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From gathering to farming in semi-arid Northern Gujarat (India): a multi-proxy approach

Juan José García-Granero Fos

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FROM GATHERING TO FARMING IN SEMI-ARID NORTHERN GUJARAT (INDIA): A MULTI-PROXY APPROACH

PhD dissertation by

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For the degree of

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Programa de doctorat *Societat i Cultura*

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To Júlia and Bruc, and to that little place in their hearts I like to call home

“Food is the bridge between nature and culture”

Alex Atala, cook

In “The Jungle Cook. How Brazil’s Alex Atala braised his inner beast”, by Lisa Abend. *Time*. October 21, 2013.

Acknowledgements

People say this is the hardest part of the PhD, and now I understand why. After postponing this until the very last minute it's time to finally say thanks to all those people who have helped me throughout this long journey. When writing the acknowledgments for my MSc dissertation (September 2011) I said I was looking forward to the amazing things that were going to happen in the following four years. Well, here we are, three and a half years later, and we certainly did good things. For all their support, their understanding and their patience, I am of course very grateful to my supervisors, but also to all those other people (CaSErs and non-CaSErs alike) who have been at the lab at some point for their willingness to share their experiences and to listen to my never-ending questions. I am also in debt with the members of the NoGAP project and other people at the MSUB for the good times spent in the field, their collaboration during the archaeobotanical sampling and our endless discussions about South Asian archaeology.

There are of course many people who should take much credit for this PhD (friends, family…), but above them all there is Júlia. She is the one who kept me on track, who understood me when I couldn't and who supported me beyond reasonable standards. For all these reasons and much more, I can only say *gràcies*.

Abstract

Understanding how human societies adapted to past environmental and climatic variability is fundamental to face present and future climatic events, particularly in highly vulnerable arid and semi-arid regions. Northern Gujarat (northwestern India) is a semi-arid ecotone where high intra- and inter-annual precipitation variability has a great impact on the availability of resources and, consequently, on human populations that depend upon them.

The main aim of this thesis is to understand how and why plant-related subsistence strategies changed throughout the Holocene in northern Gujarat, with special emphasis on the transition from gathering to farming. This study considers macro and microbotanical remains from two hunter-gatherer occupations (Vaharvo Timbo and the Mesolithic levels at Loteshwar) and two agro-pastoral camps (Datrana IV and the Anarta levels at Loteshwar) to understand how early and middle Holocene populations interacted with the environment in terms of livelihood strategies. Moreover, archaeobotanical remains from one late Holocene urban settlement (Shikarpur) are also analysed to ascertain how urban societies exploited this semi-arid environment in terms of plant acquisition and consumption.

The results show that hunter-gatherer groups that inhabited northern Gujarat during the early-mid Holocene exploited a wide range of wild plants originating from (semi)permanent water bodies, including grasses, pulses, sedges, tubers and sesame. The progressive weakening of the Indian Summer Monsoon ca. 7000 years ago compelled human populations to adopt semi-nomadic pastoralism and plant cultivation, which resulted in the domestication of several small millet species, pulses and sesame. With the advent of settled urban life in the late Holocene the inhabitants of northern Gujarat developed a more intensive land-use strategy involving a cereal-pulse intercropping agricultural system.

This study is an illustrative example of human adaptation to climatic and environmental changes in semi-arid regions. From a methodological perspective, the results of this thesis show that an integrated multi-proxy approach, in which several botanical proxies and a broad-spectrum sampling strategy are used together, is the best possible way to explore diet and plant use strategies in past societies. Future research will integrate archaeobotanical data in a multi-disciplinary perspective to help designing sustainable land use strategies in northern Gujarat and other marginal areas worldwide.

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I. Introduction

1. Presentation

This chapter introduces the context of this thesis, including the research group, the projects and the funding bodies. Moreover, it summarises the research papers included in this thesis and presents the thesis outline.

1.1. Research context

This thesis was carried out at the Complexity and Socio-Ecological Dynamics Research Group (CaSEs), Department of Archaeology and Anthropology, Institució Milà i Fontanals, Spanish National Research Council (IMF-CSIC, Barcelona, Spain). CaSEs' objectives include: a) studying the relationships between human societies and their ecological settings within a long-term perspective, b) applying quantitative methods for the development of models of social dynamics, and c) promoting new transdisciplinary research for improving our understanding of cultural change.

This research project is framed within the North Gujarat Archaeological Project (NoGAP), a collaborative initiative between the IMF-CSIC and the Department of Archaeology and Ancient History, The Maharaja Sayajirao University of Baroda (MSUB, Vadodara, India). The project promotes an interdisciplinary approach, integrating environmental, archaeological and ethnoarchaeological data to study social contacts, resource use and cultural landscape in a long-term perspective (Madella et al. 2010). The archaeological samples analysed in this work come from three sites excavated within the NoGAP project: Loteshwar (October-December 2009), Datrana IV (November-December 2010) and Vaharvo Timbo (November-December 2011). Part of the modern plant material analysed in this study was also collected during these field seasons, which were funded by the Spanish Ministry of Education, Culture and Sport (Programa de Ayudas para Proyectos Arqueológicos en el Exterior 2009, 2010 and 2011) and the Catalan Government (Programa EXCAVA 2009). As part of the collaboration between the IMF-CSIC and the MSUB I also collected archaeobotanical samples during the 2012 field season at Shikarpur (January-February 2012), conducted by the Department of Archaeology and Ancient History, MSUB and funded by the Archaeological Survey of India.

Laboratory work was carried out at the BioGeoPal Laboratory (IMF-CSIC) and funded by the former Spanish Ministry for Science and Innovation (Programa I+D) through the POBLARE project ("Poblamiento, recursos y medioambiente en zonas áridas: el Norte del Gujarat como caso de estudio" – HAR2010-16052), coordinated by Marco Madella. This research also benefitted from the synergies created within the SimulPast project ("Social and environmental transitions: simulating the past to understand human behaviour" – CSD2010-00034), funded by the Spanish Ministry of Economy and

Competiveness (Programa CONSOLIDER INGENIO 2010) and also coordinated by Marco Madella.

During the development of this thesis I was funded by a JAE-DOC PhD scholarship from the Spanish National Research Council and the European Social Fund (September 2011 – August 2015). I also received funding from the JAE programme to spend two months as a visiting researcher at the MSUB in 2012. My research stay at the MSUB in 2013 was funded by the POBLARE project, as was my participation in numerous international scientific conferences.

1.2. Thematic unity of the research papers

This thesis is presented as a compilation of six papers published in peer-reviewed international journals. Some papers are methodological and some are data-driven, and all share an ultimate goal: understanding the role of plant resources in the subsistence strategies of Holocene populations in northern Gujarat.

Plant biogeography and previous archaeobotanical research showed that millets were a pivotal resource for the inhabitants of northern Gujarat, as is the case nowadays. Within archaeobotany, millets have received relatively little attention compared to major cereals, and therefore it was necessary to create a detailed reference collection of modern plants. This was developed at two levels: morphological and morphometric analyses of microbotanical remains (phytoliths and starch grains) and a geometric morphometric (GM) analysis of small millet caryopses. The work with modern reference material resulted in the publication of two papers, one for the microbotanical remains (using only modern material) and one for the GM analysis (comparing both modern and archaeological material). The former was published in *Archaeological and Anthropological Sciences* (Madella et al. 2013), whereas the latter is currently under review in *Vegetation History and Archaeobotany* (García-Granero et al. submitted a). Subsequent work with reference material was not published in specific papers but included as part of the case study papers.

Four archaeological data-driven papers are included in this thesis. The first presents the results of archaeobotanical analyses from Shikarpur while, at the same time, discussing the benefits of integrating macro and microbotanical remains to understand past subsistence strategies (García-Granero et al. 2015, *Vegetation History and Archaeobotany*). The archaeobotanical results from Loteshwar and Vaharvo Timbo are discussed in the framework of the origins of plant cultivation in northern Gujarat (García-Granero et al. in press, *Current Anthropology*), whereas the archaeobotanical remains from Datrana IV are considered together with the mineralogical analysis of sediments to understand plant consumption and taphonomic processes in a lithic blade workshop (García-Granero et al. submitted b, *Archaeological and Anthropological*

Sciences). Finally, all the microbotanical analyses from grinding stones were compared using multivariate statistics in a diachronic study to understand how plant-related subsistence strategies changed in this semi-arid region throughout the Holocene (García-Granero et al. submitted c, *Vegetation History and Archaeobotany*).

1.3. Thesis outline

This thesis is organised in two main parts: Introduction (Chapters 1-4) and Discussion (Chapters 5-7). After the Presentation of the research context, the research papers and the thesis outline (Chapter 1), Chapter 2 presents the four Research Questions addressed in this study. Questions 1 and 2 are concerned with the study of archaeobotanical remains to understand past subsistence strategies and socio-economical structures at local and regional level, and Question 3 is concerned with methodological issues related to the study of archaeobotanical remains.

Chapter 3 presents the research background. In the theoretical background I discuss three topics related to the study of archaeobotanical remains: the study of past socio-ecological systems, current models for the study of plant cultivation and domestication processes, and the social context of food. The geographical background presents several aspects of the area under study (northern Gujarat), including present-day climatic and physiographic features, modern land use strategies and past environmental and climatic reconstructions. The archaeological background offers an overview of the archaeological record, including the Greater Indus Valley and, more specifically, the early-middle Holocene record in northern Gujarat. Finally, the archaeobotanical background reviews earlier archaeobotanical research, with a special focus on the techniques applied in this study (geometric morphometrics and the analysis of microbotanical remains from grinding stones) and previous research in Gujarat.

Chapter 4 presents the Materials and Methods. The materials include modern plant reference collection and archaeological samples from four archaeological contexts: Vaharvo Timbo, Loteshwar, Datrana IV and Shikarpur. The methods used to analyse modern and archaeological samples include the traditional and GM analysis of macrobotanical remains (seeds and fruits), the analysis of microbotanical remains (phytoliths and starch grains) and the analysis of soil pH.

Chapter 5 presents the Main Results of this research. Despite the fact that this thesis is a compilation of papers, the results are presented as a continuum. The work with modern plant material and laboratory control samples is presented first. Subsequently, the results of archaeobotanical analyses from sediment samples are presented for each site. The results of the diachronic analysis of microbotanical analyses from grinding stones are presented at the end.

Chapter 6 discusses all the evidence presented in this study that contributes towards answering the questions presented in Chapter 2. Finally, the last chapter of Section II (Chapter 7) presents the main Conclusions of this research and the perspectives for future research that arise from this thesis.

After the two main sections, the thesis further includes a Summary in Catalan (Section III) and the list of References (Section IV). Section V presents the six peer-reviewed papers, either in final form (published papers) or edited to match the style of the rest of the thesis (papers currently under review/in press). Finally, a series of Appendices are included after the research papers with the phytolith raw data (phytolith and starch counting sheets).

2. Research Questions

This chapter presents the three independent yet interrelated research questions of this study. These include the subsistence strategy of the inhabitants of northern Gujarat throughout the Holocene, their social organisation and the methodological issues involved in the integrated analysis of archaeobotanical remains.

2.1. What were the subsistence strategies of the inhabitants of northern Gujarat during the Holocene?

The main aim of this study is to understand how plant-related subsistence strategies changed throughout the Holocene in northern Gujarat, with special emphasis in the transition from gathering to farming.

Up to date there has been no study of the plant exploitation strategies of hunter-gatherer and early agro-pastoral populations in northern Gujarat. This study analyses archaeobotanical remains from two hunter-gatherer occupations (Vaharvo Timbo and the Mesolithic levels at Loteshwar) and two early agro-pastoral camps (Datrana IV and the Anarta levels at Loteshwar) to understand how early-middle Holocene populations interacted with the environment in terms of livelihood strategies. Moreover, archaeobotanical remains from one late Holocene urban settlement (Shikarpur) is also analysed to ascertain how urban societies exploited this semi-arid environment in terms of plant acquisition and consumption.

Despite the lack of systematic archaeobotanical research in hunter-gatherer and early agro-pastoral contexts, plant biogeography and archaeobotanical evidence from later occupations suggest that northern Gujarat was a primary centre of small millet and pulse domestication during the mid-Holocene (Fuller 2006a). Therefore, the study of hunter-gatherer and early agro-pastoral contexts enables the understanding of possible plant domestication processes in northern Gujarat.

The study of plant exploitation strategies also assesses the role of exogenous crops in the diet of the inhabitants of northern Gujarat. There is no consensus on when did Near Eastern, African and East Asian crops arrive to Gujarat, nor is it clear their role on the subsistence strategies of its inhabitants. Therefore, special attention is given to the identification of these crops in the archaeobotanical record.

2.2. What do plant remains tell us about the social organisation of the inhabitants of northern Gujarat?

Archaeobotanical remains not only inform about subsistence strategies but also about the socio-economic organisation of past human populations (e.g. Fuller and Stevens 2009). The study of plant remains from archaeological contexts in northern Gujarat informs on their occupants' social structure and their economic interactions at the micro (site), local (northern Gujarat) and regional (Greater Indus Valley) scale. Moreover, the study of crop-processing activities and consumption patterns provides information about labour organisation, the relationship between producers and consumers, the importance of traded goods in the diet and the social connotations of particular foodstuffs.

2.3. How can a multi-proxy approach help answering these questions?

Although macro and microremains can be recovered from the same contexts, only a few studies have actively pursued an integration of data from both lines of evidence (Delhon et al. 2008; Dickau et al. 2012). This study elaborates on previous efforts to integrate data from macrobotanical remains (seeds and fruits), phytoliths and starch grains in a multi-proxy approach. The integration of all this data is highly beneficial from an interpretational perspective, since it encompasses a more diverse anatomical and taxonomical representation of the original plant input and allows for a better understanding of taphonomic processes, both depositional and post-depositional. However, a multi-proxy approach is also methodologically challenging, particularly during the sampling and interpretation of the archaeobotanical assemblages.

3. Background

This chapter is composed of four sections presenting the theoretical, geographical, archaeological and archaeobotanical contexts of this research. The theoretical background presents a brief introduction to the study of long-term socio-ecological systems, current approaches to the transition from gathering to farming and the social context of food. The geographical and archaeological backgrounds present modern and past features of the area of study. Finally, the archaeobotanical background presents the methodological background of this thesis (a multi-proxy approach), discusses previous studies that use the methods employed in this research and reviews earlier archaeobotanical research in northern Gujarat.

3.1. Theoretical background

The study of food procurement is, as expressed by Levi-Strauss in *Le Cru et le Cuit* (1964), the study of the transformation from the natural (*le cru*) to the cultural (*le cuit*). Thus, the study of subsistence strategies leads towards an understanding of the relationships between nature and culture –also referred as human-environment interactions or, more accurately, socio-ecological systems (SESs). This section first reviews concepts related to the study of SESs, focusing on the long-term contributions of archaeological research. It then focuses on different approaches to the major shift in subsistence strategies throughout human history –the beginning of food production, which has been the subject of intense research and debate for over a century and lately characterised as a subset of human-environment interactions (Denham 2011). Finally, this section discusses the social significance of food production and consumption, and how this concept has been approached in the archaeobotanical literature.

3.1.1. Long-term socio-ecological systems

The realisation that human (cultural) and ecological (natural) processes are not independent but greatly interrelated led to the development of SES theory (Adger 2000; Collins et al. 2011; Cote and Nightingale 2012; Haberl et al. 2006; Redman et al. 2004; van der Leeuw and Aschan-Leygonie 2001). SES theory is rooted in the study of concepts such as resilience, robustness, sustainability and vulnerability, but it is concerned with a range of dynamics and attributes beyond any of these terms (for definitions of these and other concepts related to the study of SESs see Table 1) (Cumming 2008: 8).

Table 1. Definitions of some terms associated with the study of socio-ecological systems. (after Cumming 2008: Table 2.1 and references therein).

Concept	Definition
Adaptation	The improvement of fit between a system component or entire system and its environment.

Concept	Definition
Adaptive capacity	The ability of systems to maintain their identity while responding to environmental change.
Resilience	The amount of change that a system can undergo and still maintain the same controls on function and structure, the system's ability to self-organize and the degree to which the system is capable of learning and adaptation. The ability of the system to maintain its identity in the face of internal change and external perturbations.
Robustness	Maintenance of system performance either when subjected to external, unpredictable perturbations, or when there is uncertainty about the values of internal design parameters.
Sustainable development	Development that meets the needs of the present generation without compromising the ability of future generations to meet their needs.
Sustainability	The equitable, ethical, and efficient use of natural resources.
Transformation	A systemic change that alters not only the system's properties but also its state space.
Vulnerability	A measure of the extent to which a community, structure, service or geographical area is likely to be damaged or disrupted, on account of its nature or location, by the impact of a particular disaster hazard. The state of susceptibility to harm from exposure to stresses associated with environmental and social change and from the absence of capacity to adapt.

Redman et al. (2004: 163) define a SES as:

1. "a coherent system of biophysical and social factors that regularly interact in a resilient, sustained manner;
2. a system that is defined at several spatial, temporal, and organizational scales, which may be hierarchically linked;
3. a set of critical resources (natural, socioeconomic, and cultural) whose flow and use is regulated by a combination of ecological and social systems; and
4. a perpetually dynamic, complex system with continuous adaptation."

The definition proposed by Redman et al. (2004) highlights the main aspects of a SES. First, a SES is characterised by different degrees of resilience, which is defined by the system's capacity to adjust to perturbations (Folke 2006; Widlok et al. 2012). Second, multiscale approaches are best suited to study and understand SESs because the interactions between societies and their environments take place at multiple spatial and temporal scales (Anderies and Hegmon 2011; Barton et al. 2010). Third, SESs are composed by a set of different, interconnected elements (i.e. biological –including humans– and geophysical resources) that interact with one another in a shared environment (Cumming 2008: 10). Finally, SESs are complex systems organised around continuous change (Janssen et al. 2007).

Redman et al. (2004: 164) propose a conceptual model for the study of long-term socio-ecological systems (LTSESs, Fig. 1). The model recognises the existence of patterns and processes that fit mostly within ecology or social science studies, while at the same time focusing on the interaction between the human and the ecological components of an integrated SES.

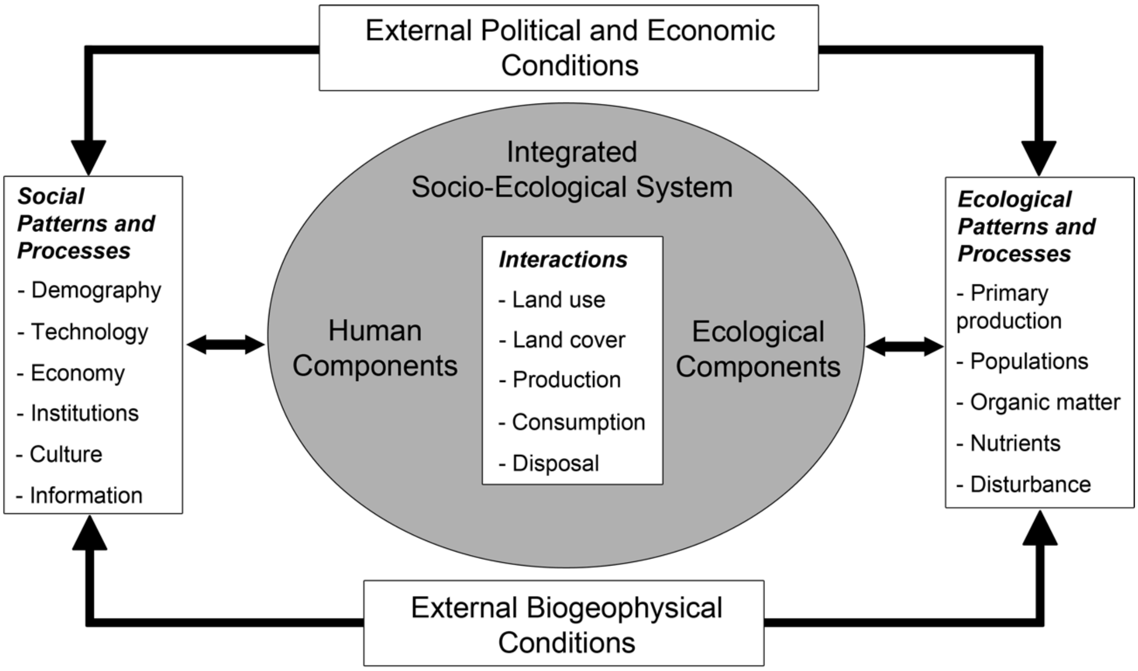


Figure 1. Conceptual framework for long-term research of integrated socio-ecological systems. (modified after Redman et al. 2004: Fig. 2).

Archaeology and the study of long-term socio-ecological systems

The long-term and multiscalar perspective inherent to most archaeological research provides an unmatched framework for the study of LTSESs (Barton et al. 2010; Redman 2005; Schoon et al. 2011). Concepts such as resilience, robustness, sustainability and vulnerability have been widely evoked in the archaeological literature of the last two decades. SES theory-inspired archaeological research has focused mostly on the study of long-term sustainable resource exploitation strategies (e.g. Barton et al. 2010; Campbell and Butler 2010; Ellis and Wang 1997; Glaser 2007; Marchant and Lane 2014; Smith 2009; Spielmann et al. 2011) and human responses to environmental and climatic variability (e.g. Anderies and Hegmon 2011; Costanza et al. 2007; Dillehay and Kolata 2004). These long-term studies have the potential to shed light on how past human populations adapted to socio-ecological crisis and thus inform future policy-making. However, the application of archaeological research to present-day challenges requires further efforts from both the scientific community and policy-making institutions.

3.1.2. The emergence of food production: current models and approaches

The transition from hunting-gathering-fishing to food production has been the focus of archaeological research for over a century. Plant and animal domestication is the most important development in the past 13,000 years, ultimately giving rise to current human cultures (Diamond 2002). The application of novel techniques (e.g. genetics) has resulted in a rapidly growing body of evidence for the origins of domestication: up to 13 primary centres of plant domestication are now recognised (Purugganan and Fuller

2009) (see Fig. 2), in contrast to the 5-9 centres identified by Diamond (2002) a decade ago.

