial theories that Australasian landscapes and inhabitants are unchanging; theories with clear associations with shameful *terra nullius* and living fossil tropes (Ulm 2013). After World War II, Australasian archaeology began to recognise complexities occurring in its prehistoric past. The development and methodological advancement of radiocarbon dating techniques throughout the 1940s–1960s, had huge impacts on Australasian prehistoric research. Researchers moved away from beliefs that Australia had a short chronology of human occupation and was relatively unchanging, to actively seek Pleistocene human occupation dates (Jones 1999). Australian archaeology in the 1980s largely encouraged studying the complexities of Australasian's deep past, as evident in 'intensification' debates of this era, and new processualist archaeological theory that argued for increased ceremonial gatherings, intergroup competition, greater food production, new technologies, new resource management/cultivation, broad-spectrum diet, population growth, the rise of elites, and regional networks in Australia's Holocene (Bender 1978; Lourandos and Ross 1994). Knowledge of ancient plant use and vegetation histories became increasing important for this narrative, which is evident with the expanding array of new archaeobotanical, ethnobotanical and palaeoenvironmental studies during this period (Golson and Hughes 1980; Gott 1983; Beck et al. 1989; Harris and Hillman 1989; Golson 1991). Australian archaeobotantists and allied researchers were frequently at the forefront of investigations into plant cultivation in the tropics and subtropics.

Phytolith research provided a reliable, independent proxy for reconstructing Australasian's deep time record during this period and was used to investigate ancient human-landscape interactions such as plant use and responses to environmental change (Table 2). Researchers at this time had to seriously consider the differences and unique challenges of native Australasian vegetation. Phytoliths were increasingly recognised as a modern tool for archaeological and palaeoenvironmental research in Australasia and known for their robust preservation at sites with difficult conditions (Bowdery 1989). Sophisticated Australasian phytolith publications were produced throughout the 1980s and early 1990s (Wallis and Hart 2003). Groundbreaking phytolith studies identified an important Holocene crop, *Musa* spp., at Kuk Swamp in Papua New Guinea (Wilson 1985) and wild rice (*Oryza* spp.) in archaeological and environmental assemblages from Kakadu National Park (Fujiwara et al. 1985). The former played a historic role in identifying the highlands of New Guinea as an early centre of the development of

Table 2 Synthesis of significant Australasian phytolith research 1984–1992

Researchers, references	Phytolith application	Specific region contributions	Specific native taxon contributions	Period
Bowdery (1984, 1989)	Archaeological; reference collection	Arid Australia		Modern; Holocene; Pleistocene
Fujiwara et al. (1985)	Archaeological; palaeoenvironmental	Kakadu National Park, NT Australia	*Oryza* spp. (wild rice cf. *O. australiensis*)	Holocene; Pleistocene
Wilson (1985)	Archaeological (interdisciplinary efforts); reference collection	Kuk Swamp, Papua New Guinea	*Musa* spp.	Modern; Holocene; Pleistocene
Fullagar (1986, 1991)	Archaeological (incl. use-wear and residue analyses); experimental			
Clark and Guppy (1988), Clark et al. (1992)	Palaeoenvironmental	Magela Creek Plain, NT Australia		Holocene
Hart (1988a, b, 1990)	Methods; pedological; reference collection	Oxford Falls, NSW Australia	Cyperaceae; Mimosaceae; Proteaceae; Casuarinaceae	Modern
Locker and Martini (1986)	Palaeoenvironmental	Australia; New Zealand; southwest Pacific		Pleistocene; Pliocene; Miocene
Boyd and Pretty (1989; 1991)	Archaeological; palaeoenvironmental	Roonka, SA Australia	*Phragmites australis* (Poaceae)	Holocene; Pleistocene

plant cultivation and domestication outside Eurasia, with mixed agricultural and horticultural practices (see Denham et al. 2003; Fuller et al. 2014; Golson et al. 2017). Significant prehistoric plant processing activities (Fullagar 1986, 1991) and funerary practices (Boyd and Pretty 1989; Boyd et al. 1991) on the Australian continent were identified using phytolith analyses during this era. Researchers also investigated deep-sea sites between Australia and New Zealand (Locker and Martini 1986). However, little reference collection work accompanied these studies.

Modern phytolith reference collections are a crucial precursor for positive identifications of past indicator phytoliths (Madella and Zurro 2007). Phytolith production patterns and the taxonomic relevance of phytolith morphotypes in modern plants must be understood prior to attempting to interpret ancient assemblages, or they cannot be assigned meaningful interpretive value. Phytolith reference collections must be highly specific to plant families and geographical localities, a laborious task (Cummings 1992; Ball et al. 1999; Wallis 2003a; Gallego and Distel 2004; Blinnikov 2005). Existing international studies on phytolith morphologies have limited relevance to Australasia, given the uniqueness of native Australasian taxa. Limited reference collections, in turn, limit our interpretations of phytolith assemblages (Bowdery 1989) leading to a substantial lag in the development of phytolith discrimination keys within Australasia, compared to advances made internationally in the decade earlier.