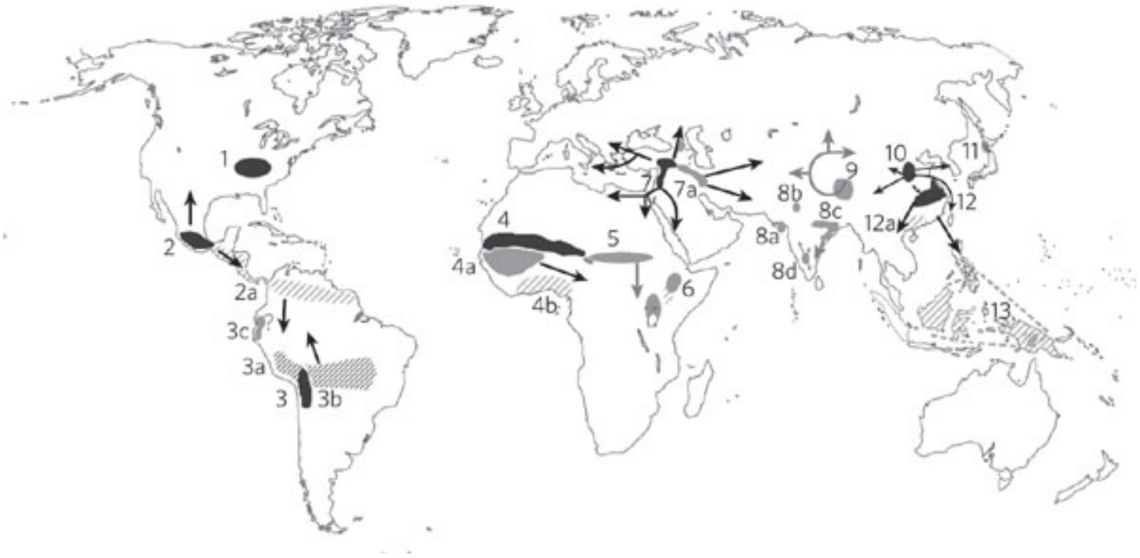


Figure 2. Centres of plant domestication. Solid-shaded areas and hatched areas indicate regions of important seed-crop domestication and vegecultural crops, respectively. Accepted primary domestication centres are shown in black, and potentially important secondary domestication centres are shown in grey. Arrows indicate major trajectories of spread of agriculture and crops out of some centres. 1) eastern North America (*Chenopodium berlandieri*, *Iva annua* and *Helianthus annuus*, 4500–4000 years yr BP); 2) Mesoamerica (*Cucurbita pepo*, 10,000 yr BP; *Zea mays*, 9000–7000 yr BP); 2a) northern lowland neotropics (*Cucurbita moschata*, *Ipomoea batatas*, *Phaseolus vulgaris*, tree crops, 9000–8000 yr BP); 3) central mid-altitude Andes (*Chenopodium quinoa*, *Amaranthus caudatus*, 5000 yr BP); 3a) north and central Andes, mid-altitude and high altitude (*Solanum tuberosum*, *Oxalis tuberosa*, *Chenopodium pallidicaule*, 8000 yr BP); 3b) lowland southern Amazonia (*Manihot esculenta*, *Arachis hypogaea*, 8000 yr BP); 3c) Ecuador and northwest Peru (*Phaseolus lunatus*, *Canavalia plagiosperma*, *Cucurbita ecuadorensis*, 10,000 yr BP; the question mark indicates that there is some question of the independence of crop origins of this centre from 3, 3a and 3b); 4) West African sub-Sahara (*Pennisetum glaucum*, 4500 yr BP); 4a) West African savanna and woodlands (*Vigna unguiculata*, 3700 yr BP; *Digitaria exilis*, *Oryza glaberrima*, <3000 yr BP); 4b, West African rainforests (*Dioscorea rotundata*, *Elaeis guineensis*, poorly documented); 5) east Sudanic Africa (*Sorghum bicolor*, >4000 yr BP?); 6) East African uplands (*Eragrostis tef*, *Eleusine coracana*, 4000 yr BP?) and lowland vegeculture (*Dioscorea cayenensis*, *Ensete ventricosum*, poorly documented); 7) Near East (*Hordeum vulgare*, *Triticum* spp., *Lens culinaris*, *Pisum sativum*, *Cicer arietinum*, *Vicia faba*, 13,000–10,000 yr BP); 7a) eastern fertile crescent (additional *Hordeum vulgare* and, 9000 yr BP, also goats); 8a) Gujarat, India (*Panicum sumatrense*, *Vigna mungo*, 5000 yr BP?); 8b) Upper Indus (*Panicum sumatrense*, *Vigna radiata*, *Vigna aconitifolia*, 5000 yr BP); 8c) Ganges (*Oryza sativa* ssp. *indica*, 8500–4500 yr BP); 8d) southern India (*Brachiaria ramosa*, *Vigna radiata*, *Macrotyloma uniflorum*, 5000–4000 yr BP); 9) eastern Himalayas and Yunnan uplands (*Fagopyrum esculentum*, 5000 yr BP?); 10) northern China (*Setaria italica*, *Panicum miliaceum*, 8000 yr BP; *Glycine max*, 4500 yr BP?); 11) southern Hokkaido, Japan (*Echinochloa crusgalli*, 4500 yr BP); 12) Yangtze, China (*Oryza sativa* ssp. *japonica*, 9000–6000 yr BP); 12a, southern China (*Colocasia*, *Coix lachryma-jobi*, poorly documented, 4500 yr BP?); 13) New Guinea and Wallacea (*Colocasia esculenta*, *Dioscorea esculenta*, *Musa acuminata*, 7000 yr BP). (after Purugganan and Fuller 2009: Fig. 1).

The last two decades have also witnessed a shift in the paradigms applied to plant domestication studies (Table 2) (Fuller 2010). First, the relationship between the adoption of domesticates and social complexity (in terms of technology, social stratification, etc.), once envisaged as linear (Fig. 3a), is now understood as a complex process involving 'false starts' and dead ends, with moments of rapid growth and decline, as well as stabilisations (Fuller et al. 2012a; Layton et al. 1991; Shennan et al. 2013; Smith 2001) (Fig. 3b and 4).

Table 2. Recent paradigm shifts in plant domestication studies.

Traditional paradigm	New paradigm
Inevitable, linear process.	Complex, non-linear process involving 'false starts' and dead ends.
Humans domesticate plants.	Plants and humans domesticate each other, co-evolutionary process.
Unique and geographically localised domestication process for each crop.	Multiregional nature of plant domestication processes.
Conscious process, humans choose to domesticate.	Unconscious selection process.
Quick process (few hundreds of years).	Slow process (1000-2000 years).
Dualistic epistemology hunter-gatherers/agriculturalists.	Recognition of the existence of a 'middle ground'.
Environmental determinism.	Importance of the 'social environment' at a local scale.

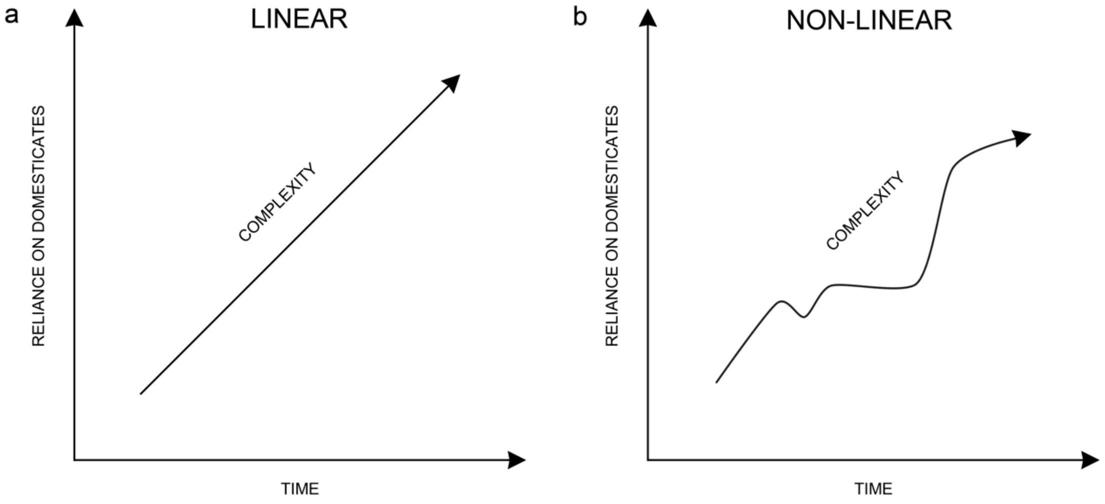


Figure 3. Simplified models of the relationship between the reliance on domesticates and social complexity. a) linear and b) non-linear.

Furthermore, the transition to food production is now seen as a co-evolutionary process between plants and humans, in which not only plants underwent genetic change but also humans adapted –both genotypically and phenotypically (Diamond 2002; Jackson 1996; Purugganan and Fuller 2009). Another rapidly changing paradigm is the 'core area hypothesis'. Genetic and archaeobotanical data has confirmed the multiregional nature of plant domestication in the Near East, similarly to other regions of the world, correcting a previous view that each crop was domesticated by a unique and geographically localised process (Brown et al. 2008; Fuller et al. 2011a, 2012a). Moreover, a distinction can be made between primary and secondary domestication centres, where local plant domestication was preceded by the introduction of domesticates from other regions (Diamond 2002) [note that Fuller (2011: Table 1) defines these as primary, inspired origins].

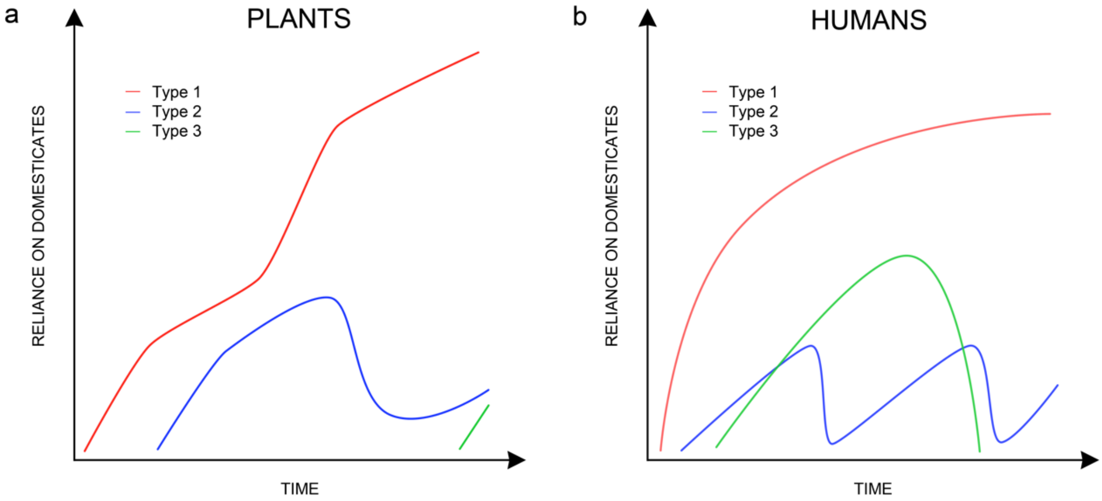


Figure 4. Examples of non-linear phenotypic models for the co-evolution of plants and humans. a) Type 1 plants are earlier domesticates that are still widely consumed, such as *Triticum* spp.; Type 2 plants are earlier domesticates that are no longer widely consumed, such as *Panicum miliaceum*; Type 3 plants are late domesticates that are widely consumed, such as *Vanilla planifolia*; and b) Type 1 curve exemplifies societies with a steady transition to agriculture; Type 2 curve exemplifies societies with a state of 'permanent transition' between hunter-gathering and food production; Type 3 curve exemplifies societies with a 'false start' process, ending rapidly.

Recent archaeological and archaeobotanical data suggests that domestication might have resulted from a series of unconscious selection pressures (Diamond 2002; Fuller and Allaby 2009; Fuller et al. 2012b, 2014a; Purugganan and Fuller 2011), instead of a conscious selection of advantageous plant traits resulting in a quick domestication (e.g. Hillman and Davies 1990). The morphological and genetic changes that characterise a plant as 'domestic' –loss of natural seed dispersal, loss of germination inhibition, changes in seed size and seasonality control– occurred through a millennial (1000-2000 years) time-span as an evolutionary adaptation by plants in response to a human driven ecology (Fuller and Allaby 2009).

The study of the origins of food production has been characterised by a dichotomous epistemology antagonising hunter-gatherers and agriculturalists (Smith 2001). However, the domestication of plants and animals "was the climax of a long process. It has to be presented as a single event because archaeology can only recognize the result: the several steps leading up thereto are beyond the range of direct observation" (Childe 1951: 87). The boundary between food procurement (plant gathering) and food production (plant cultivation) has been drawn at the human intentionality to disrupt the life cycle of a plant population to encourage growth (Ford 1985: 2; Harris 1996: 446). The intentional cultivation of plant populations might or might not end in a domestication event (Smith 2001). Despite the lack of domestic traits in archaeobotanical remains, the human intervention in a plant life cycle can be identified in the archaeological record trough the analysis of cultivation-related artefacts (e.g.

hoes) or the presence of weeds in the plant assemblage (Jones 1992). This novel epistemological and theoretical approach has resulted in the creation of a new lexicon to characterise different stages of plant domestication processes (Table 3).

Table 3. Definitions of some terms associated with the beginning of food production. (after Price and Bar-Yosef 2011: S165).

Concept	Definition
Management	Manipulation and some degree of control of wild species (plants or animals) without cultivation or morphological changes.
Cultivation	Intentional preparation of the soil for planting wild or domesticated plants. The term is often used to indicate cultivation of wild plants before domestication ("low-level food production" in Smith 2001).
Domestication	Morphological or genetic changes in plant and animal species.
Farming	Utilization of domestic plants and/or animals for food as well as other resources.
Agriculture	Farming and/or herding predominate the activities of a particular community and determine the main diet, although hunting and gathering may continue.

Finally, it is worth highlighting an aspect that most domestication studies have failed to consider: the role of social factors in the emergence of food production (for an exception see Hayden 1990 on the importance of feasting and accumulation). Notwithstanding the pivotal role of environmental shifts at a regional scale (e.g. the effect of the Younger Dryas in timing the emergence of food production in West and East Asia, Bar-Yosef 2011), any model of plant-human interaction at a local level must take into account the social processes underlying the origins of food production and the adoption of cultivars, not only as consequences of this process but also as causes.

3.1.3. The social context of food production and consumption

Food is a basic concern for all human societies, not only biologically but also from a sociocultural perspective (Messer 1984). Food is deeply embedded in a wide variety of social relations, and it can serve to express social differentiation in terms of identity, rank, belief, class, gender, etc. (Appadurai 1991; Goody 1982; Smith 2006; Twiss 2007, 2012). The interactions between producer and consumer not only inform about diet but also provide insights into the social organisation of production (Gumerman 1997). The study of archaeobotanical remains can also shed light on the presence of socially valued (i.e. high-status, luxury) foods (van der Veen 2003), defined by Curet and Pestle (2010) using a series of economic and non-economic parameters such as scarcity, labour investment, place of origin and taste.

The study of providing and transforming food covers five main areas: production, distribution, preparation, consumption and disposal (Goody 1982: 37). Archaeobotanical data has the potential to study these independent (although interrelated) processes and identify their social significance (Palmer and van der Veen 2002). The socioeconomic significance of archaeobotanical assemblages to understand food production and distribution patterns has been widely explored in terms of labour organisation and social stratification (e.g. Fuller and Stevens 2009; Fuller et al. 2014b).

Food disposal has also received much attention, particularly in relation to the study of feasting events (e.g. Dietrich et al. 2012; van der Veen 2007). Preparation and consumption activities usually take place within the intimacy of the household on a daily basis, thus reflecting household identities. As such, daily food routines serve both to reflect group membership and to set groups apart (Twiss 2007). However, cooking and eating have received comparatively much less attention (for an exception see e.g. Atalay and Hastorf 2004), mainly due to the fact that they are harder to recognise in the archaeological record (Twiss 2012). In this vein, the study of microbotanical remains from food-related artefacts is opening major inroads for the identification of preparation and consumption activities (e.g. Saul et al. 2013), although understanding the spatial distribution of food-related activities is only possible in exceptionally well-preserved archaeological contexts.

3.2. Geographical background

Gujarat, in northwestern India, is formed by a central low-lying peninsula that extends into the Arabian Sea. It is defined to the north by the Aravali-Delhi fold belt and the Kachchh Rift, and to the south by the Narmada Rift and the Gulf of Khambhat. Gujarat can be divided into three different areas: Kachchh, the peninsula of Saurashtra, and the mainland. The Great and the Little Ranns, two seasonal salt marshes, delimit the island of Kachchh on the continental side. The mainland can be further subdivided into the arid North and the fertile alluvial South Gujarat, separated by Central Gujarat, the area around the Mahi River (Fig. 5).

The following section presents the climatic and physiographic features, modern land use strategies and past environmental and climatic studies from the area of study. The current work is focused around the Little Rann, in North Gujarat (Patan district) and the eastern part of Kachchh (Kachchh district). The term “northern Gujarat” is thereafter used for simplification.

3.2.1. Northern Gujarat: an ecotone

With a mean annual precipitation of 400-600 mm, northern Gujarat is a semi-arid zone located between the Thar Desert and the sub-humid southern Gujarat (Fig. 5). Its location between two climatic regions makes northern Gujarat an ecotone, a transition area where small climatic variations can deeply affect the available resources and, thus, human populations that depend on them. Moreover, precipitation boundaries have changed over time, directly affecting the extent of the Thar Desert to the east during the late Pleistocene and early Holocene (Fig. 5) (Goudie et al. 1973). Currently most of the rainfall occurs between June and September (Indian Summer Monsoon), shaping agricultural and pastoral activities in the region, and prolonged drought is a recurrent phenomenon –the latest of which occurred between 1986-1990 (Ajithprasad and Sonawane 2011).

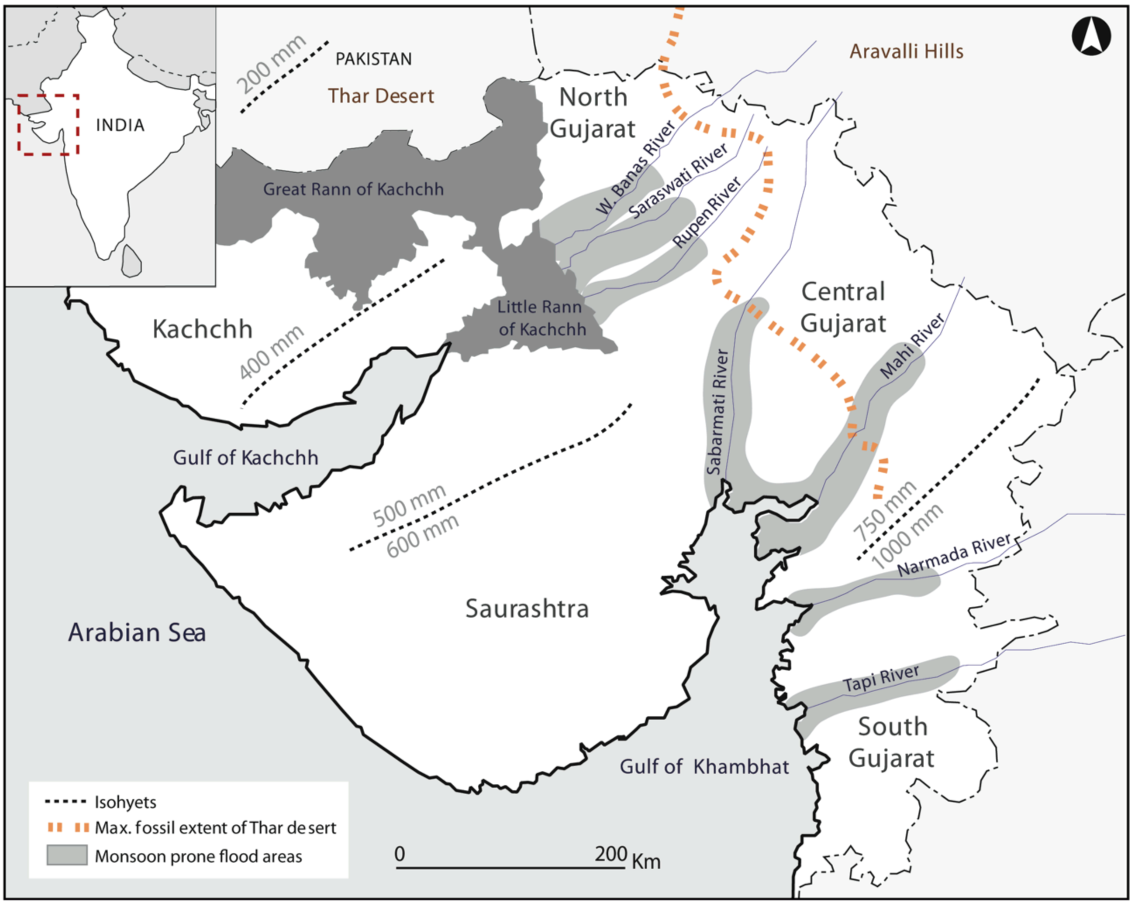


Figure 5. Map of Gujarat showing alluvial flood-prone areas, isohyet lines and the maximum fossil extent of Thar Desert. (map by Francesc. C. Conesa).

3.2.2. Physiographical settings

Both North Gujarat and Kachchh are characterised by sandy and saline soils (http://gujenvis.nic.in), but they are geomorphologically very different. North Gujarat is drained by the Banas, Rupen (of which the shorter Kari is an affluent) and Saraswati into the Little Rann, and the Sabarmati into the Gulf of Khambhat. Only the Sabarmati is perennial, yet the remaining rivers (and their tributaries) drain a large volume of water during the monsoon. Kachchh does not contain any major rivers, but there are 97 small rivers, most of which flow into the Arabian Sea.

North Gujarat can be divided in four physiographical units: the uplands (Aravalli Hills), the silt belt, the dune-interdune area and the Little Rann (Balbo et al. 2013; Conesa et al. 2014a). The main bedrock outcrops correspond to the Aravalli Hills, although smaller bedrock outcrops are observed near the Little Rann in correspondence with the Datrana Hills and Granite Lowlands. Stabilised dunes from the retreat of the Thar Desert ca. 7000 years ago can be observed in the silt belt and the dune-interdune area (Goudie et al. 1973). Interdunal depressions in this area accumulate monsoon rainwater and can retain higher moisture levels for a good part of the year, offering opportunities for pastoral and agricultural activities. On the western area, bordering the Little Rann, the river banks and large areas of wasteland (*padthar*) are rich in wild grasses, available immediately after the first monsoon showers and exploited to great advantage by present-day pastoral communities (Bhan 1994).

3.2.3. Modern land use strategies

Traditionally, the major agricultural season in northern Gujarat is the summer *kharif*, which involves sowing with the first monsoonal rains (June-July) and harvesting in October-November (Reddy 1997). Winter *rabi* cultivation occurs only with the aid of modern irrigation, although dry farming is possible in some interdunal depressions (Bhan 1994).

Modern irrigation techniques, including groundwater mining, were introduced in northern Gujarat in the 1960s as part of India's Green Revolution –together with chemical fertilisers, pesticides and high yielding varieties of seeds. Admittedly, the Green Revolution brought an extraordinary increase in crop yields, achieving self-sufficiency in food production at national level. However, it has also resulted in acute environmental degradation in many parts of India (Singh 2000). Due to the virtual absence of rainfall during the winter months, the cultivation of *rabi* crops such as wheat (*Triticum* sp.) in northern Gujarat requires constant irrigation. Extensive groundwater mining has resulted in the over-exploitation of aquifers, a continued decrease in the water table at a rate of 3-6 m per year and an increase in soil salinity (Gupta and Deshpande 2004; Kavalanekar et al. 1992; Pearce 2004).

The environmental costs of modern agriculture contrast with the low environmental impact and long-term sustainability of traditional subsistence strategies in this region. Modern examples of sustainable subsistence strategies can be found nowadays from traditional agricultural systems and semi-nomadic pastoralism. Traditional rainfed agroforestry systems incorporate indigenous trees (e.g. *Prosopis cineraria* (L.) Druce, khejri) and drought-tolerant *kharif* crops such as millets, tropical pulses and oilseeds (Singh 2010). Examples of small-scale, non-mechanised traditional agriculture can still be found in the region, such as the case of Jandhala village, Patan district (Rondelli et al. 2014).

Traditional semi-nomadic pastoralism is still practised in Gujarat. The Raika/Rabari, the most important pastoral group in India, are found all over Gujarat, showing varying degrees of sedentarisation and occupational diversification (e.g. seasonal work in road construction and maintenance). Most of the migrating shepherds are found in eastern and central Kachchh, whereas in northern and southern Gujarat the majority of the community members are involved in dairy-focused milk production, farming, trade and a wide range of other sedentary economic activities (Salpeteur et al. in press and references therein).

3.2.4. Palaeoenvironmental and palaeoclimatic studies

No exhaustive palaeoenvironmental record is yet available for the study area. On-going palaeoecological work carried out within the NoGAP project in interdunal depressions near Loteshwar and Vaharvo Timbo suggests that perennial water bodies existed in the dune-interdune area until ca. 7000 years ago (unpublished data), as opposed to present day conditions where most depressions dry up during the winter months (Conesa et al. 2014b). These data is in agreement with previous palaeoclimatic models, which show a slow but constant weakening of the Indian Summer Monsoon after the early Holocene wet phase between ca. 10,000 to 7000 years ago (Gupta et al. 2006; Liu et al. 2003).

Palaeoenvironmental information about the study area is derived mainly from studies in neighbouring Rajasthan (north of Gujarat), Saurashtra and Central Gujarat. Early palynological research at several western Rajasthan lakes aimed at understanding the climatic condition related to the rise and fall of the Indus Civilisation (see below) and suggested that climate change had a main role in these processes (e.g. Singh 1988; Singh et al. 1974, 1990; Wasson et al. 1984). According to these scholars, the development of a complex agrarian society, such as the Indus Civilisation, was favoured by wet and humid climatic conditions around 6000 BP, whereas a drying episode around 4000 BP coincided with the decentralisation of this society. Subsequent work by Kajale and Deotare (1997), which investigated seven saline lakes in eastern Rajasthan, concluded that intralake and interlake variations could not be explained simply by evoking the effect of climate change. Further research in Rajasthan showed that cultural developments were not synchronous with climatic events (Enzel et al. 1999). Madella and Fuller (2006) supported this hypothesis, arguing that it is not possible to establish a cause-effect relationship between climate change and the decline of the Indus Civilisation.

Sea level fluctuations have been recorded at the Saurashtra coast during the Holocene (Gaur and Vora 1999; Deo et al. 2011). The sea level was 6-10 m higher between ca. 6000-4000 years ago, when it stabilised at the present level (Rajaguru and Deo 2008). This hypothesis seems to be supported by ancient Indian literature as well as by archaeological (Gaur and Sundaresh 2007) and archaeobotanical evidence (Lancelotti 2010). However, it is not clear whether it was due to geological (Gaur and Vora 1999) or climatic factors (Prasad et al. 1997, 2007).

Recent multi-proxy palaeoecological research in Central Gujarat linked the high presence of pooid-type phytoliths (mainly rondels) with phases of higher winter precipitation, especially during the mid-Holocene (Prasad et al. 2007, 2014; Raj et al. 2015; Singh et al. 2007). However, there appears to be certain degree of misidentification of rondel phytoliths (Prasad et al. 2007: Fig. 4i; Prasad et al. 2014: Fig. 3d; Singh et al. 2007: Fig. 4a-b), which might undermine the general interpretation. Moreover, the high presence of rondels may also derive from a rondel-producer panicoid grass, as occurs in other areas of the world (e.g. *Panicum turgidum* Forssk. in

West Africa, Radomski and Neumann 2011: Table 3), and therefore the occurrence of winter rains in mid-Holocene Gujarat cannot be confirmed through these studies. In general, there does not seem to be concluding evidence of dramatic environmental changes affecting northern Gujarat during the last 10,000 years, and therefore it should be safe to consider that the environmental conditions during the early-middle Holocene were not much different from the ones observed today.

3.3. Archaeological background

The archaeological record of northern Gujarat is intrinsically entangled with the Indus Valley. For this reason, the following section reviews first the archaeology of the Greater Indus Valle, from the origins of food production to the demise of the Indus Civilisation, and then focuses on early-middle Holocene occupations in northern Gujarat.

3.3.1. Mehrgarh and the origins of food production in South Asia

The site of Mehrgarh, in the Kachi Plain of Baluchistan west of the Indus River, is located at the foot of the Bolan Pass, one of the main routes connecting the Iranian Plateau, Central Asia and the Indus Valley (Fig. 6).

The occupational sequence at Mehrgarh begins in the late eighth – early seventh millennium BC and stretches into the first part of the second millennium BC. The aceramic (Period I) and ceramic (Period II) Neolithic levels are characterised by the presence of mudbrick multi-roomed structures, with increasing evidence of storage facilities in the latter (Jarrige 2008). These deposits offer the first evidence of a farming economy in northwestern South Asia. Indeed, zooarchaeological and archaeobotanical analyses show that domestic goat (*Capra aegagrus* ssp. *hircus* L.), einkorn (*Triticum monococcum* L.), emmer wheat (*Triticum turgidum* ssp. *dicoccum* Schrank) and barley (*Hordeum vulgare* L.) were introduced from the Near East; whereas sheep (*Ovis aries* L.), zebu (*Bos taurus* ssp. *indicus* L.) and cotton (*Gossypium arboretum* L.) were locally domesticated (Costantini 2008; Fuller 2006a and references therein). It was this package (with some later additions), with a largely Southwest Asian origin, that formed the subsistence base of the urban settlements in the core area of the Indus Civilisation.

3.3.2. The Indus Civilisation

The Indus or Harappan Civilisation flourished throughout the Greater Indus Valley in northwest South Asia between ca. 3300-1300 cal. BC, extending from modern northeast Afghanistan to Pakistan and northwest India (Kenoyer 1991; Possehl 2002; Wright 2010) (Fig. 6). The different phases of the Indus Civilization are part of a cultural continuum, from the beginnings of village farming to the eclipse of urban communities (Table 4). The apparently sudden manifestation of Harappan urbanism at ca. 2600 BC was, in fact, the culmination of a process that started much earlier. This gestation period, known as Early or Pre-Urban Harappan (3300-2600 BC), culminated with a rapid transition of 100-150 years characterised by the widespread presence of the typical Urban Harappan traits (2600-1900 BC) (Ajithprasad 2002: 129; Kenoyer 1991: 334; Possehl 1990).

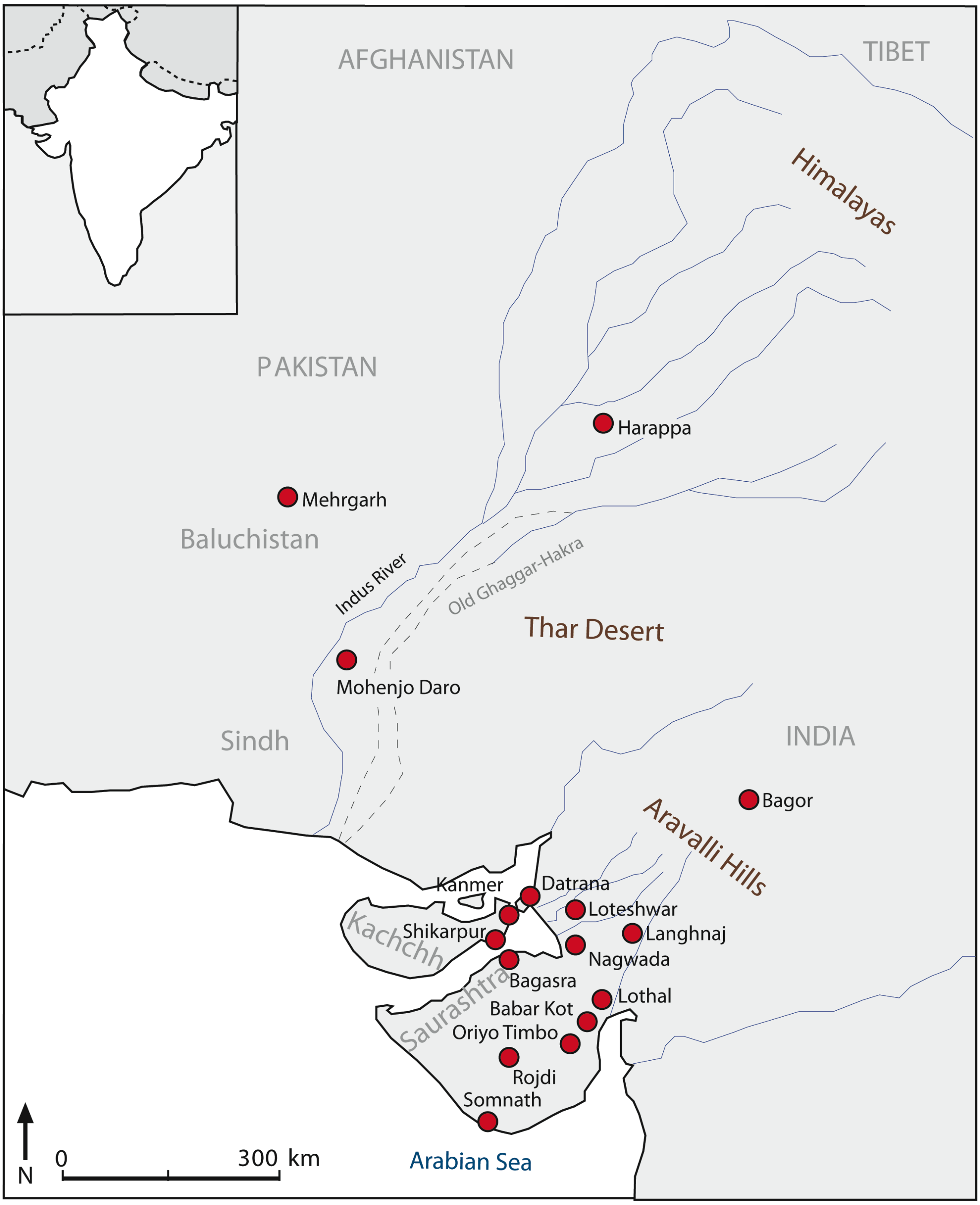


Figure 6. Map of the Greater Indus Valley showing archaeological sites mentioned in the text. (map by Francesc. C. Conesa).

Table 4. Simplified chronology of the Indus Civilisation.

Years cal. BC	Period	Defining trait
ca. 3300 – 2600	Early Harappan	gestation
ca. 2600 – 1900	Urban Harappan	urbanisation
ca. 1900 – 1300	Post Urban Harappan	decentralisation

The Urban Harappan phase (2600-1900 BC) is defined by the emergence of several new aspects (not present in the Early Harappan), such as the use of writing and standardised weights, the development of urban planning and monumental architecture, Harappan-type ceramic designs, the craft specialization and long distance trade, etc. (Kenoyer 1991: 334; Possehl 1990: 268; Sonawane 2002: 159). During the Mature Harappan period, the major urban centres such as Harappa and Mohenjo Daro (Fig. 6) were surrounded by a rural base of small settlements, demonstrating a symbiotic relationship between the two (Sonawane 2002: 159-160).

The Post Urban Harappan period (1900-1300 BC) sees a decrease in centralisation and specialisation, and it represents a phase of readjustment from an urban to a rural system without losing the ‘Harappan character’ in other aspects (Sonawane 2001).

Despite the diversity of the regions that were occupied by the Indus Civilisation, there are some similarities among all the Harappan sites, indicating the presence of certain integrative forces (Possehl 1990). The relationship between the Indus Valley and Gujarat was theorised by Herman (1996) using the Core/Periphery model. During the Urban Harappan Phase, Kachchh formed part of the Core Harappan Area, whereas the local traditions from Saurashtra and North Gujarat formed an agro-pastoral periphery (Ajithprasad 2001). In this context, the Ranns of Kachchh and the coastal borders of Saurashtra acted as frontiers of interaction (Herman 1996: 80).

Over 500 sites pertaining to the Indus Tradition have been recognized in Gujarat, spanning from Early to Urban and Post Urban Harappan phases (Possehl 1992). The recovery of Early Harappan Sindh pottery (ca. 2800-2600 cal. BC) in mortuary and residential contexts in Gujarat suggests that the interaction between the Indus Valley and Gujarat began during the early third millennium BC (Ajithprasad 2002, 2011; Mushrif-Tripathy et al. 2014). However, it is during the Urban phase that the Harappan influence is most evident in Gujarat, with the appearance of a series of walled urban settlements with the characteristic Harappan city plan and associated material culture along trade and travel corridors (Chase et al. 2014a).

Archaeological excavations in Gujarat showed that settlements such as Lothal (Saurashtra), Nagwada (North Gujarat) and Shikarpur (Kachchh) were engaged in the manufacture of semi-precious stones, steatite, faience, chank shell (*Turbinella pyrum* L.), ivory, copper, etc. for trading purposes, especially during the Urban phase (Sonawane 2001). At the beginning of the second millennium BC, long distance trade declined, affecting these urban settlements and marking the beginning of Post Urban Harappan phase in Gujarat. This period is characterised by the persistence of Urban

Harappan attributes within a process of de-urbanisation and subsistence strategy changes (Reddy 1997).

3.3.3. Early-middle Holocene occupations in northern Gujarat

During the early and middle Holocene, hunter-gatherer (HG) and agro-pastoral (AP) communities occupied northern Gujarat. HG occupations are characterised by the presence of a microlithic industry and the absence of ceramics, and are often called 'Mesolithic' (e.g. Sankalia 1987) or 'Microlithic' (Patel 2009) in the literature. The earliest Holocene HG occupation is attested at Datrana IV during the early eighth millennium BC (unpublished data, P. Ajithprasad pers. comm.). Some researchers advocate for the resilience of HG populations until the end of the third millennium BC and their interaction with AP populations (Misra 1973; Sonawane 2000). This hypothesis is based on AMS dates from allegedly HG deposits at Bagor (Rajasthan) and Langhnaj (North Gujarat), characterised by the presence of a microlithic industry (Patel 2009 and references therein). However, the analysis of the lithic assemblage from Loteshwar, a site with clearly differentiated HG and AP deposits, shows continuity in terms of tool technology (quartering technique) during the whole occupation of the dune (five thousand years), thus denying the microlithic-HG binomial association (Gadekar et al. 2014a). Moreover, the HG nature of the inhabitants of Bagor and Langhnaj (and other sites with similar 'HG' deposits) has been called into question due to the presence of domestic fauna and Harappan paraphernalia, which cannot be solely explained as a result of trading activities (Conesa 2011). Therefore, the establishment of a clear chronological framework for the HG occupation of northern Gujarat and adjacent areas (and the possible interaction with AP populations) requires a critical assessment of the available evidence and the widespread application of radiocarbon dating in securely ascribed HG deposits, as well as a thorough study of faunal and botanical remains.

Until recently, specialised literature stated that agriculture and pastoralism were introduced in northern Gujarat by migrating Harappan populations (Possehl 1980). However, over two decades ago scholars identified the existence of autochthonous food-producing communities in North Gujarat and Kachchh dating to the mid fourth millennium BC (Ajithprasad 2002; Ajithprasad and Sonawane 2011; Patel 2009; Possehl 1992; Sonawane and Ajithprasad 1994). This cultural tradition, mainly defined by a distinctive pottery assemblage, was named 'Anarta' after the traditional name of North Gujarat. Among the hundred Chalcolithic sites located in North Gujarat, 62 incorporate the Anarta ceramic assemblage, Nagwada and Loteshwar being the most studied (Ajithprasad and Sonawane 2011: Appendix).

The importance of pastoral activities for Anarta communities seems clear (Ajithprasad and Sonawane 2011 and references therein). Indeed, the study of faunal remains from Loteshwar suggested that North Gujarat had the potential for a local domestication of zebu independently from Baluchistan (Patel 2009), although Fuller (2006a) advocates for the adoption of pastoralism from neighbouring herders in the southern Indus Valley.

On the other hand, the role of plant resources in the Anarta subsistence strategies remains poorly understood (Sonawane 2000: 143). Cultivation of small millets and tropical pulses was well established in Gujarat by the Urban Harappan period (Fuller and Madella 2002), and the local character of this crop package suggests the existence of an indigenous plant domestication process (Fuller 2006a, 2011; Fuller and Murphy 2014; Purugganan and Fuller 2009). However, the existence of strong taphonomic processes and the lack of systematic archaeobotanical research impede a full assessment of the role of plants for Anarta communities and the understanding of possible local plant domestication processes.

The archaeological record of Early Chalcolithic North Gujarat also includes the Pre-Prabhas pottery tradition, identified at Datrana IV during the excavations conducted by the Department of Archaeology and Ancient History, MSUB between 1993 and 1995 (IAR 2000a, 2000b). Pre-Prabhas pottery was also recovered during explorations at nearby Datrana V and Datrana IX, but it has not been found in other Chalcolithic occupations in North Gujarat (Ajithprasad 2002, 2011). This handmade pottery was first recovered during the 1950s excavations at Somnath in the southern Saurashtra coast, located 400 km south of Datrana and dated to the early third millennium cal. BC (Ajithprasad 2002, 2011; Dhavalikar and Possehl 1992; Rajesh et al. 2013; Sonawane and Ajithprasad 1994; Subbarao 1958). At both Datrana and Somnath the Pre-Prabhas ceramic assemblage incorporated blades with crested-guiding ridges, a technique associated with Chalcolithic settlements of the Indus Civilisation and not attested earlier in Gujarat (Cleland 1977). However, the degree of interaction between Pre-Prabhas and Early Harappan and Anarta communities is not clearly understood thus far.

3.4. Archaeobotanical background

The following section illustrates the benefits of a multi-proxy approach to reconstruct past subsistence strategies as well as earlier archaeobotanical research using geometric morphometric (GM) techniques and microbotanical remains from grinding stones. It also reviews earlier archaeobotanical research in Gujarat.

3.4.1. A multi-proxy approach

Plants used and transformed by people can produce a diverse record that can be considered as a proxy of their choices and activities, and in certain cases of ecological conditions too. In a broad sense, the term ‘proxy’ is used to define a representative or intermediary. In palaeoclimatology, a proxy is defined as “a local record that is interpreted using physical or biophysical principles to represent some combination of climate-related variations back in time” (Folland et al. 2001: 130). Noise and possible biases make it necessary to calibrate and cross-validate proxies in order to obtain more accurate and reliable palaeoclimatic reconstructions. Multi-proxy approaches are also commonly adopted in palaeoecological studies, particularly in palaeolimnology (Birks and Birks 2006 and references therein). In palaeoecology, a proxy is understood as a record of changes that can be measured or analysed to reconstruct past ecosystems and biotic responses to natural or human-caused changes (Birks and Birks 2006). Palaeoecological proxies include fossil organisms, such as diatoms, phytoliths and pollen grains, as well as sediment characteristics, which are measured through physico-chemical analyses.

Despite the fact that archaeobotany shares several methodological approaches with palaeoecology, the concept of proxy has not been much theorised and, in general, the major evidence (proxy) is considered to be the charred remains record. This is due to a) visibility (charred remains can be seen by naked eye), b) relatively easy methods of recovery (handpicked or flotation) and c) direct analysis without previous chemical processing. However, the study of past subsistence strategies through the integrated analysis of charred macroremains, phytoliths and starch grains has several advantages: a more diverse anatomical and taxonomical representation of the original plant input and a better understanding of taphonomic processes, both depositional and post-depositional.

Taxonomy

The combined use of macro- and microbotanical remains increases the number of taxa identified, independently of the preservation pathways. Microremains allow for taxa seldom preserved macroscopically, such as roots and tubers (e.g. Chandler-Ezell et al. 2006) and fruits such as banana (Denham et al. 2003 for starch and Mindzie et al. 2001 for phytoliths). Charred seeds and related floral parts, on the other hand, are often strongly taxonomically diagnostic. For example, charred small millets can usually be identified to species level, whereas starch grains are, at best, diagnostic to genus level (Krishna Kumari and Thayumanaban 1998; Liu et al. 2011; Yang et al. 2012a). The potential of phytoliths to differentiate between small millets has only started to be evaluated outside the two main genera, *Panicum* and *Setaria*, but morphometric analyses suggest they could be diagnostic at species level (Lu et al. 2009; Zhang et al. 2011).

Anatomy

A multi-proxy approach allows for the identification of different plant parts, which is useful for both dietary and non-dietary investigation of plant use (Fig. 7). Plant parts such as chaff of small grasses, leaves or culms are seldom preserved in the macrobotanical record, but they can be identified from plant microremains (Lu et al. 2009; Out and Madella 2015; Yang et al. 2014; Zhang et al. 2011).

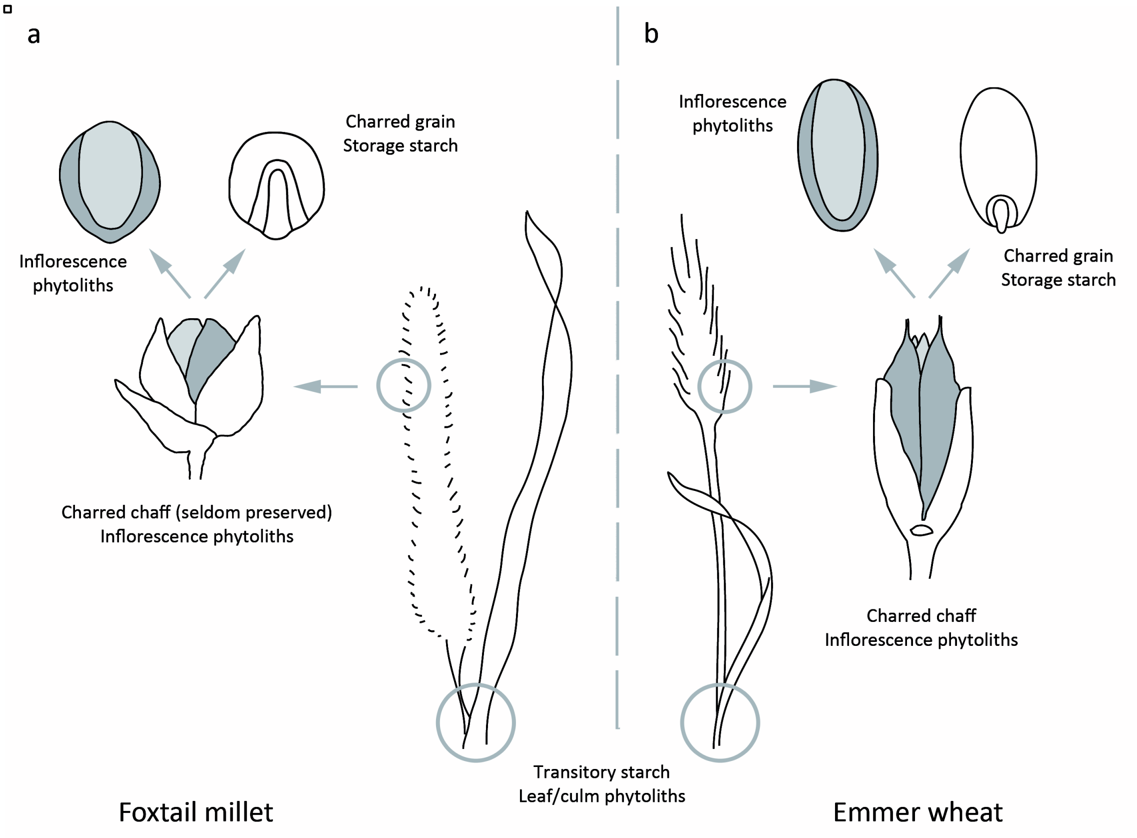


Figure 7. Idealised drawings and examples of proxies (macro and microbotanical remains produced by different plant parts). a) *Setaria italica* and b) *Triticum turgidum* ssp. *dicoccon.*

Taphonomy

The preservation of the different plant parts depends on the intrinsic characteristics of the tissues (soft vs. hard), the processing technique (roasting, boiling, etc.) and the post-depositional environment (dry vs. wet, bioturbation, etc.). A multi-proxy approach offers the possibility to analyse a wider spectrum of plant residues originating from tissues with different characteristics and with diverse taphonomy, therefore allowing more precise evaluations of the original plant input. Phytoliths are usually preserved regardless of the depositional conditions, since they are not dependent on fire for preservation, as most macroremains are. Starch grains, on the other hand, can be easily degraded by enzymes, bacteria and other organisms of the soil (Haslam 2004). However, when trapped in dental calculus or artefact pores starch can be preserved for thousands of years in diverse environmental settings (Torrence 2006: Table 1.1).