Phytolith analysts in America studied phytolith assemblages to trace prehistoric plant use and domestication (Pearsall 1982, 1989; Piperno 1984, 1985a, b, c, 1988, 1989, 2006; Piperno et al. 1985). For the first time, phytolith assemblages found in New World ceramics were used to trace the history of clay procurement and pottery manufacture (Bishop et al. 1982). New American research highlighted the robust preservation of taxonomically significant phytoliths in South American Tropical and Neotropical environments that were previously considered unfavourable for long-term plant fossil preservation due to heat, humidity and even aridity (Pearsall 1982, 1989; Piperno 1984, 1985a, b, c, 1988, 1989, 2006; Piperno et al. 1985). This shares parallels with Australasian environments also once considered unfavourable for preservation by the Australian archaeology community. Like American research, Australasian phytolith researchers started challenging these outdated notions regarding the lack of prehistoric plant preservation at this time (Bowdery 1989). However, Bowdery (1989) noted that phytolith research was not yet vigorously pursued in Australia in the late 1980s, with only two researchers actively involved in phytolith research. The two key figures of this period were Diane Hart and Doreen Bowdery (with collaborators), who promoted modern phytolith studies and advanced phytolith research in Australia, aligning their research with the international phytolith community's research directions by starting detailed reference collection work.

Hart (1988a, b, 1990) made vital contributions to pedological phytolith applications and Australian phytolith species classification criteria, investigating the role of phytoliths in the environment in terms of phytolith preservation, distribution and taphonomy. Phytolith research led by Hart also questioned species classification criteria when recording phytolith morphotypes found in native dicotyledons, documenting a phytolith morphotype established by the international phytolith community to be specific to Cyperaceae taxa in the leaves of modern Australian dicotyledon taxa (Hart 1990). Hart's most important phytolith research contribution was demonstrating how much is (and remains) unknown about the role of phytoliths in Australia's unique environments, through research that continued with collaborators into the 1990s.

Bowdery remains one of the leading experts in Australian phytolith research, who published the first comprehensive modern phytolith collection for Australian native taxa. Bowdery began publishing during the 1980s (Bowdery 1984, 1989), advocating to the wider Australian archaeological community that plant remains are preserved at Australian sites (Wallis and Hart 2003), and demonstrating the merits of the phytolith approach for reconstructing past plant use and vegetation histories. Bowdery's most important work was produced in the 1990s, the period when Australasian phytolith research officially came of age.

Coming of age: advances in Australasian phytolith research (1992–2004)

Phytolith studies in Australasia were enthusiastically pursued in the 1990s and early 2000s, with researchers producing high quality research with an extensive display of applications from across arid and tropical Australasia (Table 3). Wallis and Hart (2003) cite the first local meeting of Australian phytolith researchers; the high quality of research; and the increased number of universities adding phytolith research to undergraduate student studies, as evidence for the sub-field coming of age during this period. Processing methods improved and pedological applications continued, and significantly the improvement of local phytolith reference collections on native specimens enabled research to shift from presence/absence-based counts to more detailed quantitative analyses (Bowdery 1989, 1999). Much larger and more diverse modern reference collections were compiled, including plant species previously unknown to produce highly useful phytoliths (Wallis and Hart 2003), allowing phytolith research to be extensively applied to Australia's arid and semi-arid zones (Bowdery 1996, 1998; Wallis 2000, 2001, 2002, 2003a, b) and tropical regions (Lentfer 2003; Lentfer and Green 2004) for the first time. Due to this,

Table 3 Synthesis of significant Australasian phytolith research 1992–2004

Researchers, references	Phytolith application	Specific region contributions	Specific taxon contributions	Period
Hart (1992, 1997, 2001, 2003); Hart and Humphreys (1997); Humphreys et al. (2003); Simons (1998); Simons et al. (2000)	Chemical; pedological (interdisciplinary efforts incl. thin-section analyses); reference collection	Oxford Falls, Pilliga and Narrabeen NSW Australia		Modern
Bowdery (1996, 1998)	Archaeological (interdisciplinary efforts incl. dental calculus analyses); palaeoenvironmental; reference collection	Allen's Cave and Strzelecki Dunefield, SA; Puritijarra, NT Australia	120 modern specimens^{N}	Modern; Holocene; Pleistocene
Bowdery (1999)	Reference collection	Papua New Guinea; Malaysia	*Musa* spp.; *Metroxylon* spp. (Arecaceae); *Plectrachne* spp. (Poaceae); *Tetracera* spp. (Dilleniaceae); *Fimbristylis* spp. (Cyperaceae)^{N}	Modern
Bowdery et al. (2001)	Nomenclature			
Lentfer et al. (1997)	Archaeological; ethnographical; historical; reference collection	Hope Farm NSW Australia	*Zea mays* (Panicoid corn); *Triticum* sp. (wheat); *Avena* sp. (oat); *Hordeum* sp. (barley)^{I}; *Themeda australis* (Kangaroo grass)^{N} (Poaceae)	Modern; Historical
Lentfer (1997, 2003); Lentfer et al. (1997, 2003); Lentfer and Boyd (1998, 1999, 2000); Lentfer and Green (2004)	Archaeological (interdisciplinary efforts incl. starch, use-wear and residue analyses); methods; palaeoenvironmental; reference collection	Papua New Guinea incl. Kuk Swamp; Garua and Watom Island	2,275 modern specimens^{N}, esp. *Musa* spp.	Modern; Holocene
Thorn (2004a)	Palaeoenvironmental; reference collection	Long Pocket, QLD Australia	Arundinoideae Panicoideae and Chloridoideae^{N} (Poaceae)	Modern; Holocene
Thorn (2004b, c)	Reference collection; soil surface	Subantarctic New Zealand incl. Campbell Island & Tongariro National Park		Modern
Wallis (2000, 2001, 2002, 2003a, b); Clarkson and Wallis (2003a, b)	Archaeological; palaeoenvironmental (interdisciplinary efforts incl. thin-section analyses); palaeoclimatic; reference collection; soil surface	Kimberly, WA Australia incl. Carpetner's Gap 1; Northern Australia	338 modern specimens^{N}	Modern; Holocene; Pleistocene
Parr (2002, 2004); Parr et al. (2001a, b); Parr and Farrugia (2003)	Methods; reference collection			
Parr and Carter (2003)	Reference collection	Dauar Island, Torres Strait NE Australia	*Musa* spp.^{N}	Modern
Fullagar (1993); Fullagar and Field (1997); Field and Fullagar (1997); Field et al. (2002)	Archaeological (interdisciplinary efforts incl. pollen, starch, use-wear and residue analyses)	Cuddie Springs, NSW Australia; Jinmium WA Australia	Poaceae^{N}	Holocene; Pleistocene
Boettinger (1994)	Pedological	Northern QLD, Australia		Modern
Kondo et al. (1994)	Archaeological; reference collection; soil surface	New Zealand; Ross Sea (Antarctica)	76 modern specimens^{N}	Modern; Pleistocene
Kealhofer and Piperno (1994, 1998)	Archaeological; reference collection	Southeast Asia	377 modern specimens^{N}	Modern; Holocene
Boyd et al. (1998)	Archaeological; methods	Papua New Guinea		Modern; Holocene
Kealhofer et al. (1999)	Archaeological (interdisciplinary efforts incl. thin-section, use-wear and residue analyses)	Papua New Guinea		Modern; Holocene
Horrocks et al. (2000)	Archaeological/Palaeoenvironmental (interdisciplinary efforts incl. pollen)	Great Barrier Island, Northern New Zealand		Holocene
Denham et al. (2003)	Archaeological (interdisciplinary efforts incl. charcoal, diatom, pollen, starch and micromorphology analyses); reference collection	Papua New Guinea	*Musa* spp.^{N}	Modern; Holocene