3.4.2. Geometric morphometrics in archaeobotanical research

Geometric morphometrics (GM) are a relatively novel approach to shape analyses based on Cartesian coordinates of anatomical points –called landmarks (Slice 2007). GM emphasise the complete retention of geometric information throughout the analytical process, as opposed to the mere collection of distances or angles. 2D landmark-based GM is a method that uses two-dimensional (x, y) coordinates to define a series of (preferably) homologous points on an anatomical structure as variables to conduct numerical analyses of shape (Bookstein et al. 1999; Zelditch et al. 2012). This method is most suited for the analysis of shape in biological structures (Slice 2007) and it has have been widely used in (palaeo)anthropological, zoological and botanical research (e.g. Cope et al. 2012; Lawing and Polly 2010; Slice 2007). Its application in archaeology is relatively recent. Examples include artefact studies such as ceramics (Wilczek et al. 2014) and lithics (e.g. Buchanan et al. 2013), and the study of the evolution and dispersion of pigs (*Sus* spp.) (Cucchi et al. 2009, 2011; Evin et al. 2013; Krause-Kyora et al. 2013; Ottoni et al. 2013; Owen et al. 2014). In archaeobotany, this approach has been employed to study the domestication and dispersion of *Olea* spp. (Newton et al. 2006, 2014; Terral et al. 2004), *Prunus* spp. (Burger et al. 2011; Depypere et al. 2007, 2009; Nielsen and Olrik 2001), *Hordeum* spp. (Ros et al. 2014), *Vitis* spp. (Pagnoux et al. 2015; Terral et al. 2010) and *Phoenix* spp. (Terral et al. 2012).

3.4.3. Microbotanical analyses and grinding stones

The potentials of microresidue studies from stone tools have long been recognised (Briuer 1976). However, the analysis of microbotanical remains from grinding stones only recently started to be routinely carried out as part of the archaeobotanical research, greatly contributing to the understanding of plant-related subsistence strategies worldwide (see e.g. Liu et al. 2011 in East Asia; Field et al. 2009 in Oceania; Piperno and Holst 1998 in the Americas; Radomski and Neumann 2011 in Africa; and Aranguren et al. 2007 in Europe). In spite of this, only few studies analyse both phytoliths and starch grains in an integrated approach (Dickau et al. 2012; Pearsall et al. 2004; Perry et al. 2006; Piperno et al. 2009; Zarrillo et al. 2008).

The methods employed in the recovery, extraction and analysis of plant microremains from grinding stones vary greatly depending on: a) the state of the tool (washed/unwashed, mode of storage, likelihood of contamination, etc.), b) the research questions (qualitative vs. quantitative data), c) the analyses carried out (phytoliths and/or starch grains), d) the available equipment (e.g. ultrasound) and e) the environmental settings of the archaeological context (e.g. dry vs. wet environments). Moreover, there are variants related to each research group or laboratory. Table 5 summarises the methods employed in 32 microbotanical studies on grinding stones. This review includes all major studies published in the last two decades and considers a wide geographical range, both in terms of archaeological context and research laboratories.

Microremains recovery

The highest methodological variability between different studies occurs during the recovery of microbotanical remains. The most common approach involves the preliminary assessment of the presence of plant microremains prior to the removal of sediment from the grinding stone by placing the artefact directly under a microscope.

This approach, known as spot sampling, allows for an in situ observation of microremains and their controlled removal through either the point of a fine needle (Piperno and Holst 1998) or by applying a small amount of distilled/ultra-pure water to the area of interest, which is then recovered with a disposable pipette (Atchinson and Fullagar 1998). However, plant residues are not always visible using this approach (Perry 2004), particularly when the tools are unwashed (Mercader 2009). Moreover, this approach is very time-consuming (Piperno et al. 2009) and it requires the artefact to be examined in a field laboratory during the excavation process or transported to a place where a suitable microscope is available.

Table 5. Summary of recovery, extraction and analysis methods in 32 microbotanical studies on grinding stones. x = performed. ~ = performed, but not consistently. - = not performed/not specified.

	Recovery					**Extraction**					**Analysis**				
	Spot sampling	**Dry brushing**	**Wet brushing**	**Ultrasonic bath**	**Deflocculation**	**Starch separation**	**Carbonates dissolution**	**Organic matter oxidation**	**Phytolith separation**	**Starch**	**Biological stains**	**Phytoliths**	**Use-wear**	**Control samples (arch)**	**Control samples (lab)**
Albert and Portillo 2005	-	-	-	-	x	-	x	x	x	-	-	x	-	~	-
Aranguren et al. 2007	-	-	-	-	-	-	-	-	-	x	-	-	-	-	-
Atchinson and Fullagar 1998	x	-	-	-	-	-	-	-	-	x	-	-	-	-	-
Babot and Apella 2003	-	-	-	-	-	-	-	-	-	x	x	-	-	-	-
Balme et al. 2001	x	-	-	-	-	-	-	-	-	x	x	-	x	-	-
Barton 2007	x	-	-	-	-	-	-	-	-	x	x	-	-	-	-
Dickau et al. 2007	-	-	-	x	-	x	-	-	-	x	-	-	-	-	-
Dickau et al. 2012	-	-	-	x	x	x	x	x	x	x	-	x	-	-	-
Field et al. 2009	x	-	-	-	-	-	-	-	-	x	-	-	~	-	-
Langejans 2006	-	-	-	~	-	-	-	-	-	x	-	-	-	-	-
Liu et al. 2010a	x	-	-	-	-	x	-	-	x	x	-	-	x	-	-
Liu et al. 2010b	x	-	-	-	-	x	-	-	x	x	-	-	x	-	-
Liu et al. 2011	x	-	-	-	-	x	-	-	x	x	-	-	x	-	-
Mercader 2009	-	-	~	x	-	-	-	-	-	x	-	-	-	x	x
Pearsall et al. 2004	x	x	x	x	x	x	x	x	x	x	-	x	-	-	-
Perry 2004	x	-	-	x	x	~	-	-	-	x	-	-	-	-	-
Perry et al. 2006	-	-	-	-	x	x	x	x	x	x	-	x	-	-	-
Piperno and Holst 1998	x	-	-	-	-	-	-	-	-	x	-	-	-	-	-
Piperno et al. 2000	x	-	x	x	-	x	-	-	-	x	-	-	-	x	-
Piperno et al. 2004	x	-	-	x	-	x	-	-	-	x	-	-	-	-	-
Piperno et al. 2009	~	-	x	x	-	x	-	-	-	x	-	x	-	x	-
Portillo et al. 2009	-	-	-	-	-	-	x	x	x	-	-	x	-	x	-
Radomski and Neumann 2011	-	x	x	x	x	-	x	x	x	-	-	x	-	-	-
Revedin et al. 2010	-	-	x	-	-	x	-	-	-	x	x	-	x	-	-
Tao et al. 2011	x	-	-	-	-	-	-	-	-	x	-	-	-	-	-
Weber et al. 2011	x	-	-	~	-	x	-	-	-	x	-	-	-	x	-
Yang et al. 2009	-	-	-	x	-	x	-	-	-	x	-	-	-	x	x
Yang et al. 2012b	-	-	-	x	-	x	-	-	-	x	-	-	-	-	-

	Recovery					Extraction					Analysis				
	Spot sampling	**Dry brushing**	**Wet brushing**	**Ultrasonic bath**	**Deflocculation**	**Starch separation**	**Carbonates dissolution**	**Organic matter oxidation**	**Phytolith separation**	**Starch**	**Biological stains**	**Phytoliths**	**Use-wear**	**Control samples (arch)**	**Control samples (lab)**
Yang et al. 2013	x	-	-	-	-	-	-	-	-	x	-	x	-	~	-
Zarrillo and Kooyman 2006	-	-	-	~	-	-	-	-	-	x	-	-	x	x	x
Zarrillo et al. 2008	-	x	x	x	x	x	x	x	x	x	-	x	-	-	-
Zucol and Bonomo 2008	-	x	x	-	x	-	x	x	x	-	-	x	-	x	-

Another common approach is the three-step method proposed by Chandler-Ezell and Pearsall (2003) –dry brushing, wet brushing and sonicating. One or more of these sampling stages are usually carried out alone (e.g. Radomski and Neumann 2011) or in combination with spot sampling (Pearsall et al. 2004). The sonic bath is applied either to the whole tool (e.g. Dickau et al. 2012) or immersing the part that is going to be sampled (Yang et al. 2012b). Some grinding stones are too big to fit into the sonic bath, thus impeding a standard recovery protocol in all artefacts (Langejans 2006). Moreover, sonicating whole, unwashed tools is problematic, since the residue recovered comes equally from used and unused surfaces of the tools. For this reason, some researchers wash the tools before applying the sonic bath (Mercader 2009), whereas others employ an ultrasonic brush as an alternative to the sonic bath (Radomski and Neumann 2011). Despite some disadvantages, sonicating a grinding stone allows for the recovery of microbotanical remains from previously washed artefacts, which is often the case with finds coming from museum collections and old excavations (Yang et al. 2009), or from recent excavations in which artefacts were not sampled with attention for microbotanical analysis.

Microremains extraction

The methods for extracting microremains vary depending on the recovery method and the microbotanical remain(s) to be analysed. Spot sampling is usually employed for starch analysis, although Yang et al. (2013) also used it for recovering phytoliths. After the residue has been recovered, it may be directly mounted on a microscopy slide for analysis (e.g. Babot and Apella 2003) or treated with a heavy liquid to isolate starch grains (e.g. Liu et al. 2011). Samples recovered for phytolith analysis are usually chemically processed to deflocculate clays, dissolve carbonates, oxidise organic matter and isolate phytoliths (Albert and Portillo 2006).

Microremains analysis

During the microscopic analysis of the samples some researchers employ biological stains –such as Iodine Potassium Iodide or Congo red– to help identifying starch grains or to determine any change in the microstructure of the granules due to grinding/pounding (e.g. Barton 2007). A technique carried out in parallel with microbotanical remains and employed to better understand the history of the artefact is use-wear analysis (e.g. Revedin et al. 2010), although this approach is more common on other types of lithic tools (e.g. Barton et al. 1998).

In order to establish the primary context of the microremains analysed, the need of comparison with control samples is generally acknowledged (e.g. Yang et al. 2009). However, a literature survey (Table 5) seems to indicate that the recovery and analysis of control samples is not a common practice, mostly due to the lack of specifically designed sampling strategies during archaeological fieldwork.

Archaeological control samples can be obtained from the sediment beneath or around a tool and/or from an unused surface. When control samples are collected, the issue remains on how to compare them with the grinding stones.

For phytolith samples, both types of control samples may be used to check for contamination. However, phytoliths are generally ubiquitous, and a simple presence/absence assertion may not be enough to discard contamination. Phytolith concentration has been used as a contamination marker (e.g. Portillo et al. 2009), but concentrations depend on a number of factors –type of plants processed, type of context, etc.–, and this approach may yield inconclusive results. Kealhofer et al. (1999) proposed the use multivariate statistics (Correspondence Analysis) to compare phytoliths extracted from artefacts and the surrounding sediment matrix, but this method has not been generally adopted.

For starch samples, the most common approach is the assemblage comparison between artefacts and the archaeological context from which they were recovered (e.g. Dickau et al. 2012). However, this approach may also be inconclusive due to preferential preservation of starch grains in artefacts (Haslam 2004). Instead, a presence/absence comparison between used and unused surfaces seems a better strategy (e.g. Piperno et al. 2009), although some recovery methods (i.e. sonic bath) may prevent such comparison.

Another possible source of contamination, in particular for starch grains, is the laboratory where microremains extraction takes place. Starch is commercially used in a variety of products, including laboratory gloves –even when they are advertised as “powder-free” (Crowther et al. 2014). It is to be stressed that, despite the relatively high likelihood of contamination during sample processing, the analysis of control samples from laboratory consumables is very rare (see Table 5).

3.4.4. Earlier archaeobotanical research in Gujarat

Earlier archaeobotanical research in Gujarat has focused mostly on macrobotanical remains from Harappan settlements. Harappan subsistence strategies varied between the core Indus Valley and the periphery. In the core Indus, subsistence relied on *rabi* crops such as wheat, barley, chickpea (*Cicer arietinum* L.), lentil (*Lens culinaris* Medik.) and pea (*Pisum sativum* L.); whereas in Gujarat crops were mainly cultivated in summer, including large and small millets, rice (*Oryza* sp.) and tropical pulses such as mung bean (*Vigna radiata* (L.) R. Wilczek), black gram (*Vigna mungo* (L.) Hepper) and pigeon pea (*Cajanus cajan* (L.) Huth) (Fuller and Madella 2002).

The agricultural model proposed by Fuller and Madella (2002) for Harappan Gujarat was based on archaeobotanical remains from Urban and Post-Urban settlements in Saurashtra, such as Rojdi, Oriyo Timbo and Babar Kot (Reddy 1997; Weber 1999), and further supported by subsequent research at Bagasra (Luddy 2008, in Fuller 2011). However, the model was recently challenged by archaeobotanical research at Kanmer, a settlement in Kachchh occupied from the Early to the Post Urban Harappan Period (Pokharia et al. 2011). The archaeobotanical assemblage shows a switch from a predominance of *rabi* crops, mainly barley (93%), in the earlier phases towards a more diversified strategy at the end of the Harappan occupation, when the assemblage is dominated by *kharif* crops. Thus, the archaeobotanical assemblage from Kanmer seems to advocate for the existence of *rabi* cultivation in Early Harappan Gujarat. However, these results must be considered cautiously due to several reasons. First, 114 out of 117 barley seeds (97%) from the Early Harappan/Anarta assemblage come from a single deposit, which also included the only examples of other *rabi* crops in this phase –bread wheat (*Triticum aestivum* L.) and field pea (*Pisum sativum* ssp. *arvense* (L.) Asch.). The archaeological deposit where the *rabi* crops were encountered was probably the result of a single deposition event, and therefore cannot be considered representative of the plant-related subsistence strategy. Moreover, a directly dated barley caryopsis yielded a mid-third millennium cal. BC chronology, further questioning the Early Harappan categorisation of the deposit. Since these crops were found as a "cache" and there is no evidence of glumes either in the cache or anywhere else in the contemporaneous deposits, we also have to consider the (strong) possibility of trade with the core Indus valley. Therefore, the archaeobotanical assemblage from Kanmer cannot be taken as irrefutable proof of the existence of *rabi* cultivation in Early Harappan Gujarat.

The archaeobotanical remains from the Urban and Post-Urban deposits at Kanmer are not exempt from controversy either. The graphs presenting the percentage of crop taxa recovered from each phase do not include small millets (*Setaria* sp.) and *Coix* spp. (Pokharia et al. 2011: Fig. 5), thus inducing a bias in the interpretation of plant exploitation strategies and their change through time. This is particularly true for the Urban Harappan phase, in which 62.13% of the crops are calculated as *rabi* (mainly barley), but dropping to 36.05% when *Setaria* sp. caryopses are included (the remaining 63.95% being *kharif* crops). The percentage of *kharif* summer crops during the Post-

Harappan phase is >90%, either with or without *Setaria* and *Coix* spp. From the illustrations (Pokharia et al. 2011: Fig. 4a), the grains identified as *Setaria* sp. might belong to yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.) and/or browntop millet (*Brachiaria ramosa* (L.) Stapf), both of which are still consumed in modern southern India (Kimata et al. 2000). Their consumption in Kanmer seems plausible, especially considering the presence of weeds commonly associated with small millet cultivation, such as *Trianthema* spp. A similar scenario can be envisaged for *Coix* spp., which are commonly used as beads but also consumed nowadays in northeastern India (Arora 1977). Therefore, when analysed critically, the plant remains from Kanmer do agree with the model proposed by Fuller and Madella (2002). The relatively high presence of barley and wheat during the Urban Harappan phase (28.15% and 3.46% of the total crop taxa, respectively) was probably the result of trade contacts with the Indus Valley, clearly reflected in the site's material culture (Kharakwal et al. 2011). A minor presence of these cereals is echoed in the archaeobotanical assemblage from other Urban Harappan settlements in Gujarat such as Rojdi or Bagasra (Fuller 2011; Weber 1999).

Archaeobotanical discussion in Harappan Gujarat has also revolved around the identification of African crops, especially finger millet (*Eleusine coracana* Gaertn.), pearl millet (*Pennisetum glaucum* (L.) R.Br.) and sorghum (*Sorghum bicolor* (L.) Moench) (e.g. Misra and Kajale 2003). African millets have been identified in several Urban Harappan contexts (for a review see Pokharia et al. 2014). However, these identifications have been called into question, and the arrival of African crops in South Asia –including millets but also non-cereal crops such as cowpea (*Vigna unguiculata* (L.) Walp.) and hyacinth bean (*Lablab purpureus* (L.) Sweet)– is usually dated to the early second millennium BC, during the Post-Urban Harappan phase (Fuller 2003a, 2006a; Fuller and Boivin 2009; Fuller et al. 2011b; Weber 1998).

4. Materials and Methods

This chapter describes the materials analysed in this study and the methods used to process and analyse modern plant material and archaeological samples, including sediment samples and residue from grinding stones.

4.1. Reference collections

As part of this study, a modern plant reference collection (PRC) based on savannah-type South Asian flora was developed and integrated in the pre-existing collection of the BioGeoPal Laboratory (Table 6). The list of taxa selected was based on previous ethnobotanical and archaeobotanical research in Gujarat and other parts of South Asia, and it included Near Eastern, African and East Asian crops (Arora 1977; Constantini 2008; Fuller 2001, 2002, 2003a, 2005, 2006a, 2006b, 2011; Fuller and Boivin 2009; Fuller and Madella 2002; Fuller et al. 2001, 2004; Gupta and Sharma 1971; Kashyap and Weber 2010; Kimata et al. 2000; Lancelotti 2010; Parmar et al. 2012; Patel et al. 2013; Pokharia et al. 2011, 2014; Reddy 1997; Singh 2010; Tengberg 1999; Weber 1998, 1999; Webber and Fuller 2008; Webber and Kashyap 2013; Weber et al. 2011). The materials for the PRC were mostly obtained through the National Plant Germplasm System of the U.S. Department of Agriculture (USDA). Modern plants collected in the filed (such as one unidentified sedge, locally known as '*moot*') and materials from the PRCs of the University College London (Institute of Archaeology), the University of Sheffield (Department of Archaeology) and the Botanical Institute of Barcelona (IBB-CSIC) were also consulted.

Table 6. List of taxa of the modern plant reference collection developed as part of this study.

Family	**Subfamily**	***Species***	**Vernacular name**
Amaranthaceae	Chenopodioideae	*Chenopodium album* L.	white goosefoot
Cyperaceae	–	*Cyperus esculentus* L.	chufa sedge
		Undetermined	moot
Fabaceae	Faboideae	*Cajanus cajan* (L.) Huth	pigeon pea
		Cicer arietinum L.	chickpea
		Crotalaria sp.	rattlepod
		Lablab purpureus (L.) Sweet	hyacinth bean
		Lathyrus sativus L.	grass pea
		Lens culinaris Medik.	lentil
		Macrotyloma uniflorum (Lam.) Verdc.	horse gram
		Pisum sativum L.	pea
		Trigonella foenum-graecum L.	fenugreek
		Vicia sativa L.	common vetch
		Vigna aconitifolia (Jacq.) Marechal	moth bean
		V. mungo (L.) Hepper	black gram
		V. radiata (L.) R.Wilczek	mung bean
		V. umbellata (Thunb.) Ohwi & H.Ohashi	rice bean
		V. unguiculata (L.) Walp.	cowpea

Family	**Subfamily**	***Species***	**Vernacular name**
Linaceae	–	*Linum usitatissimum* L.	flax
Papaveraceae	Papaveroideae	*Papaver somniferum* L.	poppy seed
Pedaliaceae	–	*Sesamum indicum* L.	sesame
Poaceae	Chloridoideae	*Eleusine coracana* Gaertn.	finger millet
	Ehrhartoideae	*Oryza sativa* L.	rice
	Panicoideae	*Brachiaria ramosa* (L.) Stapf.	browntop millet
		Coix lacryma-jobi L.	Job's tears
		Digitaria ciliaris (Retz.) Koeler	southern crabgrass
		Echinochloa crus-galli (L.) P.Beauv.	barnyard millet
		E. colona (L.) Link	shama millet
		E. frumentacea Link	sawa millet
		Panicum miliaceum L.	proso millet
		P. sumetrense Roth	little millet
		Paspalum scrobiculatum L.	kodo millet
		Pennisetum alopecuroides (L.) Spreng	fountain grass
		P. glaucum (L.) R.Br.	pearl millet
		Setaria italica (L.) P.Beauv.	foxtail millet
		S. pumila (Poir.) Roem. & Schult.	yellow foxtail
		S. verticillata (L.) P.Beauv.	bristly foxtail
		S. viridis (L.) P.Beauv.	green foxtail
		Sorghum bicolor (L.) Moench	sorghum
		Zea mays L.	maize
	Pooideae	*Avena sativa* L.	oat
		Hordeum vulgare L.	barley
		Triticum aestivum L.	bread wheat
		T. aest. ssp. *sphaerocuccum* (Perc.) MK.	dwarf wheat
		T. turgidum ssp. *dicoccum* Schrank	emmer wheat
Solanaceae	Solanoideae	*Solanum melongena* L.	aubergine
Zingiberaceae	Zingiberoideae	*Curcuma longa* L.	turmeric
		Zingiber officinale Roscoe	ginger

4.1.1. Macrobotanical remains

Understanding the processes of plant domestication and dispersion is necessary to fully comprehend human-plant coevolution (Jackson 1996; Purugganan and Fuller 2009, 2011; Rindos and Dunell 1984). Nowadays regarded as a minor cereal, foxtail millet (*Setaria italica* (L.) P.Beauv.) was widely cultivated across Eurasia during prehistoric times (Hunt et al. 2008). *S. italica* presumably originated from green foxtail (*Setaria viridis* (L.) P.Beauv.) and was domesticated in the upper Yellow River basin (northern China) during the eighth millennium BP, from where it dispersed east and westwards (Nasu et al. 2007). The time and route of introduction of *S. italica* in South Asia is a controversial issue (Hunt and Jones 2008). Findings of this crop have been reported from archaeological sites in India and Pakistan during the third millennium BC (Pokharia et al. 2014 and references therein). However, after a review of published literature, Fuller (2002, 2003a, 2006a) argued that earlier findings of this crop actually belong to browtop millet (*Brachiaria ramosa* (L.) Stapf.) or other *Setaria* spp., and that *S. italica* most likely reached South Asia during the second millennium BC. Identification of charred *S. italica* usually relies on length to breath ratio of the caryopses and the surface sculpture of the lemma (Nasu et al. 2007). However, there is a wide range of variation in the size and shape of many wild and cultivated *Setaria* and related species, and carbonisation often deforms the grain morphology. Small millet husk, which could help in the identification, is seldom recovered from archaeological contexts. Furthermore, the rugose husk patterns of *S. italica* are also likely to be confused with those of *B. ramosa* (Fuller 2006a).