^{I} Introduced, ^{N} Native

Australasian phytolith research was recognised for its ability to identify complex plant cultivation and plant-processing activities and was becoming a crucial component of multi-proxy archaeobotanical studies.

Determining best practices in phytolith processing methods has been a long-standing issue within the phytolith community, particularly how to effectively and consistently isolate phytoliths from plant materials and 'difficult' sediments and soils with high clay, peat or quartz components. Driven by Carol Lentfer and Jeffrey Parr, a series of processing and pre-treatment techniques were developed and tested to enhance the visibility of phytoliths under the microscope and remove potential contamination (Lentfer 1997; Lentfer and Boyd 1998, 1999, 2000; Parr et al. 2001a, b; Parr 2002, 2004; Lentfer et al. 2003; Parr and Farrugia 2003). In particular, the chemical and equipment recommendations offered by Parr (2001a, b, 2002, 2004) and colleagues (Parr et al. 2001a, b, 2003) during this time were methodological innovations for the international phytolith community. Lentfer and Parr established strong research clusters at the University of Queensland and Southern Cross University.

Hart (1992, 1997, 2001, 2003), Humphreys et al. (2003), Simons (1998; et al. 2000), Boettinger (1994) and colleagues continued research into how phytoliths are deposited into soils and preserve in Australia, studying the effect of taphonomy, bioturbation, soil mobility, elements and fire in phytolith deposition. Hart's research was primarily based in the Pilliga region (NSW) in non-archaeological contexts (Hart 1992, 1997, 2001, 2003) and argued for movement of phytoliths in Australian contexts. However, the Pilliga assemblages are likely an exceptional example of phytolith taphonomy in sediments (Bowdery 1999). Thin section sampling was implemented in these pedological studies (Hart and Humphreys 1997; Simons 1998; Simons et al. 2000; Hart 2003; Humphreys et al. 2003), to strengthen inferences about phytolith deposition processes. Aside from Hart and colleagues (Hart and Humphreys 1997; Simons 1998; Simons et al. 2000; Hart 2003; Humphreys et al. 2003), Wallis (2000) and Kealhofer et al. (1999) are the only other Australasian phytolith researchers during this period exploring phytolith analyses with micromorphological techniques, by using thin sections to provide in situ details about phytoliths within sediments from different geogenic and anthropogenic features. Hart focuses on pedological applications and does not continue any modern reference work during this period, meanwhile, three major modern phytolith reference collections are constructed by Bowdery, Wallis and Lentfer.

Bowdery was the first to successfully apply phytolith analysis to Australia's arid zone during this period with her PhD thesis (Bowdery 1996) which later became a monograph (Bowdery 1998) examining sites in the Puritjarra, the Strzelecki Dunefields and the Nullabor Plain. A large modern reference collection consisting of phytoliths extracted primarily from the leaves of 120 modern native plant specimens from central and southern Australia's arid zone was a critical component of Bowdery's research. Bowdery assessed each plant specimen for phytolith content and developed a classification key to identify phytolith morphotypes. These phytoliths were then compared to phytoliths found in sediments from archaeological sites such as Allen's Cave and Puritjarra, with human occupation extending back at least 20,000 years and 37,000 years respectively. Phytolith analysis was also applied to samples obtained from the dental calculus of burials at Roonka (Bowdery 1996, 1998). Bowdery demonstrated for the first time that phytoliths in Australia's arid zone can effectively provide information regarding vegetation change when no other palaeoenvironmental information is available.

Lynley Wallis continued the research directions of Bowdery, extending Australasian modern reference collection work into tropical and semi-arid northwest Australia as part of her PhD, allowing for new archaeological and palaeoenvironmetal applications. Wallis also focused primarily on the leaves of specimens (due to sample availability), extracting phytoliths from 229 species of tropical/arid Australia plants, mostly from the Kimberly region (Wallis 2000). The reference collection was tested by analysing phytolith assemblages recovered from modern surface sediments from different ecological and vegetational settings, similar to Baker's (1959b) original approach. Correspondence was observed, but many soil phytolith assemblages did not match phytolith assemblages found in surface vegetation (Wallis 2000; also republished in 2013). Co-concurrently, significant progress is made in phytolith applications in Queensland, Australia (Thorn 2004a), and continental (Kondo et al. 1994) and sub-Antarctic New Zealand (Thorn 2004b, c), using modern reference collections and the same modern surface sediments testing method used by Baker (1959a, b, c) and Wallis (2013, 2000).

Unlike Hart (1990), in her reference collection Wallis did not observe the phytolith morphotype considered diagnostic for Cyperaceae in Australian dicotyledon taxa, but Wallis does argue for a diagnostic phytolith for the *Triodia* genus in the Poaceae family. Wallis then applied phytolith analyses to sediments from Carpenter's Gap 1, an archaeological site with an occupation sequence spanning ~ 43,000 years (Wallis 2000, 2001, 2002, 2003a, b). Wallis' phytolith investigations created a long-term history for this region, documenting water availability changes and shifts in vegetation.

Lentfer undertook extensive comparative reference collection research examining the phytoliths produced by modern economic and wild flora of Papua New Guinea to assess potential for archaeological and palaeoenvironmental reconstruction as part of her PhD (Lentfer 2003). This remains the largest Australasian reference collection ever assembled with 2,275 samples from 731 plant species. Lentfer's reference collection was compared to phytolith assemblages from sediments excavated from key Holocene archaeological sites, including Kuk Swamp and other sites on Garua Island and Watom Island, to investigate the origins of agriculture, horticulture, and other subsistence patterns (Lentfer 2003). Outside of the Pacific, Lentfer also used phytoliths to investigate agricultural practices at an archaeological site in Australia from the historical period (Lentfer et al. 1997).

One of Lentfer's (2003; with Green 2004) lasting contributions is recommencing Australasian phytolith research of *Musa* spp. cultivation and domestication, as part of the 'New Guinea Banana Project' (see Lentfer 2009), which built upon Wilson's (1985) foundational research nearly two decades earlier at Kuk Swamp. This included the development of new detailed phytolith discrimination keys for *Musa* spp. (Lentfer 2003; Lentfer and Green 2004), which enabled new interpretations beyond just presence-absence observations. During this period, Parr (with Carter 2003) and Bowdery (1999) are simultaneously working on *Musa* spp. phytolith research in other Australasian regions. Lentfer's phytolith research formed part of revitalising new interdisciplinary research at Kuk Swamp, which in collaboration with Denham et al. (2003) integrated phytolith analyses with charcoal, diatom, pollen, and starch analyses. These collaborative efforts continued into the 2000s. Cuddie Springs in semi-arid Australia, is another key archaeological site where an interdisciplinary approach was adopted during this period, by integrating phytolith analyses with pollen, starch, use-wear and residue analyses (Fullagar 1993; Field and Fullagar 1997; Fullagar and Field 1997; Field et al. 2002).

Advances in international phytolith research during the 1990s enabled high-resolution identification of phytoliths found in archaeological and palaeoenvironmental sediments. Phytolith studies globally developed stringent diagnostic criteria with detailed descriptions and comparison of morphological attributes from closely related taxa including major economic crops and their wild ancestors (Kaplan et al. 1992; Rosen 1992; Ball et al. 1993, 1996, 1999; Rosen and Weiner 1994; Pearsall 1995; Zhao et al. 1998; Iriarte 2003). Phytolith research in Australasia followed this trend and actively influenced global research directions and debates, as particularly evident in Australasian phytolith discrimination studies of *Musa* spp. (Bowdery 1999; Denham et al. 2003; Lentfer 2003; Parr and Carter 2003; Lentfer and Green 2004; Piperno 2006; Lentfer 2009; Vrydaghs et al. 2009; see Ball et al. 2016) previously discussed.

Phytolith nomenclature and processing methods are other areas of Australasian phytolith research that actively influenced international phytolith directions and debates during this period. Historically, phytolith researchers used different terminologies for phytolith morphotypes, creating confusion and great difficulty comparing phytolith results from different studies. Many studies frequently borrowed terms indiscriminately from botanical and palynological literature (Bowdery 1999; Piperno 2006). Australian phytolith analysts developed universal phytolith keys during this period, clarifying and standardising phytolith naming protocols (Bowdery et al. 2001), and providing a basis for later development of an international phytolith nomenclature outlined in the first edition (2015) of the International Code for Phytolith Nomenclature (ICPN) by the International Committee for Phytolith Taxonomy (ICPT).