An experiment using geometric morphometrics (GM) was carried out to securely distinguish among charred caryopses of *S. italica* and *B. ramosa*. Over 30 modern *S. italica* and *B. ramosa* caryopses were randomly selected for the experiment. GM were conducted both before and after charring to understand the morphological variation that occurs in these taxa during carbonisation. Previous charring experiments, carried out with *S. italica* and *P. miliaceum*, showed that small millet caryopses are usually deformed when carbonised, and that charring conditions (oxidising/reducing, temperature, time) greatly affect their likelihood of preservation in the archaeological record (Märkle and Rösch 2008; Motuzaite-Matuzeviciute et al. 2012; Yang et al. 2011). After a series of charring experiments (Table 7), the optimum carbonising conditions for *S. italica* and *B. ramosa* for this study were determined; grains were individually wrapped in aluminium foil (ensuring totally anoxic conditions) and charred into a furnace for 3h at 250°C.

Table 7. Charring experiments with modern *Setaria italica* and *Brachiaria ramosa* caryopses.

Temp	Time	Condition	*Species*	Result
250 °C	3h	Oxidising	*Setaria italica*	Open crease
			Brachiaria ramosa	Deformed
250 °C	3h	Reducing	*Setaria italica*	Deformed
			Brachiaria ramosa	Deformed
200 °C	3h	Reducing	*Setaria italica*	Not charred
			Brachiaria ramosa	Not charred
200 °C	5h	Reducing	*Setaria italica*	Partly charred
			Brachiaria ramosa	Partly charred
200 °C	8h	Reducing	*Setaria italica*	Partly charred
			Brachiaria ramosa	Partly charred
250 °C	3h	Totally anoxic	*Setaria italica*	Charred, optimum
			Brachiaria ramosa	Charred, optimum

Modern caryopses were photographed before and after charring with a Leica EZ4D stereoscope. TPSdig software (Rohlf 2013) was used to scale the photographs and manually apply the landmark configuration designed for this study. In order to overcome the morphological bias caused by carbonisation on the overall grain shape, the landmark configuration focused on the shape of the embryo, less affected by charring. A total of nine homologous points were recorded (Table 8; Fig. 8); L1 to L3 are anatomical, type II landmarks that further served as anchors for sliding the semilandmarks (SL1 to SL6). The use of semilandmarks enables the quantification of homologous curves and their analysis together with traditional landmarks (Gunz and Mitteroecker 2013). Semilandmark sliding was conducted using the approach of minimising the Procrustes distance, where each landmark separately slides on tangent lines to the respective curve (outline of the embryo). Sliding removes the effect of arbitrary placing by minimising the position of the semilandmarks respect to the average shape of the sample (Adams and Otárola-Castillo 2013; Bookstein 1997; Gunz and Mitteroecker 2013; Gunz et al. 2005). Semilandmark sliding was computed in the Geomorph package for geometric morphometric analyses (Adams and Otárola-Castillo 2013) developed for R (R Development Core Team 2008).

Table 8. Description of the landmark configuration used in this study.

Name	Type	Description
L1	II	Maximum curvature point of the superior aspect of the embryo outline.
L2	II	Distal end of the left half of the embryo outline.
L3	II	Distal end of the right half of the embryo outline.
SL1	III	Middle point between L1 and SL2.
SL2	III	Middle point between L1 and L2.
SL3	III	Middle point between L2 and SL2.
SL4	III	Middle point between L1 and SL5.
SL5	III	Middle point between L1 and L3.
SL6	III	Middle point between L3 and SL5.

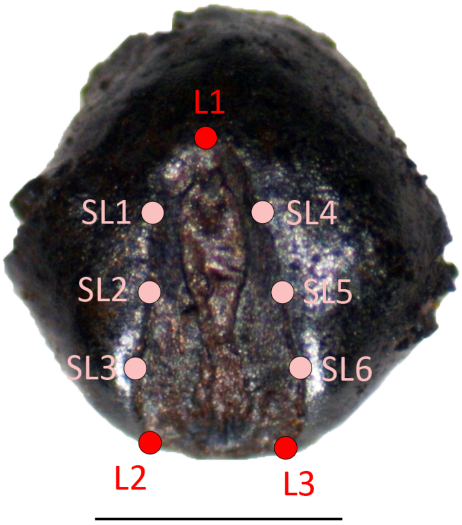


Figure 8. Landmark configuration used in this study implemented on a modern *Setaria italica* caryopsis after charring at 250°C in totally anoxic conditions for 3h. Scale bar 1 mm.

A General Procrustes Analysis (GPA) was carried out in MorphoJ (Klingenberg 2011) to perform the superimposition in which the landmark configuration of each individual was rotated, translated to an origin point and scaled to unit of centroid size (CS) minimising the sum of square differences among configurations (Rohlf 1999; Zelditch et al. 2012). The coordinates were afterwards projected onto the tangent space to allow flat-space (Euclidean) statistical implementation. A permutation test of 1,000 replicates was performed using both Procrustes and Mahalanobis distances to test for significant differences between groups for charred and uncharred modern caryopses (Klingenberg 2011).

Principal Components Analysis (PCA) was used to ordinate the Procrustes aligned coordinates, reducing the multidimensional data to a set of eigenvectors according to the accumulation of maximum variability criteria in each vector. PCAs were conducted before and after charring the modern caryopses, and the distribution of the samples was explored by plotting the first against the second PC.

4.1.2. Phytoliths

Certain taxa were processed for the observation of phytoliths in anatomical connection, focusing on those species not previously assessed in the literature. An earlier study showed that South Asian pulses (including woody Fabaceae) do not produce taxonomically diagnostic phytoliths (Lancelotti 2010), and therefore the phytolith reference collection focused on grasses, particularly millets. I focused on floral parts (glumes, paleas and lemmas), as they have been found to be the most taxonomically diagnostic (Lu et al. 2009; Zhang et al. 2011). Phytolith samples were prepared according to the following procedure:

1. Separate the floral parts from the grains using tweezers and a scalpel.
2. Clean the floral parts with distilled H_2O in an ultrasonic bath for 10 minutes to remove any dust or contaminant.
3. Soak the floral parts in bleach until they become transparent and subsequently rinse with distilled H_2O.
4. Mount the floral parts on a microscope slide with distilled H_2O and cover with a covering slip fixed at the four corners with transparent nail polish. With this technique, the preparations can be stored dehydrated and H_2O can be added before further observations at the microscope.

4.1.3. Starch grains

All starchy taxa in the PRC were processed for the observation of starch grains. The starch reference collection included maize to check for potential contamination, as it is the most common source of commercial starch (Crowther et al. 2014). Starch samples were prepared according to the following procedure (modified after Field 2006):

1. Mill one levelled teaspoon of seeds in an agate mortar.
2. Sieve the residue through a 0.25 mm mesh.
3. Mount the resulting powdered starch on a microscope slide with 50% glycerol and cover with a covering slip fixed at the four corners with transparent nail polish. With this technique, the preparations can be stored flat for months and, when dehydrated, 50% glycerol can be added before further observations at the microscope.

4.2. Archaeological contexts

The materials analysed in this study were collected from four archaeological occupations excavated between 2009 and 2012 in northern Gujarat: Vaharvo Timbo (VHV), Loteshwar (LTS), Datrana IV (DTR) and Shikarpur (SKP) (Fig. 9). The archaeological contexts cover the transition from hunter-gatherer groups to fully agro-pastoral urban societies (Table 9).

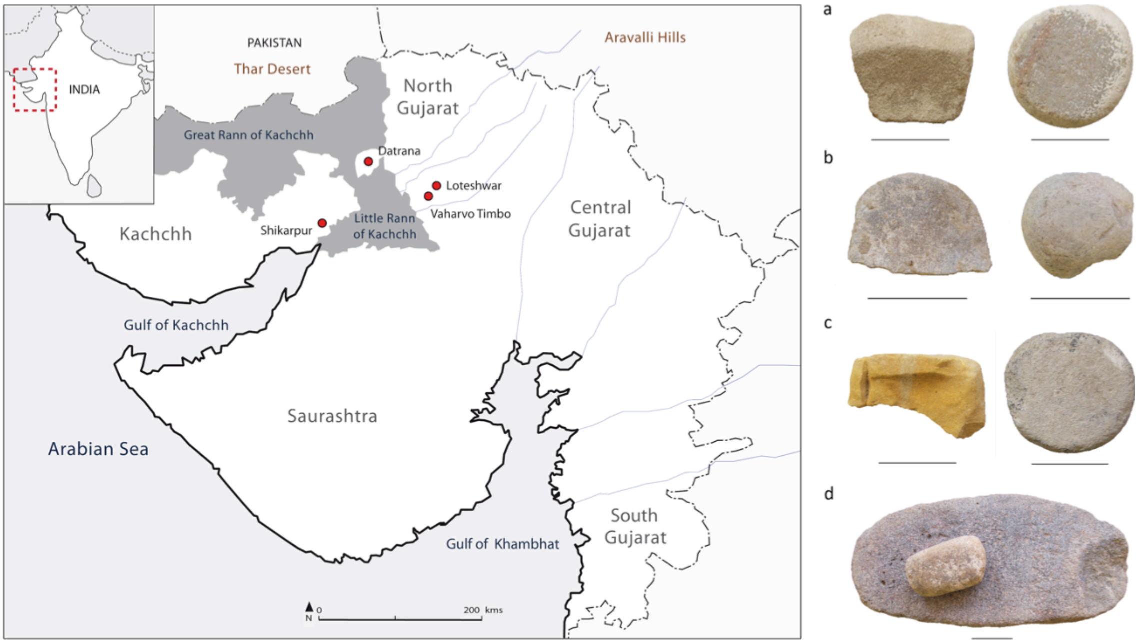


Figure 9. Map of Gujarat showing the location of the sites and examples of grinding stones analysed in this study. a) Vaharvo Timbo, b) Loteshwar, c) Datrana IV and d) Shikapur. Scale bars 5 cm. (map by Francesc. C. Conesa).

Table 9. Context of the archaeological samples analysed in this study.

Site	Code	Chronology (cal. BC)	Type of occupation
Vaharvo Timbo	VHV	ca. 5600-5000	Hunter-gatherer camp
Loteshwar (hg)	LTS_HG	ca. 7150-5550	Hunter-gatherer camp
Loteshwar (mix)	LTS_MIX	–	–
Loteshwar (ap)	LTS_AP	ca. 2700-2300	Anarta agro-pastoral camp
Datrana	DTR	ca. 3300-3000	Pre-Prabhas lithic blade workshop
Shikarpur	SKP	ca. 2200-1900	Urban Harappan settlement

4.2.1. Sampling strategy

The excavation proceeded in trenches of 4x4 m divided into 2x2 m sub-squares, treating the materials from each sub-square separately during and after the excavation. Floatation was systematically applied to recover both microfaunal and macrobotanical remains. Bulk samples (10-20 l of sediment) were floated from each excavation spit (ca. 10 cm) of each sub-square and from all the archaeological features identified during the excavation (e.g. fire-related contexts). Moreover, loose sediment samples were collected from each homogenised floatation sample, prior to floatation, for the extraction of microbotanical remains and soil pH analysis.

Grinding stones were collected foreseeing the analysis of microbotanical remains. In order to minimise the possibility of contamination during artefact recovery, direct touching of the used surface/s of the grinding stones with bare hands was avoided and powder-free gloves were used when available. After retrieval, the single artefact was bagged in a zip-lock plastic bag and sealed. The bag containing the artefact together with a label tag was placed into a second bag.

Small zip-lock plastic bags with approximately 25 g of sediment from the context related to the artefact –the area surrounding the artefact, but not the sediment directly in contact with it– were collected as control samples. Control samples were gathered from different spots all around the artefact to average the signal and avoid the possibility of unintentionally recovering sediment representing a specific activity area. When two or more artefacts were recovered from the same archaeological context, a single control sample was collected for all of them.

A total of 1,840 l of floated sediment were sorted and 47 phytolith and starch samples were analysed from archaeological contexts, including general sediments and control samples for the grinding stones. Moreover, soil pH was measured in 25 sediment samples. Finally, microbotanical remains were analysed from 67 grinding stones for a total of 80 samples –multiple surfaces and broken pieces from the same tool were analysed separately.

4.2.2. Vaharvo Timbo

Vaharvo Timbo (23^{o} 33’ 17.05”; 71^{o} 48’ 12.01”), locally known as Wasaro no Timbo, is located near Runi village, Patan district (Fig. 9). It is part of a group of five top-dune hunter-gatherer occupations around a large interdunal depression in the dune-interdune area (Balbo et al. 2013: Fig. 7c). A preliminary assessment of the sedimentary deposit of the large interdunal depression showed that it was a permanent water body until ca. 7000 years ago, when it became a seasonal marsh probably due to changes in the monsoon regime (NoGAP unpublished research).

The site was reported in the early 1980s but never excavated (Bhan 1994: Appendix). The members of the NoGAP project visited the mound during a field survey in 2010, when it attracted our attention due to the high number of grinding tools and small animal bone fragments dispersed over its surface and the absence of pottery. The top of the dune was not being cultivated either when it was first visited in 2010 or when it was excavated in 2011. However, local peasants claimed that big bones had been removed when ploughing the field some seasons back.

The 2011 excavation

The NoGAP team excavated two trenches at VHV in 2011 to gather information on hunter-gatherer subsistence strategy (Madella et al. 2012a). Trench I presented a uniform aceramic hunter-gatherer occupation of ca. 100 cm with three pits of different size and shape down to about 135 cm. Pits were detected only after the excavation, when they could be observed in the sections. Therefore, during the excavation materials from the pits were not separated from those recovered in the general sediment. Materials collected during the excavation of Trench I included worked bone fragments, an unusual large number of crayon fragments, grinding tools, 93 small potsherds –most of which are modern or non-diagnostic–, small bone fragments and several tusk shell (*Dentalium* sp.) beads. Chert and chalcedony tools dominated the microlithic assemblage. Trench II had also an aceramic deposit cut by a human burial. The grave goods included two full pots identified as Early Harappan Sindh pottery type (ca. 2800-2600 BC, Ajithprasad 2011).

Charcoal was not encountered during the excavation of either trench; therefore, special care was taken to collect charred bones for radiocarbon dating. Three AMS dates, provided by Beta Analytics, were obtained from charred faunal remains recovered from Trench I (Table 10), showing a relatively long hunter-gatherer occupation of the dune (ca. 5600-5000 cal. BC).

Table 10. AMS radiocarbon dates from the 2011 excavation at Vaharvo Timbo.

Context	Description	Depth (cm)	^{14}C-age (yr BP)	2-σ cal. age (yr BC)	Lab code
HG 2	General Mesolithic deposit	17-21	6160 ± 40	5220-5000	Beta-366711
HG 5	S pit, Mesolithic	64-78	6290 ± 40	5320-5210	Beta-366709
HG 6	N pit, Mesolithic	119-135	6650 ± 40	5640-5510	Beta-366710

Samples

A total of 1,480 l of sediment were floated from Trench I during the 2011 field season at VHV, of which 380 l were analysed for this study. Moreover, seven phytolith and starch samples were analysed from sediment samples to study the distribution of microbotanical remains throughout the site and as control samples for the grinding stones (Table 11). It was not possible to collect floatation samples from the pits because they were not detected during the excavation. Finally, a total of 20 microremain samples were analysed from 19 grinding tools recovered at VHV in 2011, including 10 fragmented grinding slabs and nine handstones (Table 12).

Table 11. Sediment samples from Vaharvo Timbo analysed in this study.

Context	Sample ID	Description	Sediment volume (l)	Phytolith samples	Starch samples
HG 1	Dep 1	General Mesolithic deposit	80	1	1
HG 2	Dep 2	General Mesolithic deposit	60	1	1

Context	Sample ID	Description	Sediment volume (l)	Phytolith samples	Starch samples
HG 3	Dep 3	General Mesolithic deposit	140	1	1
HG 4	Dep 4	General Mesolithic deposit	100	1	1
HG 5	Pit S	S pit, Mesolithic	✗	1	1
HG 6	Pit N1	N pit, Mesolithic, upper part	✗	1	1
HG 6	Pit N2	N pit, Mesolithic, lower part	✗	1	1
–	–	**Total**	**380**	**7**	**7**

Table 12. Morphotypological description of the grinding stones from Vaharvo Timbo analysed in this study. (descriptive terms after Wright 1992).

Context	Sample ID	Description	Control sample
HG 1	GS 1	Fragmented basin grinding slab	Control 1 (Dep 1)
HG 1	GS 2	Fragmented unifacial rectilinear handstone	Control 1 (Dep 1)
HG 1	GS 3	Fragmented basin grinding slab	Control 1 (Dep 1)
HG 1	GS 4	Fragmented basin grinding slab	Control 1 (Dep 1)
HG 1	GS 5	Fragmented unifacial ovate handstone	Control 1 (Dep 1)
HG 2	GS 6	Fragmented basin grinding slab	Control 2 (Dep 2)
HG 2	GS 7	Fragmented basin grinding slab	Control 2 (Dep 2)
HG 1	GS 8	Fragmented basin grinding slab	Control 1 (Dep 1)
HG 2	GS 9	Fragmented unifacial rectilinear handstone	Control 2 (Dep 2)
HG 2	GS 10	Fragmented unifacial rectilinear handstone	Control 2 (Dep 2)
HG 2	GS 11	Fragmented basin grinding slab	Control 2 (Dep 2)
HG 2	GS 12	Fragmented basin grinding slab	Control 2 (Dep 2)
HG 2	GS 13	Fragmented unifacial rectilinear handstone	Control 2 (Dep 2)
HG 3	GS 14	Fragmented. unifacial rectilinear handstone	Control 3 (Dep 3)
HG 3	GS 15	Unifacial discoidal handstone	Control 3 (Dep 3)
HG 3	GS 16a	Fragmented unifacial rectilinear handstone, fragment a	Control 3 (Dep 3)
HG 3	GS 16b	Fragmented unifacial rectilinear handstone, fragment b	Control 3 (Dep 3)
HG 3	GS 17	Fragmented basin grinding slab	Control 3 (Dep 3)
HG 4	GS 18	Fragmented basin grinding slab	Control 4 (Dep 4)
HG 4	GS 19	Fragmented unifacial rectilinear handstone	Control 4 (Dep 4)

4.1.3. Loteshwar

Loteshwar (23^{o} 36′ 1.8″ N; 71^{o} 50′ 11.8″ E), locally known as Khari no Timbo, is situated near Loteshwar village, Patan district, about 500 m east from the Khari River (Fig. 9). The site is located in the dune-interdune area, 6 km northeast of Vaharvo Timbo. Excavations conducted by the Department of Archaeology and Ancient History, MSUB in the early 1990s uncovered two levels: a Mesolithic hunter-gatherer occupation with superimposed Anarta Chalcolithic deposits (IAR 1995a). The study of faunal remains indicated that HG populations exploited a wide range of wild animals, including blackbuck (*Antilope cervicapra* L.) and chinkara (*Gazella bennetti* Sykes), whereas the Anarta populations exploited mostly domestic zebu (Patel 2009). The Mesolithic deposits from LTS were AMS dated between 7168-4703 cal. BC, pre-dating the hunter-gatherer occupation of VHV and placing LTS as one of the earliest Holocene hunter-gatherer occupations in northwestern India (Ajithprasad 2002, 2004; Patel 2009;

Sonawane and Ajithprasad 1994). Moreover, the Anarta occupation of the dune (3681-2243 cal. BC) predates the establishment of Urban Harappan communities in Gujarat (Ajithprasad and Sonawane 2011).

The 2009 excavation

The NoGAP excavated one trench at LTS in 2009 (Madella et al. 2011). The stratigraphic sequence uncovered features comparable to those identified in the previous excavations: an aceramic hunter-gatherer (Mesolithic) deposit of about 80 cm and an Anarta deposit of about 60 cm, separated by a mixed deposit of about 40 cm with a few, small potsherds. The hunter-gatherer and the mixed levels were cut by three Anarta pits down to 50/170 cm, presenting a lining of plant material preserved as a pure phytolith layer (Balbo et al. 2014).

Artefacts recovered from the AP deposit include almost 13,000 sherds of Anarta pottery –some of them reworked, such as perforated discs–, two sherds of Harappan pottery, three copper objects, several beads made from different stones such as steatite and lapis lazuli, bone fragments, tusk shell beads, chank shell bangle pieces, worked bone fragments, terracotta objects –including a singular human figurine– and a great number of grinding tools. The HG deposit was composed mainly of grinding tools, small bone fragments and a microlithic assemblage similar to the one from the upper levels. Indeed, a typo-technological analysis of the lithic assemblage, in particular the cores, shows continuity of the quartering technique of stone tool manufacturing for over five thousand years (Gadekar et al. 2014a).

Seven AMS dates were obtained from single wood charcoals at the CNA (Centro Nacional de Aceleradores, Sevilla, Spain) (Table 13). The dates of the 2009 excavation show a shorter Anarta occupation of the dune (ca. 2700-2300 cal. BC) than the dates obtained in the previous excavations (ca. 3700–2250 cal. BC). The Mesolithic and mixed levels were also dated ca. 2700-2300 cal. BC, suggesting that there was a post-depositional infiltration of wood charcoal from the Anarta deposits.

Table 13. AMS radiocarbon dates from the 2009 excavation at Loteshwar.

Context	**Description**	**Depth (cm)**	**^{14}C-age (yr BP)**	**2-σ cal. age (yr BC)**	**Lab code**
AP 1	General Anarta deposit	57-64	3975 ± 35	2577-2438	2219.1.1
AP 2	NE pit, Anarta	140-150	3910 ± 35	2477-2291	2224.1.1
AP 4	NW pit, Anarta	129-137	3925 ± 35	2491-2295	2225.1.1
AP 5	NE ashy patch, Anarta	77-85	4055 ± 35	2678-2475	2220.1.1
MIX	Mixed level, general sed	114-123	3915 ± 35	2487-2290	2221.1.1
MIX	Mixed level, general sed	123-140	3985 ± 35	2580-2455	2222.1.1
HG	General Mesolithic deposit	138-151	4075 ± 35	2701-2557	2223.1.1

Samples

A total of 2,156 l of sediment were floated during the 2009 field season at LTS, of which 740 l were analysed for this study. Moreover, eight sediment samples were analysed for phytolith and starch to study the distribution of microbotanical remains throughout the site and as control samples for the grinding stones (Table 14). It was not possible to analyse floatation samples from the NE sub-square due to a mishap during the laboratory work. Finally, a total of 19 microremain samples were analysed from 13 grinding tools recovered at LTS in 2009, including five fragmented grinding slabs and eight handstones (Table 15).