Consolidation of Australasian phytolith research (2005-present)

Despite Wallis and Hart describing Australasian phytolith research as finally coming of age in 2003, phytolith research in Australasia has slowed down considerably, indicating that 1992–2004 was a peak period of research. Phytolith analyses have sporadically continued to be applied to archaeological and palaeoenvironmental research in recent years (2005-present) (Table 4) with an increasing amount of interdisciplinary studies, but modern reference work has diminished substantially. Modern reference work was undertaken on the flora of eastern Australia (Parr and Watson 2007), and morphometric discrimination keys have been developed for other tropical flora such as Arecaceae (Fenwick et al. 2011) and *Musa* spp. (Horrocks et al. 2008), signalling a shift in Australian phytolith research around 2007, from arid and tropical Australasian studies to more tropical and coastal environments. Moreover, phytolith reference collections for new localities, large enough for comprehensive archaeological and environmental reconstructions, have not been developed in the last decade. Since 2005, 2.1 Australasian phytolith publications have come out per year (mean) (Fig. 3), in contrast to the 3.61 of the previous period (1992–2004). Leading researchers of the previous period of Australasian phytolith research have continued to publish modern (Thorn 2006, 2008; Wallis 2013), historic (Bowdery 2007; Denham et al. 2012), ancient (Lentfer et al. 2013, 2021; Bowdery 2015) and chemical-based (Parr 2006; Parr et al. 2009, 2010; Parr and Sullivan 2011, 2014) studies with important interpretations for archaeology and palaeoecology.

Where other applications decreased in the mid-2000s and 2010s, understanding the chemistry and isotopic signatures of phytoliths was a thriving area of Australasian phytolith research. International phytolith research has demonstrated that isotopic signatures of phytoliths can potentially be used as proxies in archaeology and palaeoecology, but some procedural issues have emerged (Sangster et al. 2001; Piperno 2016; Hodson 2016). Phytolith chemistry was globally explored in studies from the 1960s to the 1980s (see Jones and Beavers 1963; McKeague and Cline 1963; Siever and Scott 1963; Hopps et al. 1977; Hodson et al. 1985; Perry

1989) including some work from Australian researchers (Jones and Handreck 1963, 1965b, 1967), which then expanded internationally in the 2000s with more comprehensive botanical and physiological research (see Hodson and Sangster 2002; Hodson et al. 2008; Leng et al. 2009; Hodson 2016; Piperno 2016). Australian researcher Jeffrey Parr studied the uptake of carbon in phytoliths (PhytOC) from native Indo-Pacific and introduced Eurasian economic species, the findings of which had global importance for isotope studies, dating of sediments and understanding how plants capture and store carbon (Parr 2006; Parr et al. 2009, 2010; Parr and Sullivan 2011, 2014).

Parr was one of the first phytolith researchers to assert that PhytOC contributes substantially to the global carbon cycle, which holds great relevance regarding discussions surrounding climate change, and the management of economic and wild plants. This research had an exponential impact on the international phytolith community, igniting intense debate about the validity and limitations of phytoliths for radiocarbon dating and isotopic reconstructions in archaeology and palaeoecology (Piperno 2006). Parr's research influenced further international research, particularly in China where research was revitalised in 2010 after earlier efforts in the 1990s (Zuo and Lu 2019; Yang et al. 2020). Other Australian chemical-isotope phytolith applications from this time come from Alexandre et al. (2012), who studied the oxygen isotopic composition of woody phytoliths from tropic rainforest soils along altitudinal gradients in northern Queensland. Findings from this research suggests that the $\delta^{18}O$ signature of woody phytoliths are a potential proxy for annual soil water and temperatures. After Alexandre et al. (2012) and the efforts led by Parr (Parr 2006; Parr et al. 2009, 2010; Parr and Sullivan 2011, 2014), Australian phytolith chemical and isotopic applications have not continued. However, despite a decline in important areas of Australasian phytolith research during the last decade, phytoliths are more frequently included in interdisciplinary archaeobotanical and micromorphological research efforts.

Interdisciplinary research efforts using multi-proxy approaches including phytolith analyses have continued at Cuddie Springs (Fullagar et al. 2008) and Kuk Swamp (Fullagar et al. 2006; Lentfer 2009; Haberle et al. 2012; Denham and Grono 2017; Golson et al. 2017; Lentfer and Denham 2017). New archaeological and palaeoecological studies using multi-proxy analyses emerge during this period, investigating sites from coastal and arid Australia (Fullagar and Wallis 2012; Taffs et al. 2010; Lentfer et al. 2013), island Melanesia and Polynesia (Horrocks et al. 2008, 2014, 2017; Horrocks and Nunn 2007; Horrocks and Rechtman 2009; Kahn et al. 2014; Lentfer et al. 2021), and the Torres Strait (Williams et al. 2020). The latter used phytoliths analyses (coupled with other proxies), to identify *Musa* spp. crops, providing evidence for extensive low-intensity plant management in the Torres Strait over 2,000 years ago. The new array of interdisciplinary research signifies that studies of phytoliths alongside other plant remains have begun to find its place in Australasian archaeology and palaeoecology. In particular, the integrated multi-proxy archaeobotanical (Fullagar et al. 2006; Haberle et al. 2012; Golson et al. 2017) and micromorphological (Denham and Grono 2017) approach at Kuk Swamp serves as a benchmark for Australasian archaeological and palaeoecological research, exemplifying the strength and complementary nature of investigating all available plant remains. This research is globally significant to understanding the spread of agricultural and horticultural practices in the Indo-Pacific, the geo-domestication pathways of banana cultivars and vegetative domestication processes in tropics and subtropics (Lentfer 2009; Perrier et al. 2011; Fuller et al. 2014; Golson et al. 2017; Lentfer and Denham 2017; Denham et al. 2020).