Table 14. Sediment samples from Loteshwar analysed in this study.

Context	Sample ID	Description	Sediment volume (l)	Phytolith samples	Starch samples
AP 1	Dep 1	General Anarta deposit	240	1	1
MIX	Dep 2	Mixed between Dep 1/3	75	1	1
HG	Dep 3	General Mesolithic deposit	50	1	1
AP 3	Pit 1	SE pit, Anarta	135	1	1
AP 2	Pit 2	NE pit, Anarta	✗	1	1
AP 4	Pit 3	NW pit, Anarta	160	1	1
AP 5	Ash 1	NE ashy patch, Anarta	✗	1	1
AP 6	Ash 2	NW ashy patch, Anarta	80	1	1
–	–	**Total**	**740**	**8**	**8**

Table 15 Morphotypological description of the grinding stones from Loteshwar analysed in this study. (descriptive terms after Wright 1992).

Context	Sample ID	Description	Control sample
AP 1	GS 1a	Fragmented bifacial discoidal/lens handstone, face a	Control 1 (Dep 1)
AP 1	GS 1b	Fragmented bifacial discoidal/lens handstone, face b	Control 1 (Dep 1)
AP 1	GS 2a	Half bifacial ovate/oval handstone, face a	Control 1 (Dep 1)
AP 1	GS 2b	Half bifacial ovate/oval handstone, face b	Control 1 (Dep 1)
AP 2	GS 3a	Fragmented bifacial handstone, face a	Control 2 (Pit 2)
AP 2	GS 3b	Fragmented bifacial handstone, face b	Control 2 (Pit 2)
AP 3	GS 4	Fragmented basin grinding slab	Control 3 (Pit 1)
HG	GS 5	Fragmented saddle-shaped grinding slab	Control 5 (Dep 3)
AP 4	GS 6a	Broken handstone, used as grinding slab	Control 6 (Pit 3)
AP 4	GS 6b	Unifacial ovate handstone	Control 6 (Pit 3)
MIX	GS 7a	Half basin grinding slab, face a (not used?)	Control 4 (Dep 2)
MIX	GS 7b	Half basin grinding slab, face b	Control 4 (Dep 2)
MIX	GS 8	Half basin grinding slab	Control 4 (Dep 2)
MIX	GS 9	Half bifacial ovate/oval handstone	Control 4 (Dep 2)
MIX	GS 10	Half unifacial rectilinear handstone	Control 4 (Dep 2)
HG	GS 11	Half unifacial ovate handstone	Control 5 (Dep 3)
HG	GS 12a	Fragmented bifacial rectilinear/flat handstone, face a	Control 5 (Dep 3)
HG	GS 12b	Fragmented bifacial rectilinear/flat handstone, face b	Control 5 (Dep 3)
HG	GS 13	Fragmented basin grinding slab	Control 5 (Dep 3)

4.2.4. Datrana IV

Datrana IV (23° 46’ 41.7” N, 71° 07’ 26.2” E), locally known as Hadka valo Timbo, is located on a large crescent-shaped stabilised dune about 2 km north east of Datrana village, Patan district (Fig. 9). This site is part of a large (40 ha) archaeological complex formed by discrete clusters of artefacts spread through ten mounds around a large interdunal depression.

The excavations conducted by the Department of Archaeology and Ancient History, MSUB between 1993 and 1995 uncovered a Mesolithic hunter-gatherer occupation with superimposed Chalcolithic deposits (IAR 2000a, 2000b). Otoliths from the Mesolithic level were AMS dated to the early eighth millennium cal. BC (unpublished data, P. Ajithprasad pers. comm.). The majority (>95%) of the ceramic assemblage from the Chalcolithic deposits was characterised as Pre-Prabhas (Ajithprasad 2002, 2011; Rajesh et al. 2013; Sonawane and Ajithprasad 1994). The ceramic assemblage from DTR further included a minor (<5%) presence of Early Harappan Sindh (Indus Valley, ca. 2800-2600 cal. BC) and Anarta pottery (Ajithprasad 2002). Moreover, the evidence suggested the production of beads from agate, carnelian, chert and amazonite using a technology not attested in other Chalcolithic sites in North Gujarat or the Indus Valley (Madella et al. 2012b).

The 2010 excavation

The NoGAP project excavated one trench at DTR in 2010 (Madella et al. 2012b). The excavation revealed a 50 cm cultural deposit belonging to the Chalcolithic occupation. Four single wood charcoals were AMS dated ca. 3300-3000 cal. BC at the CNA (Table 16). Unlike the previous excavations, no hunter-gatherer occupation was uncovered during the 2010 field season. The artefacts recovered included lithic implements, pottery, copper/bronze punch points, stone beads and bead roughouts, a cluster of burned carnelian nodules, stone drill bits, facetted crayons, hammer stones and grinding tools. No structural remains, hearths or ash concentrations were found. No evidence of a clear activity floor could be identified during the excavation, but several clusters of animal bones, potsherds and lithic tools (‘trash pits’) were encountered. Faunal remains were very fragmented, and some were partially charred.

Table 16. AMS radiocarbon dates from the 2010 excavation at Datrana IV.

Context	**Description**	**Depth (cm)**	**^{14}C-age (yr BP)**	**2-σ cal. age (yr BC)**	**Lab code**
AP 4	Cluster of remains (‘trash pit’)	17-19	4465 ± 35	3339-3204, 3197-3023	2227.1.1
AP 7	General Pre-Prabhas deposit	24-28	4505 ± 35	3353-3096	2229.1.1
AP 5	General Pre-Prabhas deposit	42-47	4465 ± 35	3339-3204, 3197-3022	2226.1.1
AP 9	General Pre-Prabhas deposit	58-68	4460 ± 35	3339-3204, 3197-3018	2228.1.1

An exhaustive study of the lithic assemblage revealed over 10,000 stone blades, few geometric and non-geometric tools and over 77,000 pieces of lithic debitage, mostly made of chalcedony (Gadekar et al. 2013). Two nearby sources of chalcedony nodules were encountered during an exploratory survey, both located about 20 km from the site (Madella et al. 2012). Blades were removed by crested guiding ridge technique, a practice associated with Chalcolithic settlements of the Indus Civilisation (Cleland 1977). In addition, the lithic assemblage included a few examples of Rohri chert blades from the Rohri Hills in Sindh, Pakistan (Biagi and Cremaschi 1991), over 500 km northwest of Datrana. The absence of Rohri chert debitage indicates that these blades were not locally produced but imported (Gadekar et al. 2013).

Samples

A total of 1,000 l of sediment were floated during the 2010 field season at DTR, of which 480 l were analysed for this study. Moreover, 10 phytolith and starch samples were analysed from sediment samples to study the distribution of microbotanical remains throughout the site and as control samples for the grinding stones (Table 17). Floatation samples from context AP 5 were not analysed due to a mishap during laboratory work. Finally, a total of 21 microremain samples were analysed from 17 grinding tools, including 16 fragmented grinding slabs and one handstone (Table 18).

Table 17. Sediment samples from Datrana IV analysed in this study.

Context	Sample ID	Description	Sediment volume (l)	Phytolith samples	Starch samples
AP 1	DTR 9	General Pre-Prabhas deposit	60	1	1
AP 2	DTR 10	Cluster of remains (‘trash pit’)	20	1	1
AP 6	DTR 11	Cluster of remains (‘trash pit’)	20	1	1
AP 3	DTR 12	Cluster of remains (‘trash pit’)	20	1	1
AP 4	DTR 13	Cluster of remains (‘trash pit’)	80	1	1
AP 7	DTR 25	General Pre-Prabhas deposit	80	1	1
AP 5	DTR 27	General Pre-Prabhas deposit	✗	1	1
AP 8	DTR 30	Cluster of burned carnelian nodules	40	1	1
AP 9	DTR 34	General Pre-Prabhas deposit	60	1	1
AP 10	DTR 44	General Pre-Prabhas deposit	100	1	1
–	–	**Total**	**480**	**10**	**10**

Table 18. Morphotypological description of the grinding stones from Datrana IV analysed in this study. (descriptive terms after Wright 1992).

Context	Sample ID	Description	Control sample
AP 2	GS 1	Fragmented basin grinding slab	Control 2 (DTR 10)
AP 3	GS 2	Fragmented saddle-shaped grinding slab	Control 3 (DTR 12)
AP 3	GS 3	Fragmented saddle-shaped grinding slab	Control 3 (DTR 12)
AP 3	GS 4a	Fragmented saddle-shaped grinding slab, face a	Control 3 (DTR 12)
AP 3	GS 4b	Fragmented saddle-shaped grinding slab, face b	Control 3 (DTR 12)
AP 3	GS 5	Fragmented saddle-shaped grinding slab	Control 3 (DTR 12)
AP 3	GS 6a	Fragmented saddle-shaped grinding slab, face a	Control 3 (DTR 12)
AP 3	GS 6b	Fragmented saddle-shaped grinding slab, face b	Control 3 (DTR 12)

Context	Sample ID	Description	Control sample
AP 3	GS 7	Fragmented saddle-shaped quern	Control 3 (DTR 12)
AP 3	GS 8	Unifacial discoidal handstone	Control 3 (DTR 12)
AP 2	GS 9	Fragmented saddle-shaped grinding slab	Control 2 (DTR 10)
AP 1	GS 10	Fragmented saddle-shaped grinding slab	Control 1 (DTR 9)
AP 3	GS 11a	Fragmented saddle-shaped grinding slab, face a	Control 3 (DTR 12)
AP 3	GS 11b	Fragmented saddle-shaped grinding slab, face b	Control 3 (DTR 12)
AP 4	GS 12a	Fragmented saddle-shaped grinding slab, face a	Control 4 (DTR 13)
AP 4	GS 12b	Fragmented saddle-shaped grinding slab, face b	Control 4 (DTR 13)
AP 4	GS 13	Fragmented saddle-shaped grinding slab	Control 4 (DTR 13)
AP 4	GS 14	Fragmented saddle-shaped grinding slab	Control 4 (DTR 13)
AP 4	GS 15	Fragmented saddle-shaped grinding slab	Control 4 (DTR 13)
AP 4	GS 16	Fragmented saddle-shaped grinding slab	Control 4 (DTR 13)
AP 5	GS 17	Fragmented saddle-shaped grinding slab	Control 5 (DTR 27)

4.2.5. Shikarpur

Shikarpur (N 23^{o} 14' 15", E 70^{o} 40' 39"), locally known as Valmio Timbo, is located about 4.5 Km south of the Shikarpur village, Kachchh district, at the edge of the narrow creek extending eastward from the Gulf of Kachchh (Fig. 9). The rectangular mound measures ca. 3.4 Ha and covers the entire elevated top of a stabilised dune. The overall height of the mound is about 7.5 to 8 m from the surrounding ground, which is about 8 m asl. The inner part of the site is fortified, surrounded by a mud-brick wall measuring ca. 130 x 110 m (Bhan and Ajithprasad 2008).

The site was first excavated from 1987 to 1989 by the Gujarat State Archaeology Department. However, excavation reports were never published. The Department of Archaeology and Ancient History of the M. S. University of Baroda decided to re-excavate the site between 2007 and 2013 due to its strategic location (between the Indus Valley and the Gulf of Kachchh) aiming at establishing the cultural sequence as well as the settlement features in terms of economic activities carried out at the site.

The excavations at Shikarpur have revealed three phases of Harappan occupation throughout a total of 6.4 m of cultural deposit. Phase I (ca. 2500-2200 cal. BC) corresponds to the Classical Harappan period and spans about 3 m of deposit. Structures belonging to this phase are built of mud-bricks. Archaeological materials of Phase I include Classical Harappan and a few regional pottery, chert blades and cores, several terracotta objects, stone beads, some shell bangles and copper objects. Phase II (ca. 2200-1900 cal. BC) shows extensive use of locally quarried stone for the construction of structures and lies on a deposit of 1.4 to 1.6 m. Together with Classical Harappan, regional pottery types (Sorath Harappan) are present in a greater number than in Phase I. Other artefacts remain the same as on the previous phase. Phase III (ca. 1900-1300 cal. BC) is the last phase of the Harappan occupation. The deposit is thin and patchy, and generally confined to the top 10 to 20 cm. Very few artefacts have been recovered from this phase other than Late Sorath Harappan pottery. Structures correspondent to this phase seem to have been built using the stones from the preceding phase.

The analysis of faunal remains from Phase II suggests that cattle and buffalo were probably kept for secondary products prior to consumption at advanced age while goats and sheep were consumed at younger ages (Chase 2014). Moreover, the comparison between intra- and extra-mural deposits shows that the residents of the walled enclosure consumed a more varied diet than their neighbours outside the walls, possibly suggesting the existence of socio-economic differences among them.

Macrobotanical analyses from the 1987-1989 field seasons at Shikarpur showed the presence of bread wheat and small millets (finger millet and *Setaria* sp.) (IAR 1995b). However, the presence of African and East Asian crops at Shikarpur and other Harappan settlements during the 3rd millennium BC has been questioned (see Section 3.4.4), and therefore the identification of finger millet and *Setaria* sp. at this settlement cannot be taken as conclusive.

The 2012 excavation

The aim of the 2012 field season was to excavate the fortified area close to the East entrance to expose the structures corresponding to the occupational Phase II. A total of ten trenches were excavated in this area (Fig. 10). Several fire-related features were identified within the excavated area, including two open hearths, a small oven delimited by brick, stone and clay plaster, ashy patches, pits and areas where burning activity was detected but not delimited.

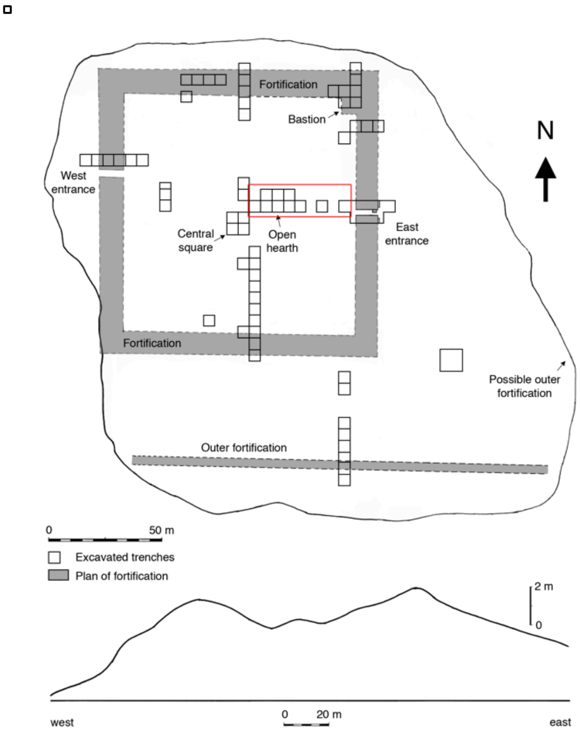


Figure 10. Plan of Shikarpur. (modified after Gadekar et al. 2014b). Squared in red is the area excavated in 2012.

Table 19. Sediment samples from Shikarpur analysed in this study.

Context	Sample ID	Description	Sediment volume (l)	Phytolith samples	Starch samples
Hc2	Ash 1	Area with ash	20	1	1
Ew2	Ash 2	Area with ash	40	1	1
Ew10	Ash 3	Area with ash	20	1	1
Er2	Pit 1	Pit	60	1	1
Er2	Pit 2	Pit	20	1	1
Ew10	BA 1	Area with burning activity	20	1	1
Er9	BA 2	Area with burning activity	10	1	1
Er6	Hearth 1	Fireplace	30	1	1
Er2	Hearth 2a	Fireplace, upper level (ashy)	20	1	1
Er2	Hearth 2b	Fireplace, lower level (compact)	✗	1	1
Er10	Oven	Small oven delimited by brick, stone and clay plaster	✗	1	1
Ew2	Control 1	Control sample for grinding stone	✗	1	1
Er6	Control 2	Control sample for grinding stone	✗	1	1
Er10	Control 3	Control sample for grinding stones	✗	1	1
Ew10	Control 4	Control sample for grinding stone	✗	1	1
Er10	Control 5	Control sample for grinding stone	✗	1	1
Er9	Control 6	Control sample for grinding stone	✗	1	1
Er6	Control 7	Control sample for grinding stone	✗	1	1
Er9	Control 8	Control sample for grinding stone	✗	1	1
Er10	Control 9	Control sample for grinding stone	✗	1	1
Er13	Control 10	Control sample for grinding stone	✗	1	1
Er5	Control 11	Control sample for grinding stones	✗	1	1
–	–	**Total**	**240**	**22**	**22**

Table 20. Morphotypological description of the grinding stones from Shikarpur analysed in this study. (descriptive terms after Wright 1992).

Context	Sample ID	Description	Control sample
Er10	Quern 1	Quern fragment	Control 3
Er9	Quern 2	Saddle-shaped quern	Control 8
Er9	Quern 3	Half saddle-shaped quern	Control 6
Er10	Quern 4	Half saddle-shaped quern	Control 3
Er13	Quern 5	Saddle-shaped quern	Control 10
Er5	Quern 6	Half saddle-shaped quern	Control 11
Er5	Quern 7a	Half saddle-shaped quern, face a	Control 11
Er5	Quern 7b	Half saddle-shaped quern, face b	Control 11
Er10	Quern 8	Saddle-shaped quern	Control 3
Er10	Quern 9a	Basin grinding slab, fragment a	Control 3
Er10	Quern 9b	Basin grinding slab, fragment b	Control 3
Ew2	Hand 1	Spherical handstone	Control 1
Er6	Hand 2	Oval, irregular handstone	Control 2
Ew10	Hand 3	Bifacial, rectilinear handstone	Control 4
Er10	Hand 4	Spherical handstone	Control 5
Er6	Hand 5	Spherical handstone	Control 7
Er5	Hand 6	Bifacial, rectilinear handstone	Control 11
Er5	Hand 7	Bifacial, rectilinear handstone	Control 11
Er10	Mortar	Boulder mortar	Control 9

Context	Sample ID	Description	Control sample
Er10	Pestle	Bipolar cylindrical pestle	Control 3

4.3. Laboratory procedures

Laboratory work was carried out at the Department of Archaeology and Ancient History, MSUB and the BioGeoPal Laboratory. Laboratory procedures included the recovery of macrobotanical remains from floatation samples, the recovery and extraction of microbotanical remains and the collection of laboratory control samples.

4.3.1. Macrobotanical remains

Light fraction floatation samples were sieved through a column of 2 mm, 1 mm, 0.5 mm and 0.25 mm meshes. All faunal (bones and shells) and botanical (wood charcoal, seeds and fruits) remains in the fractions >0.5 mm were sorted using a Leica EZ4 D stereoscope.

4.3.2. Microremains recovery from grinding stones

The recovery of plant microremains took place in a controlled environment –a clean, closed room with no airstream– at the Department of Archaeology and Ancient History, MSUB. To create a clean working surface, laboratory paper was used and disposed after each sample processing. The instruments were cleaned between artefacts by washing with starch-free detergent and rinsing with distilled water. A new set of powder-free gloves was used for each step of the procedure.

The residue was recovered by dry and wet brushing as described by Chandler-Ezell and Pearsall (2003). When dealing with artefacts too big to be single-handled (e.g. querns), a pipette was used to recover and transfer the wet sediment directly into a previously weighed centrifuge tube. Sonication was not carried out because some grinding stones were too big to fit in the ultrasound –thus impeding protocol standardisation– and several had two used surfaces. To facilitate transportation, wet samples were left to settle for at least 24h and then decanted. All further extraction steps and analysis were carried out at the BioGeoPal Laboratory.

The likeliness of contamination from the archaeological sediments is higher in the first layer of sediment attached to the artefact (dry sample), and once this layer is removed it decreases considerably (Hart 2011). Thus, comparing the wet sample with the control sample offers a more robust framework to understand whether the residue recovered resulted from the actual use of the tool or a posterior contamination. Therefore, I decided to process and analyse only the wet and control samples, whereas the dry sample was stored.

4.3.3. Microremains extraction

One of the aims of this study was to extract both phytoliths and starch grains from the same initial sediment sample (Chandler-Ezell and Pearsall 2003). The same protocol –a combination of Horrocks (2005) and Madella et al. (1998)– was used for grinding stones and sediment samples. Chemicals were applied in a pre-set sequence in order to prevent any damage to the starch grains, which are degraded or destroyed by HCl and H_2O_2 (Chandler-Ezell and Pearsall 2003; Coil et al. 2003). Furthermore, before starch recovery the temperature was always kept below 40 ˚C to prevent starch gelatinisation (Gott et al. 2006). To minimise contamination clean equipment was used at all times, as well as new Pasteur pipettes for each sample. Samples for phytolith and starch grain analyses from grinding stones were processed according to the following procedure:

1. Top up the tubes with distilled H_2O, centrifuge for 5' at 3000 rpm and decant. Dry into the oven (<40°C) and weigh the tube with the residue.
2. Top up the tubes containing the samples with a 5% weight solution of Sodium Hexametaphosphate, shake and leave overnight.
3. Shake the samples and then centrifuge for 3' at 1500 rpm and discard the supernatant. Top up with distilled H_2O and repeat this step at least three more times (more if the supernatant is still not clear). Dry into the oven (<40°C).
4. Add 5 ml of Sodium Polytungstate (SPT) with a specific gravity of 1.8 g/cm^3, shake and centrifuge for 3' at 1500 rpm.
5. Recover the floating fraction with a Pasteur pipette and transfer to labelled new tubes.
6. Top the recovered floating fraction up with distilled H_2O and centrifuge for 3' at 3000 rpm.
7. Decant pouring just half of the content of the tubes. Top up with distilled H_2O, shake gently and centrifuge for 3' at 3000 rpm four more times. Do not decant the tubes after the last centrifuge. Instead, pipette out the supernatant leaving about 5-10 ml in the tube.
8. Transfer the starch residue to a labelled glass vial with distilled H_2O and dry into the oven (<40°C). Starch samples are ready to be mounted or stored.
9. Top the original tubes up with distilled H_2O, centrifuge for 3' at 1500 rpm and discard the supernatant. Top up with distilled H_2O and repeat this step at least three more times (more if the supernatant is still not clear).
10. Add up to 15 ml of a 5% solution of HCl. Place the tubes with the samples in a water-bath at approx. 40°C until the reaction stops (i.e. no more bubbling occurs when adding a drop of HCl). Do not seal the tubes to allow for gas releasing. Stir occasionally.
11. When the reaction stops, top up with distilled H_2O, shake gently and centrifuge for 3' at 1500 rpm and discard the supernatant. Repeat this step at least three more times (more if the supernatant is still not clear).

12. Add up to 15 ml of 33% volume H_2O_2. Place the tube in a water-bath at approx. 40°C until the reaction stops (i.e. no more bubbling occurs when adding a drop of H_2O_2). Do not seal the tube to allow for gas releasing. Stir occasionally.
13. When the reaction stops, top up with distilled H_2O, shake gently and centrifuge for 3’ at 1500 rpm and discard the supernatant. Repeat this step at least three more times (more if the supernatant is still not clear). Dry and weigh the tube with the Acid Insoluble Fraction (AIF) of the sample.
14. Add 10 ml of a solution of SPT with a specific gravity of 2.35 g/cm^3, shake gently and centrifuge for 3’ at 1500 rpm.
15. Recover the floating fraction with a Pasteur pipette and transfer it to a labelled new tube. Shake gently and centrifuge the remaining suspension for 3’ at 1500 rpm and recover again. The entire floating fraction has to be recovered.
16. Top the recovered floating fraction up with distilled H_2O and centrifuge for 3’ at 2000 rpm.
17. Pour out the supernatant leaving only the residue at the bottom. Top up with distilled H_2O, shake gently and centrifuge for 3’ at 2000 rpm three more times.
18. Label and weigh a glass vial. Transfer the silicates to the vial with distilled H_2O and dry.