During the last decade integrated phytolith-micromorphological research has also garnered interest, not only in Papua New Guinea (Denham and Grono 2017), but on the Australian continent at Carpenters Gap (Vannieuwenhuyse et al. 2017), Riwi Cave (Whitau et al. 2018), and Glendswood Shelter 1 (Lowe et al. 2018). Integrated phytolith-micromorphological analyses developed globally around the 2010s as an important technique to understand stratigraphic control, in situ decay, and depositional and post-depositional processes, which strengthen phytolith interpretations (Goldberg et al. 2009; Albert et al. 2012; Weiner 2010; Shillito 2011; see Shillito 2013). Australasian studies over the last decade, however, have been interdisciplinary efforts limited to providing phytolith concentrations or noting the inclusion of phytoliths (presence/absence information) (Denham and Grono 2017; Vannieuwenhuyse et al. 2017; Whitau et al. 2018; Lowe et al. 2018). While these formative phytolith-micromorphological analyses represent an important starting point, no detailed interpretations have been produced, making integrated phytolith-micromorphological applications underutilised in Australasia.

Adjacent to international advancements in integrated-phytolith research, international phytolith researchers have also continued addressing global questions surrounding the origins, development and spread of agriculture (Piperno 2006; Ball et al. 2016), often using phytolith discrimination keys to do so (Ball et al. 2006, 2009, 2016; Portillo et al. 2006; Lu et al. 2009; Zhang et al. 2011; Shakoor and Bhat 2014; Out and Madella 2016). Australasian interest in phytolith discrimination key applications (Horrocks et al. 2008; Fenwick et al. 2011) is relatively brief from 2005-present, when compared to ongoing international efforts, and like chemical and isotopic applications, have ceased in the last decade. Recent international efforts have resulted in large modern reference collections that have enabled the identification of more genus or species-specific phytoliths (Piperno

Table 4 Synthesis of significant Australasian phytolith research 2004–2022

Researchers, references	Phytolith application	Specific region contributions	Specific taxon contributions	Period
Thorn (2006, 2008)	Reference collection; soil surface	Subantarctic New Zealand incl. Campbell Island and Tongariro National Park		Modern
Parr and Watson (2007)	Reference collection	Eastern Australia	Gymnosperms (7 species)^{N}	Modern
Parr et al. (2009, 2010); Parr and Sullivan (2011)	Chemical		*Saccharum* (sugarcane); Bambusoideae (bamboo)^{N}; *Triticum* spp. (wheat cultivars) ^{I} (Poaceae)	Modern
Parr 2006; Parr and Sullivan (2005; 2014)	Chemical; methods			Modern
Lentfer (2009); Lentfer et al. (2013, 2021); Lentfer and Denham (2017)	Archaeological (interdisciplinary efforts incl. starch/use-wear and residue analyses)	Lizard Island, NE QLD Australia; SE Solomon Islands incl. Reef and Santa Cruz Islands	*Australimusa*; *Eumusa*; *Metroxylon* sp. (sago palm)^{N}	Modern; Holocene
Bowdery (2007)	Archaeological; historical	Ambathala, QLD Australia		Historical
Bowdery (2015)	Palaeoenvironmental; reference collection	Rapa Nui (Easter Island)	Arecaceae^{N}	Modern; Historical; Holocene
Denham et al. (2012)	Archaeological	Willunga Plains, SA Australia		Historical
Fullagar et al. (2008); Fullagar and Wallis (2012)	Archaeological (interdisciplinary efforts incl. starch/use-wear and residue analyses); reference collection	Cuddie Springs, NSW Australia; Pilbara WA Australia		Pleistocene; Holocene; Modern
Fullagar et al. (2006); Haberle et al. (2012); Denham and Grono (2017); Golson et al. (2017)	Archaeological (interdisciplinary efforts incl. charcoal, diatom, pollen, starch and micromorphology analyses); geoarchaeological; reference collection	Kuk Swamp, Papua New Guinea		Modern; Holocene
Krull et al. (2006)	Soil chemistry	Gartners Vineyard, SA Australia		Modern; Holocene
Horrocks and Nunn (2007); Horrocks and Rechtman (2009); Horrocks et al. (2008, 2017); Kahn et al. (2014)	Archaeological (interdisciplinary efforts incl. dental calculus, pollen and starch analyses); reference collection	Fiji; Hawaii; New Zealand; Papua New Guinea; Rapa Nui; Society Islands; Vanuatu	*Musa* spp.^{N}	Modern; Holocene
Fenwick et al. (2011)	Archaeological; reference collection	SE Asia/Oceania; Papua New Guinea incl. Watom Island	*Areca catechu*; *Calamus aruensis*; *Cocos nucifera*; *Metroxylon sagu* (Arecaceae)^{N}	Modern; Holocene
Alexandre et al. (2012)	Palaeoenvironmental; elemental/isotopic	Northern QLD Australia	Woody plants ^{N}	Modern
Moravek et al. (2012)	Palaeoenvironmental; reference collection	Bunya Mountains QLD Australia	*Phragmites australis*; *Poa* spp.^{N} (Poaceae)	Modern; Holocene
Taffs et al. (2010)	Palaeoenvironmental (interdisciplinary efforts incl. pollen and diatom analyses)	Bryon Bay, NSW Australia		Holocene; Pleistocene
Wallis (2013) (republished data from 2000)	Soil surface	SW Kimberly, WA Australia		Modern
Field et al. (2016)	Archaeological (interdisciplinary efforts incl. use-wear and residue analyses); ethnographical	NE QLD Australia		Historical; Holocene
Vannieuwenhuyse et al. (2017); Whitau et al. (2018)	Archaeological (interdisciplinary efforts incl. micromorphology analyses); geoarchaeological	Riwi Cave; Carpenters Gap 1 shelter; Carpenters Gap 3 cave, WA Australia		Holocene; Pleistocene
Lowe et al. (2018)	Archaeological (interdisciplinary efforts incl. micromorphology and FTIR analyses); geoarchaeological	North QLD Australia		Holocene; Pleistocene
Williams et al. (2020)	Archaeological (interdisciplinary efforts)	Mubuyag Island, Torres Strait NE Australia	*Musa* spp.^{N}	Holocene
De Tombeur et al. (2021)	Soil chemistry	Jurien Bay; Guilderton, WA Australia		Holocene; Pleistocene

^{I}Introduced, ^{N}Native

2006), reinforcing the value of establishing large modern sample collections for systematic baseline reference work. Between 2005 and 2011, five major Australasian phytolith reference collections investigating native taxa were published (Parr and Watson 2007; Horrocks et al. 2008; Fenwick et al. 2011) and none have been published since. Furthermore, there has been no re-evaluation of existing reference collections using modern techniques to glean further insights into their morphometric variability. As a direct result, Australasian phytolith research now lags behind the rest of the world in our ability to differentiate between and within Australasian endemic plant families. Until further Australasian reference collections are established and baseline morphometric analyses are completed, our ability to move beyond broad interpretation of Australasian phytolith assemblages towards higher quality, family or even species-specific resolution will be limited.

Phytoliths are dispersed in most organs of phytolith-producing plants, including leaves, inflorescence bracts, bark, stems, roots/rhizomes and other parts, and reference collections should reflect this (Shakoor and Bhat 2014). Not all plants are prolific producers of phytoliths, but this varies within and between families (Piperno 2006). Hence, phytolith reference collections should endeavour to sample all respective parts for an optimal evaluation of phytolith production patterns and morphologies, when parts are available and logistically possible. Only leaf specimens are typically investigated for phytolith production in most Australasian reference collection research (Hart 1990; Bowdery 1996, 1998; Wallis 2000; Parr and Watson 2007), often due to sample availability, thus limiting our knowledge of phytolith production in Australian flora. International phytolith studies do not only investigate leaves, and in recent decades have particularly focused on examining inflorescence phytoliths in Poaceae, where phytolith production tends to be greatest. The phytoliths produced in different components of the inflorescence, such as the glumes, lemma and palea, were found to have morphological characteristics that can distinguish specific wild species from domesticated species (Ball et al. 2006, 2009, 2016; Lu et al. 2009; Le Moyne et al. 2023a, b).

The ability to differentiate phytoliths at finer taxonomic levels has benefited from standardised phytolith nomenclature culminating in the second edition of the ICPT which provided further clarity on confusion surrounding phytolith morphotypes (ICPT 2019). Early Australasian phytolith research, conducted prior to standardised phytolith nomenclature, contained some uncertainty, speculation and subjectivity due to the plethora of terms that existed to describe phytolith categories (Bowdery 1999; Piperno 2006) Modern phytolith nomenclature employs universal, non-subjective and geometric terms, to better understand and clarify which phytolith categories belong to which plant taxa (ICPT 2019).

Pollen tends to be favoured over other plant remains for palaeovegetation reconstructions in Australasia (Thomas et al. 2001; Field et al. 2002; McKenzie 1997; Cupper 2005; Darrénougué et al. 2009; Mackenzie et al. 2020; De Deckker et al. 2021). Pollen degradation has been widely documented in inland Australia, likely contributing to the lack of information regarding arid Australasian vegetation dynamics and plant-use (Cupper 2005). The study of other past plant remains (i.e. wood charcoal, macrofossils, starches and residues) in Australasian archaeology and palaeoecology has broadly followed a similar trajectory to phytoliths, from historically being marginalised from mainstream practice, to making significant international contributions in the 1990s and 2000s (Loy 1990; Loy et al. 1992; Hather 1991, 1994, 2000; Fullagar and David 1997; McConnell and O'Connor 1997; McConnell 1998). However, while Australasian phytolith studies have lost momentum in recent years (2005-present), studies of other past plant remains have flourished. There have been noteworthy advancements in studies of wood charcoal (anthracology) (Byrne et al. 2013, 2021; Dotte-Sarout et al. 2015; Wood et al. 2016; Whitau et al. 2017), starches, residues, use-wear (Wallis et al. 2020; Hayes et al. 2021, 2022) and macro-botanical remains (Dilkes-Hall et al. 2019; Fairbairn et al. 2006; Florin et al. 2020, 2021, 2022), in particular fruits, nuts (Fairbairn and Florin 2022) and underground storage organs (Lewis et al. 2016; Pritchard et al. 2019; Barron et al. 2022) (see Denham et al. 2022).