Phytolith samples were prepared for observation according to the following procedure:

1. Label and weigh a microscopy slide. Place ca. 1 mg of silicates on a microscopy slide and weigh.
2. Add 11 drops of Entellan® with a pipette. Mix the silicates and the Entellan® with a stainless steal gouge.
3. Cover it with a slide cover.
4. Leave it on a flat position under the extractor fan for two weeks to let the Entellan® dry. Once dried, store the slide in a slide folder.

Starch samples were prepared for observation according to the following procedure:

1. Add 200 µl of distilled water to the vial containing the dry starch residue.
2. Mix the residue with a pipette tip and place 20 µl of liquid on a microscopy slide. Cover with a Petrie dish to avoid contamination and allow drying under the fume cupboard. By measuring the exact quantity of liquid placed on a slide (20 µl) the percentage of starch residue analysed per sample is standardised (10%), thus allowing for a quantitative analysis of the results.
3. Once the residue is dry, add a drop of 50% glycerol and cover with a covering slip fixed at the four corners with transparent nail polish.

4.3.5. Laboratory control samples

Recently, Crowther et al. (2014) called attention to the likelihood of starch contamination from laboratory consumables (e.g. gloves). In this study, laboratory consumables were tested *a posteriori*. The methods employed to collect and analyse control samples from laboratory consumables were designed to allow for comparability with the archaeological samples. Consumables used during all laboratory work (both at the MSUB and the BioGeoPal Laboratory) were tested at the BioGeoPal Laboratory. A total of 12 samples were analysed. All the process was carried out without wearing gloves to avoid possible starch contamination. Hands were thoroughly washed with starch-free detergent between each sample to avoid cross-contamination. Sample collection methods were adapted to each consumable:

Gloves

1. Introduce one glove into a glass beaker and top up with distilled H_2O. Sonicate for 15'. Cover the beaker while sonicating.
2. Transfer the distilled water to a new 50 ml centrifuge tube.
3. Centrifuge for 5' at 3000 rpm.
4. Pipette out the supernatant with a disposable pipette until only 5 ml are left in the tube. Transfer to a glass vial with distilled H_2O and dry into the oven (<40°C).
5. Add 200 µl of distilled H_2O to the vial using a precision pipette. Recover 20 µl and place on a microscopy slide. Cover with a Petrie dish and let dry under the fume.
6. Add a drop of 50% glycerol and cover with a covering slip fixed at the four corners with transparent nail polish.

Beaker

1. Add 40 ml of distilled H_2O to a beaker. Sonicate for 15'. Cover the beaker while sonicating.
2. Repeat steps 2-6 from "Gloves".

Tubes

1. Top up a new 50 ml centrifuge tube with distilled H_2O. Sonicate for 15'.
2. Repeat steps 3-6 from "Gloves".

Paper

1. Introduce paper sherds into a new 50 ml centrifuge tube and top up with distilled H_2O. Sonicate for 15'.
2. Repeat steps 3-6 from "Gloves".

Vial

1. Repeat steps 5-6 from "Gloves".

Glycerol 50%

1. Repeat step 6 from “Gloves”.

Sodium polytungstate

1. Add a drop of sodium polytungstate on a microscopy slide and cover with a covering slip fixed at the four corners with transparent nail polish.

Sodium hexametaphosphate

1. Add 20 µl of sodium hexametaphosphate on a microscopy slide. Cover with a Petrie dish and let dry under the fume.
2. Repeat step 6 from “Gloves”.

4.4. Analysis

The analysis of macro and microbotanical remains, laboratory control samples and soil pH was carried out at the BioGeoPal Laboratory. Software used to carry out statistical analyses included MorphoJ, R and SPSS v.20.

4.4.1. Macrobotanical remains

Macrobotanical remains were analysed with a Leica EZ4D stereoscope. Taxonomical identification of plant remains not included in the PRC relied on seed atlases (Cappers and Bekker 2013; Cappers et al. 2009; Neef et al. 2012) and other published literature.

Geometric morphometrics

The results of the experimental GM analysis of modern *S. italica* and *B. ramosa* caryopses (see Section 4.1.1) were compared with SEB type (*Setaria*, *Echnochloa* and *Brachiaria* genera) small millets from SKP. Severe damage on most caryopses, due to charring and post-depositional processes, prevented a more accurate taxonomical identification (see Section 5.4.1). Despite the damage to the overall grain morphology, in most cases the shape of the embryo was still clearly distinguishable. After close examination, only 15 grains from SKP were suitable for the implementation of GM.

The landmark configuration designed for modern *S. italica* and *B. ramosa* caryopses was applied on the archaeological caryopses. A PCA was conducted on charred modern and archaeological caryopses in order to assess the morphological affinities of the latter group. I further conducted a Discriminant Analysis on the Procrustes coordinates using SPSS v.20 (Chigaco, IL). The modern charred caryopses were given an *a priori* group ascription while leaving the archaeological ones ungrouped. Thus, the archaeological specimens were classified by the analysis based on classification probabilities –in turn, derived on the basis of Mahalanobis square distances, D^2. Only those discriminant functions with a significant Wilk's lambda were employed. The performance of the analysis for discriminating among extant taxa was assessed on the basis of cross-validation percentages.

4.4.2. Microbotanical remains

Microbotanical remains were analysed with a Leica DM2500 microscope equipped with a Leica DFC490 camera for microphotography. Taxonomical identification of plant remains not included in the PRC relied on published literature.

Phytoliths

Slides were first quick-scanned at 200x magnifications to obtain an approximate estimate of the phytolith concentration and to identify possible diagnostic morphotypes (Piperno 2006: 102). Counting was carried out at 630x magnifications. When possible, 300 identifiable single-cell phytoliths were counted. Since phytoliths do not distribute uniformly on the slide (Zurro 2011), different areas were randomly scanned during counting. In samples with very low phytolith concentrations the whole slide was scanned, and those with less than 100 phytoliths per slide were considered sterile. When present, multi-cell phytoliths (silica skeletons) were counted independently and photographed to allow further analysis, since they can be taxonomically diagnostic at genus or even species level (Ball et al. 1996, 1999, 2009; Portillo et al. 2006). Phytoliths forming each silica skeleton were individually counted and described using the International Code for Phytoliths Nomenclature (ICPN – Madella et al. 2005).

Concentration was calculated per g of AIF (Acid Insoluble Fraction) according to the formula proposed by Albert and Weiner (2001):

$$C = \frac{P\left(\frac{A}{a}\right)\left(\frac{S}{s}\right)}{AIF}$$

where P is the total number of phytoliths counted (including those phytoliths part of silica skeletons and unidentified phytoliths), A is the total area of the slide, a is the area of the slide effectively scanned (i.e. area of visited fields of view), S is the weight of total silicates in the sample (after recovery with 2.35 s.g. SPT), s is the weight of silicates mounted on the slide and AIF represents the fraction of the sample not dissolved by chemicals.

Starch grains

The whole slide was scanned under half cross-polarised light at 200x magnifications, and grains were photographed and described under both transmitted and cross-polarised light at 630x magnifications. Grain features were described using a set of pre-established parameters (Table 21) according to the International Code for Starch Nomenclature (ICSN 2011).

Table 21. List of starch grain descriptors used in this study. (modified after Lentfer 2009).

Type		**Shape – 2D**		**Shape – 3D**		**Facet**		**Hilum - Position**	
S	simple	SR	sub-round	EHSP	elong hemisph	FL	flat	C	centric
C	compound	R	round	HSP	hemispherical	CC	concave	E	eccentric
SC	semi-comp	OV	ovate	SP	spherical	CV	convex	HE	highly ecc
Size		PL	polygonal	OV	ovoid	**Texture**		**Hilum - Type**	
		TR	triangular	GL	globose				
VS	<5 µm	IR	irregular	PL	polyhedral	WR	wrinkle	LV	large vacuole
S	>5-10 µm	CR	crescent	QU	quadrilateral	S	smooth	SV	small vacuole
M	>10-20 µm	BS	bell-shaped	IR	irregular	R	rough	CR	crystal
L	>20-50 µm			GLE	globose elong	RD	ridged	SL	slot
VL	>50 µm			TPR	tri-prismatic	**Lamellae**		**Hilum - Fissure**	
Extinction cross				WE	wedge				
				KI	kidney	Y	yes	L	linear
R	regular			CO	cone	N	no	Y	y-shaped
IR	irregular			DI	discoidal			ST	stellate
FL	flared			TO	torroid			OS	open simple
				BS	bell-shaped			OI	open irreg

The concentration of starch grains was calculated per gram of initial weight of the sediment processed for microremains extraction, either from artefact or sediment samples, through the formula:

$$C = \frac{SG * R}{initial\ sed}$$

where *SG* is the total number of starch grains encountered and *R* is the reciprocal of the fraction of residue effectively analysed –in this case 1/10, and therefore *R*=10. This formula allows for the comparison of samples regardless of the fraction of residue analysed simply modifying the value of *R*.

Multivariate statistics

Statistical analyses, performed with the free software R (R Development Core Team 2014), aimed at:

1. Testing the correlation between the total number of microbotanical remains and initial sediment weight through simple regressions to understand how sample weight affects the likelihood of recovering phytoliths and starch grains.
2. Identifying patterns in data between sites and periods through Principal Component Analysis (PCA) to understand differences and similarities in the microbotanical assemblages.

3. Comparing the results of phytolith analyses from grinding stones and archaeological control samples through indices of compositional similarity based on morphotypes abundance to establish the primary context of the microremains.
4. Identifying groups of tools within the same site also through indices of similarity to recognise possible spatial patterns and understand the post-depositional trajectories of the artefacts.

For multivariate statistical analyses (PCAs and indices of similarity), phytolith morphotypes were grouped into 12 categories in order to reduce the number of variables, facilitate the interpretation of the results and allow for comparability between samples (Table 22). Starch grains were classified according to groups identified during the microscopic analysis (Table 23). For the PCAs, the phytolith and starch grain counts were normalised by log10 transformations, to minimise the impact of the variables variance. A plot with the two first Principal Components of the PCA (PC1 and PC2) is shown for visualisation, with ellipses around the 95% confidence interval of the mean.

Table 22. Phytolith groups used for multivariate statistics.

Group	Morphotypes
Grass LC inflorescence	elongate echinate, elongate dendritic, elongate crenate, elongate columellate
Grass LC leaf/culm	elongate psilate, elongate sinuate
Grass LC undetermined	elongate irregular, other grass long cells
Grass bulliform	cuneiform bulliform
Grass SC chloridoid	saddle
Grass SC panicoid	bilobate, trilobate, polylobate, cross
Grass SC pooid	rondel, trapeziform sinuate, trapeziform polylobate, trapeziform. ovate, trapeziform bilobate, trapeziform elongate
Grass SC undetermined	trapeziform, cork cell, short cell undetermined
Cyperaceae	tabular scrobiculate, tabular conical
Arecaceae	globular echinate
Dicot	globular psilate, globular granulate, schlereid, scalloped, irregular
Undetermined	parallelepipedal, trichome, trichome base, papillae, stoma, mesophil, tracheid, elongate undetermined

The method used to calculate the compositional similarity indices includes the effect of unseen shared species, which makes it less biased than classic indices when a substantial proportion of species are missing from samples (Chao et al. 2005). This is particularly relevant when working with archaeobotanical data, where a particular taxon (a species or morphotype) may be absent from most samples. The compositional similarity indices were plotted on dendrograms for visualisation, where the clusters were defined by the 0.95 percentile of the index score.

Table 23. Starch groups used for multivariate statistics. The list of descriptors can be found in Table 21.

Type	Size	Ext. cross	Shape	Facets	Texture	Lamellae	Hilum	Taxonomy
1a	VS/S	R	PL, PL	FL	WR	N	C, variable	Panicoideae
1b	M	R	PL, PL	FL	WR	N	C, variable	Panicoideae
1c	L	R	PL, PL	FL	WR	N	C, variable	Panicoideae
2	M/L	R	OV, OV	.	S	Y	C, L	Faboideae
3	M	R	R, SP	.	S	N	C, SV	cf. Trititceae
4	M/L	R	R, DI	.	S	Y/N	not visible	Triticeae
5	M/L	R	R, SP	.	RD	N	C, L	cf. Panicoideae
7	M	IR	OV, OV	.	S	N	EC, SV	tuber
8	M	R	BS, BS	FL	S	N	EC, L	cf. Triticeae
9	VL	R	OV, TPR	.	S	Y	HEC, L	tuber
14	L	R	OV, OV	.	S	N	HEC, L	Zingiberaceae

4.4.3. Laboratory control samples

Laboratory cosumables were analysed with a Leica DM2500 microscope equipped with a Leica DFC490 camera for microphotography. The whole slide was scanned under half cross-polarised light at 200x magnifications, and microbotanical remains were photographed and described under both transmitted and cross-polarised light at 630x magnifications.

4.4.4. Soil pH

Soil pH was measured in samples from VHV, LTS and DTR to understand how soil acidity/alkalinity might have affected the preservation of plant remains. Soil pH was determined using a Combo pH & EC HI98129 by HANNA® instruments according to the following procedure:

1. Mix 20 ml of distilled water with 10 ml of sediment in a beaker.
2. Place the meter into the beaker until the reader stabilises.

II. Discussion

5. Main Results

This chapter summarises the results of the analysis of plant reference collections, laboratory control samples and archaeological samples. Only the main findings are presented, a more detailed description of the results for each study is available in the research papers.

5.1. Reference collections

Plant reference collections were analysed at two levels: a) uncharred and charred caryopses of *S. italica* and *B. ramosa* were quantitatively analysed using a GM approach, and b) microbotanical remains from several species were morphologically and morphometrically assessed.

5.1.1. Macrobotanical remains

Over 30 modern *S. italica* and *B. ramosa* caryopses were randomly selected for the experiment. GM were conducted both before and after charring to understand the morphological variation that occurs in these taxa during carbonisation.

The PCA with uncharred caryopses reflects the differentiation between the two groups, with *B. ramosa* falling towards the positive end of the axis of PC1, and *S. italica* towards the negative (Fig. 11a). There is overlapping between the two groups around the zero value of the axis. *B. ramosa* is characterised by having a wider embryo in its lower half than its upper half, resembling an arch; whereas *S. italica* is characterised by having an overall longer and narrower embryo, with a characteristic constriction in the middle (semilandmarks SL2 and SL5). The second Principal Component (PC2) does not portray group differentiation, with both *B. ramosa* and *S. italica* broadly overlapping.

The PCA with charred caryopses also reflects the differentiation between the two groups (*B. ramosa* towards the positive end and *S. italica* towards the negative axis of PC1), although there is a more visible overlap in respect to uncharred caryopses (Fig. 11b). PC2 does not reflect group differentiation. The vectors of shape change (for both PC1 and PC2) are virtually the same than those of the previous PC analysis, with the particularity that towards the negative end of the PC1 axis L2 and L3 are brought closer together by charring –narrowing the embryo on its lower end.

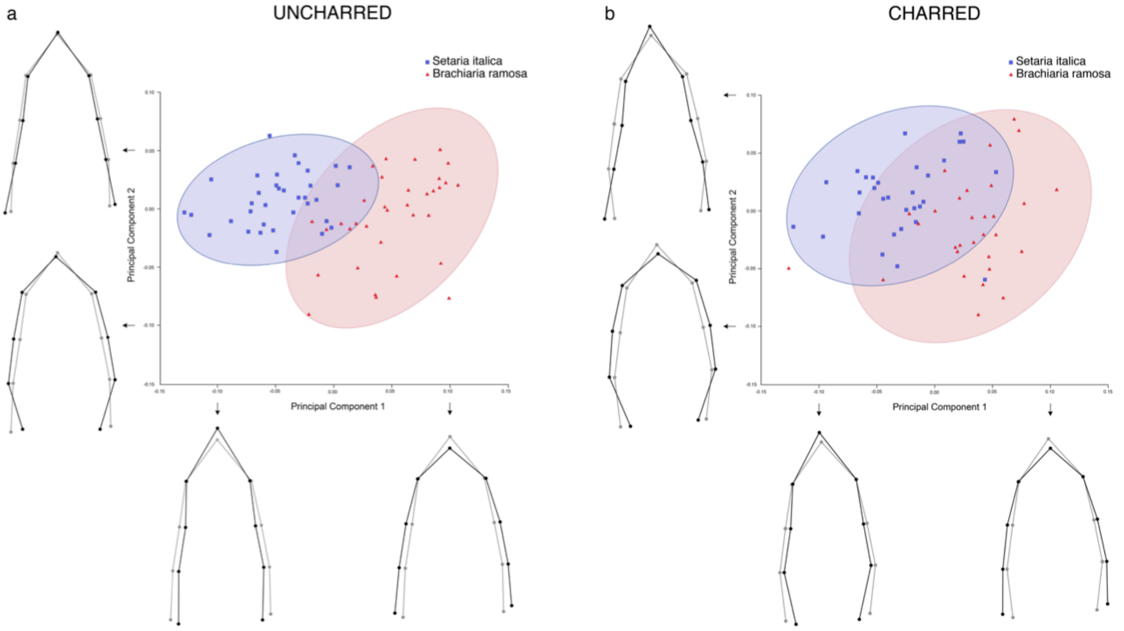


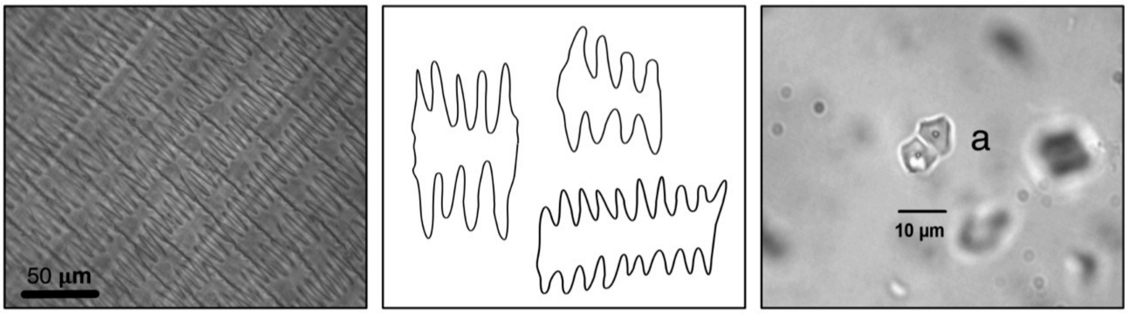
Figure 11. PC1 and PC2 scatterplots of the Principal Components Analyses (PCAs) of modern *Setaria italica* and *Brachiaria ramosa*. a) before charring, and b) after charring. Grey outlines represent the main shape (0.00/0.00) of the scatterplot and black outlines represent the shape changes at the extremes of each Principal Component.

The results from the permute test show significant pairwise differences ($p \leq 0.05$) between uncharred and charred caryopses of *S. italica* and *B. ramosa* for both the Mahalanobis and the Procrustes distances. Overall, the results show that the shape of the embryo of *S. italica* and *B. ramosa* can be clearly distinguished using a geometric morphometric approach, both before and after charring. However, charring tends to smooth the shape differences between the two groups.

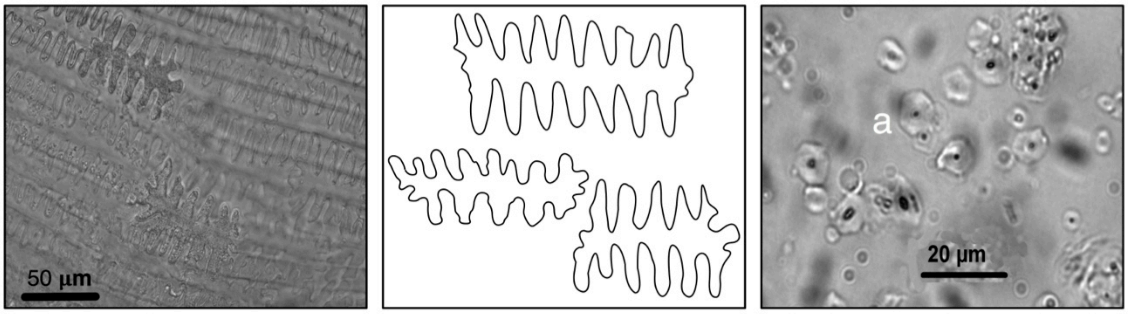
5.1.2. Microbotanical remains

The preliminary analysis of long-cell phytoliths of millet glumes showed a great potential for their identification at genus level (for an example see Fig. 12). Further work with other inflorescence parts showed not only the possibility of distinguishing among millet genera but also among different plant parts, particularly a) leaves/culm, b) inflorescence external parts (glumes, lower lemma and lower palea) and c) inflorescence internal parts (upper lemma and palea) (for an example with *B. ramosa* see Fig. 13). Overall, long cells from the internal parts of the inflorescence tend to be more intricate than the external parts, which makes them more diagnostic (Lu et al. 2009; Zhang et al. 2011). The linear parameters used by Zhang et al. (2011) to distinguish between long cell inflorescence phytoliths from *S. italica* and *S. viridis* were preliminarily applied to other small millet species, showing great prospectives for their identification at species level.

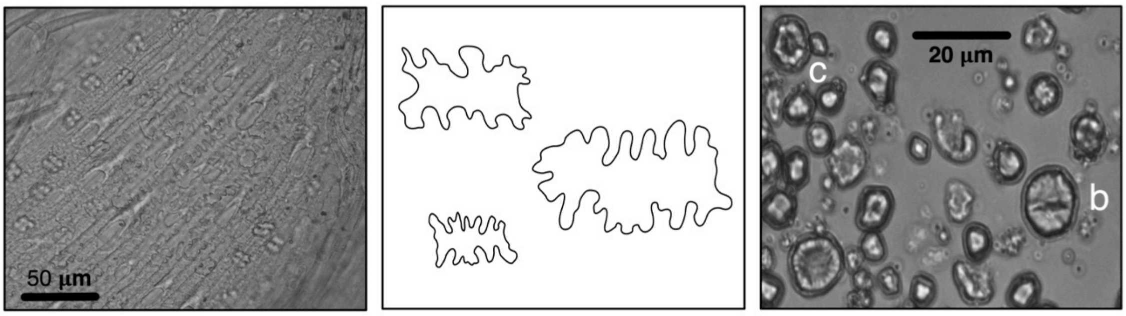
Digitaria ciliaris (Retz.) Koeler - Southern crabgrass



Echinocloa colona (L.) Link. - Jungle rice



Echinochloa frumentacea Link. - Billion-dollar grass



Brachiaria ramosa (L.) Stapf. - Browntop millet

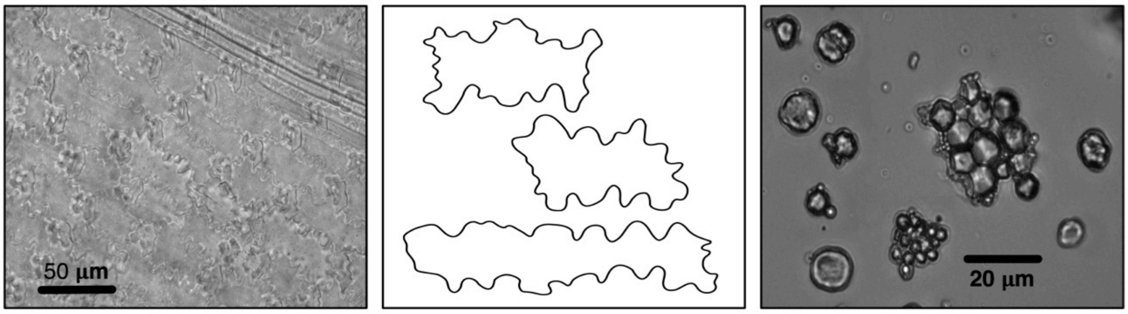


Figure 12. Comparative diagram of glume phytoliths, long cell line drawings and starch grains from *Digitaria ciliaris*, *Echicnochloa colona*, *Echinochloa frumentacea* and *Brachiaria ramosa*. a) centric, small vacuole hilum, and b) hilum with linear fissure.