Summary and future directions

This paper is a testament to the progress that Australasian phytolith research has made from confused and intermittent beginnings in the early twentieth century. Australasian phytolith research went on to make significant global contributions to archaeology and palaeoecology in the 1980s, 1990s and 2000s. In our historiographical review we have defined five periods of Australasian phytolith research, which is summarised below:

1. Mistaken identity—the early arrival of phytoliths in Australia (1903–1959)

Phytolith research starts in Australasia with infrequent references to plant silica in early forestry/agronomy and earth science-based literature. Earth science studies most frequently misidentify phytoliths as 'sponge spicules' throughout the 1930s–1950s.

2. Formal phytolith research—fundamental studies in Australia and globally (1959–1980)

This period, led by George Baker, is characterised by foundational earth science-based phytolith research. While this research is often allied with archaeology and palaeoecology, there is a strong interest in modern agricultural applications, with researchers yet to explicitly consider the deep past.

3. Entering the deep past—the modern period of Australasian archaeological and palaeoenvironmental research (1984–1992)

Australasian phytolith research directions shift to explicitly considering the deep past, with studies using phytoliths to reconstruct Pleistocene and Holocene plant-use and vegetation histories. There are some early modern reference efforts during this period were led by Hart and Bowdery.

4. Coming of age—advances in Australasian phytolith research (1992–2004)

Phytolith research cements its place in Australasian archaeology and palaeoecology. This period is characterised by improvements in processing methods and nomenclature, and a shift from presence/absence-based counts to more detailed quantitative analysis, which was empowered by the development of detailed reference collections on native specimens. Large collections for tropical and arid Australasia are developed by leading researchers such as Doreen Bowdery, Carol Lentfer and Lynley Wallis.

5. Consolidation of Australasian phytolith research (2005–present)

Recent years have had more sporadic phytolith studies with some continuation of the strong efforts of the previous period. Influential chemical/isotope phytolith research emerges in the 2000s, led by Australian researcher Jeffrey Parr, but does not continue after 2014. Large, localised reference collections for comprehensive archaeological and palaeoecological reconstructions are no longer being produced. Despite this, phytoliths are increasingly used in interdisciplinary studies, perhaps not yet to their full potential.

Collectively, the historic efforts of Australasian phytolith research achieved global significance by providing direct evidence for early Australasian plant cultivation and processing activities in the Pleistocene and Holocene (Wilson 1985; Fullagar 1986, 1991; Boyd and Pretty 1989; Boyd et al. 1991; Bowdery 1999; Denham et al. 2003; Lentfer 2003; Parr and Carter 2003; Lentfer and Green 2004; Williams et al. 2020), both challenging and overturning long-held attitudes relating to Indigenous People and their environment and Country. Particularly, the collective importance of Australiasia's long-history of *Musa* spp. phytolith research from the 1980s to present (Wilson 1985; Bowdery 1999; Denham et al. 2003; Lentfer 2003; Parr and Carter 2003; Lentfer and Green 2004; Horrocks et al. 2008; Williams et al. 2020) cannot be overstated in terms of its global influence on phytolith, archaeobotanical and archaeological research (see Lentfer 2009; Vrydaghs et al. 2009; Fuller et al. 2014; Ball et al. 2016; Golson et al. 2017; Denham et al. 2020). Much foundational scientific research was led by women such as Doreen Bowdery, Diane Hart, Lynley Wallis, Vanessa Bowman (nee Thorn), Carol Lentfer and Lisa Kealhofer, who in addition to conducting ground-breaking research, also published reviews (Bowdery 1989; Wallis and Hart 2003) and contributed to early international phytolith nomenclature efforts (Bowdery et al. 2001). This formed the basis of modern phytolith research in Australasia. Jeffrey Parr also made internationally important contributions to our understanding of phytolith chemical and isotopic applications, and offered extraction methods still widely used today (Piperno 2006).

Quality phytolith research is still being carried out at major Australian research centres. The Australian National University and The University of New South Wales continue to produce applied phytolith studies from archaeological sites in Australia and the Pacific. The legacy of the University of Queensland and Southern Cross University phytolith researchers endures today with the University of Queensland's School of Social Sciences Archaeobotany Reference Collection, which houses Australasian phytolith reference material with a focus on tropical flora. The school also has a specialised starch and phytolith chemical extraction laboratory, which currently pursues new methodologies and techniques (Le Moyne and Crowther 2021) and applications to archaeological sites in Australasia (Lentfer et al. 2021) and outside Australasia (Le Moyne et al. 2023a, b). This reflects the long-tradition of Australasian-based researchers at various institutions making significant global contributions to regions outside Australasia, further discussion of which being outside the scope of this review.

Much remains unknown about phytoliths in Australasia's unique environments. Revitalising Australian phytolith research will require highly localised modern reference collections to enhance analyses of phytoliths from sediments, artefacts and other contexts. New Australasian reference collections that include all plant parts (not only leaves), will likely uncover more diagnostic morphotypes (ICPT 2019), that will enable higher quality taxonomic resolution. Phytolith analyses need to be incorporated at the beginning stages of planning fieldwork and projects and not merely considered post-excavation (Denham et al. 2009). There are enormous opportunities for phytolith applications in Australasia to investigate the complexities of past human–environment interactions. Phytolith analyses can reconstruct how people settled early and more recent landscapes of Australasia using specialised floristic resources and the vegetation communities they adapted to, in some of the oldest localities continuously occupied by people in the world (Clarkson et al. 2017). Without considering phytolith applications, especially in the absence of other plant remains, archaeobotanical and palaeoecological interpretations in Australasia will be limited.

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