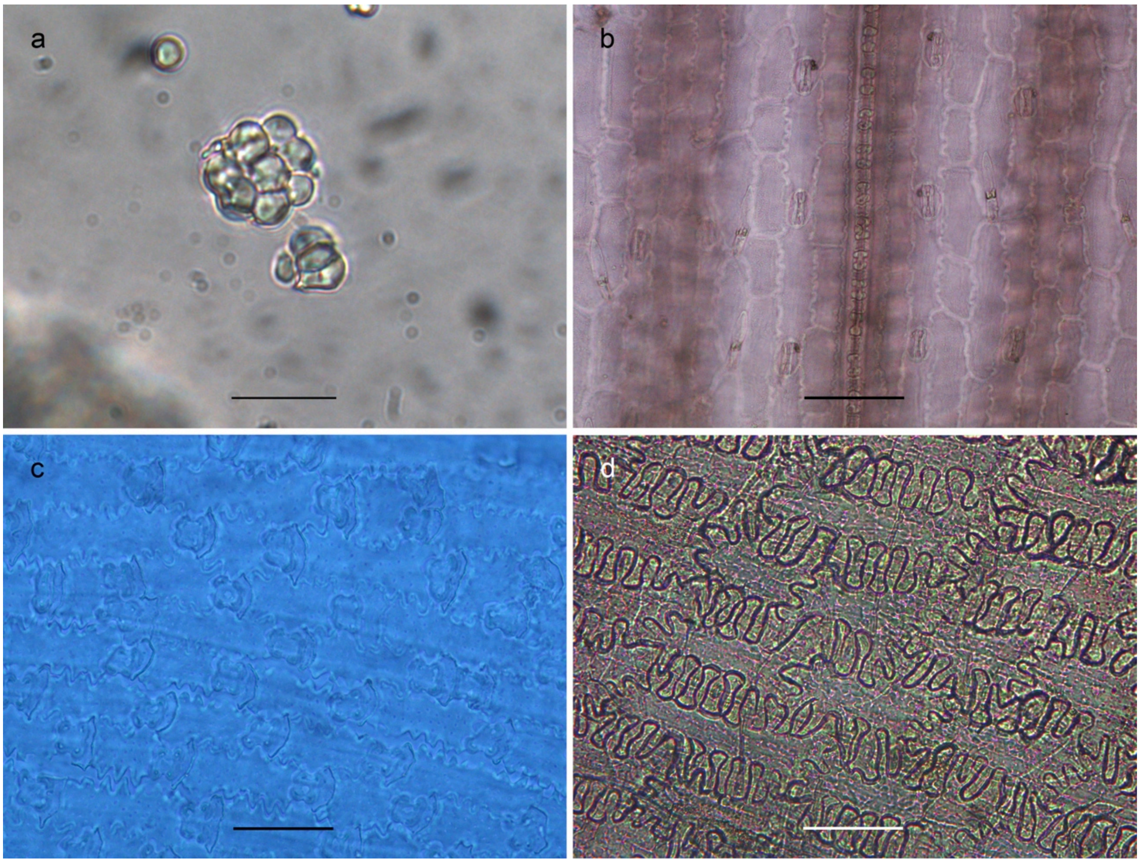


Figure 13. Microbotanical remains produced by *Brachiaria ramosa*. a) starch grains from the caryopsis, b) phytoliths from the leaves, c) phytoliths from the external parts of the inflorescence, and d) phytoliths from the internal parts of the inflorescence. Scale bars 20 µm in a, 60 µm in b-d.

The analysis of starch from modern seeds and fruits focused mostly on grasses and pulses. Panicoids have faceted polyhedral grains with no lamellae and a centric hilum (Fig. 14a-b). The size of the grains varies between <5-30 µm, and it is possible to distinguish among certain taxa based on grain size (Ge et al. 2010; Krishna Kumari and Thayumanavan 1998; Mercader 2009; Yang et al. 2012a). Small (5-10 µm) and very small (<5 µm) grains are characteristic of small millets (as well as rice, Yang et al. 2012a), whereas large (>20 µm) grains occur mostly in big millets such as sorghum, pearl millet and Job's tears. Medium (10–20 µm) grains can represent any of the previous taxa within the Panicoideae. Pooids have mainly two types of grains: Type A, large (20-50 µm) discoidal grains with a smooth surface and lamellae (Fig. 14c-d); and Type B, small (5-10 µm) spherical grains with a smooth surface and small centric hila. Bell-shaped grains are also sometimes observed in pooids (Aceituno Bocanegra and López Sáez 2012). Size can be used to distinguish among taxa (Yang and Perry 2013), although the damage suffered by archaeological starch grains (e.g. through grinding, Henry et al. 2009) makes it unfeasible to apply a morphometric approach in most cases. Faboids have medium to large (10-50 µm) ovoid grains with a smooth surface, lamellae and a linear hilum (Fig. 14e-f). Although morphometric analyses have never been carried out on starch grains from the Faboideae subfamily, a qualitative appraisal shows that there are no apparent size or shape differences between genera.

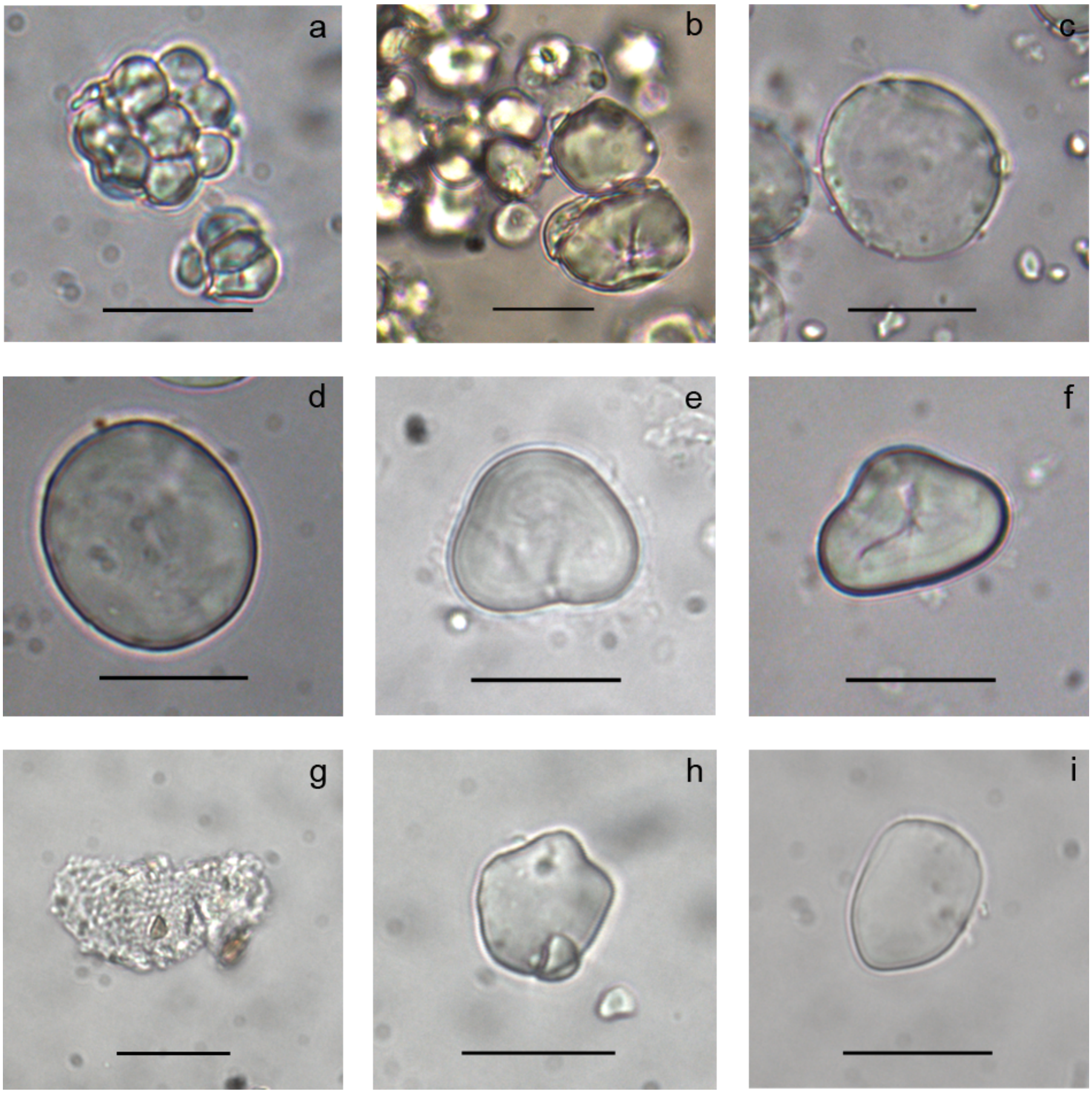


Figure 14. Examples of modern starch grains from the reference collection. a) *Brachiria ramosa*, b) *Coix lacryma-jobi*, c) *Hordeum vulgare*, d) *Triticum aestivum*, e) *Vigna radiata*, f) *Vigna mungo*, g) *Chenopodium album*, h) moot, unidentified sedge, and i) *Zingiber officinale*. Scale bars 20 µm.

A few taxa within the Amaranthaceae, Cyperaceae and Zingiberaceae families were also consulted for the identification of potential diagnostic traits at family level. White goosefoot (*Chenopodium album* L.) has very small (1-2 µm) polyhedral compound grains (Fig. 14g) and sedges have smooth globose grains with no lamellae and a centric small hilum (Fig. 14h). Finally, starch grains from taxa within the ginger family are relatively similar to sedges (Fig. 14i). However, their hila are highly eccentric, which is most evident under cross-polarised light.

5.2. Laboratory control samples

A total of 12 samples from laboratory consumables were tested at the BioGeoPal Laboratory. Among the four brands of powder-free gloves used in this study, only one contained a significant amount of starch grains (Table 24) –mostly Type 1b/c (Panicoideae), characteristic of corn (*Zea mays* ssp. *mays* L.), the most common source of commercial starch (Crowther et al. 2014). These gloves were used exclusively during the extraction of microbotanical remains from samples from VHV, where Type 1b/c starch grains were the most commonly recovered. In this case, as we cannot exclude that the starch assemblage from VHV is not the result of contamination during laboratory processing, the starch remains from VHV are not further discussed. No significant amounts of starch grains (≤1) were recovered from the other laboratory consumables used during the different stages of this study, and no phytolith was encountered in any laboratory control sample.

Table 24. Starch grains encountered in control samples from laboratory consumables analysed in this study. A description of the types can be found in Table 23.

Consumable	Type 1	Type 2	Type 4	Type 8	Unid	Total
Gloves (brands)						
Care Supply	.	.	.	.	1	1
Kimberly-Clark	.	.	.	.	.	0
Naturflex	.	.	.	.	.	0
Cuatrogasa	60	1	.	1	.	62
Tube 1	.	.	1	.	.	1
Tube 2	.	.	.	.	.	0
Paper	.	.	.	.	.	0
Beaker	.	.	.	.	.	0
Vial	.	.	.	.	.	0
Glycerine 50%	.	.	.	.	1	1
SPT 1.8	1	.	.	.	.	1
Calgon	.	.	.	.	.	0

5.3. Archaeological samples

The results from sediment samples and grinding stones are presented separately. Phytolith and starch data are presented simplified according to the groups used for statistical analyses (see Section 4.4.2). Phytolith counting sheets are provided in the appendices. Pictures of the main phytolith and starch morphotypes identified during the analyses are shown in Figures 15 and 16.

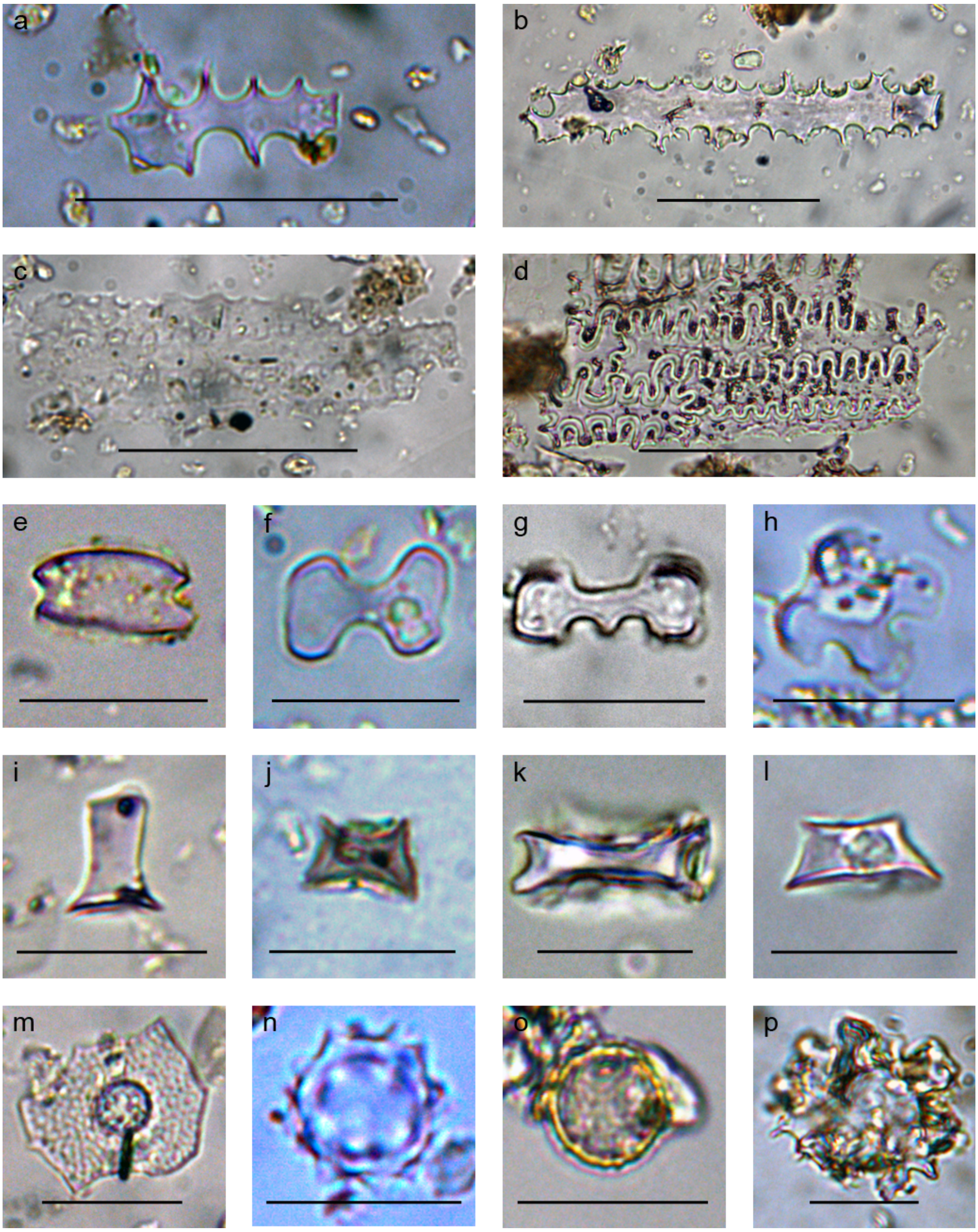


Figure 15. Main phytolith morphotypes recovered from archaeological samples from Vaharvo Timbo, Loteshwar, Datrana IV and Shikarpur. a) Elongate echinate, b) elongate dendritic, c) elongate crenates (silica skeleton), d) elongate columellates (silica skeleton), e) saddle, f) bilobate, g) trilobate, h) cross, i) rondel, j) trapeziform, k) trapeziform elongate, l) trapeziform bilobate, m) tabular conical (Cyperaceae), n) globular echinate (Arecaceae), o) globular psilate, and p) irregular morphotype from a dicotyledon. Scale bars 50 µm in a-d and 20 µm in e-p.

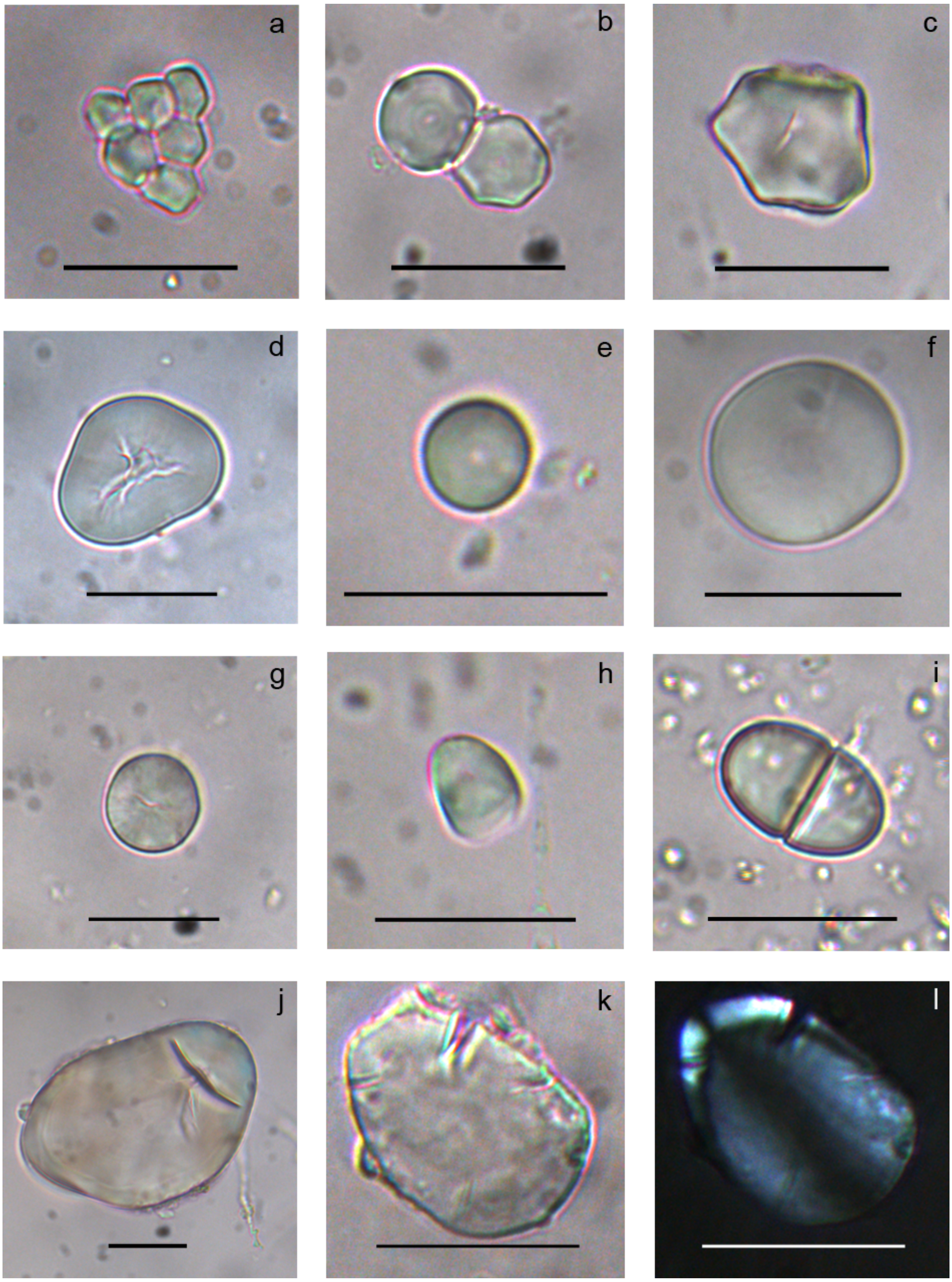


Figure 16. Starch grains recovered from archaeological samples from Loteshwar, Datrana IV and Shikarpur. a-c) Panicoideae (Types 1a, 1b and 1c), d) Faboideae (Type 2), e) cf. Triticeae (Type 3), f) Triticeae (Type 4), g) cf. Panicoideae (Type 5), h) tuber undetermined (Type 7), i) cf. Triticeae (Type 8), j) tuber undetermined (Type 9), and k-l) Zingiberaceae (Type 14). Scale bars 20 µm. Image l is under cross-polarised light.

5.3.1. Sediment samples

Macro and microbotanical remains were analysed from sediment samples from VHV, LTS, DTR and SKP. Additionally, soil pH was measured on samples from VHV, LTS and DTR. Finally, a GM approach was used to identify small millet caryopses from SKP.

Vaharvo Timbo

Macrobotanical remains were analysed from the four stratigraphic units identified during the excavation, and a total of seven samples were analysed for microbotanical remains and soil pH.

Macrobotanical remains were only recovered from the upper layer of the archaeological sequence (Table 25, Fig. 17), and included two morphologically wild *Sesamum* grains (tentatively identified as *Sesamum* cf. *malabaricum* Burm.), one *Digitaria* sp. grain and one possible crowfoot grass inflorescence (cf. *Dactyloctenium aegyptium* L.). Additionally, several unidentified grass inflorescences, glumes, nodes and spikelet bases were recovered.

Table 25. Macrobotanical remains from Vaharvo Timbo.

	Dep 1	**Dep 2**	**Dep 3**	**Dep 4**
Sediment volume (l)	80	60	140	100
Pedaliaceae				
Sesamum cf. *malabaricum*	2	.	.	.
Poaceae				
Chloridoideae				
cf. *Dactyloctenium aegyptium* inflorescence	1	.	.	.
Panicoideae				
Digitaria sp. caryopsis	1	.	.	.
Poaceae undet. inflorescence	3	.	.	.
Poaceae undet. glume	3	.	.	.
Poaceae undet. node	4	.	.	.
Poaceae undet. spikelet base	27	.	.	.

All phytolith samples were quick-scanned at 200x but, due to the extreme scarcity of phytoliths, only three samples were fully scanned at 630x. Of these, only one sediment sample had enough phytoliths for quantitative analysis (Dep 1), presenting mainly grass leaf/culm and a few grass inflorescence phytoliths (Table 26). It is worth highlighting the presence of one small (ca. 10 µm) globular echinate, characteristic of palms (Arecaceae). Soil pH values were slightly alkaline and relatively constant throughout the sequence (Table 26).

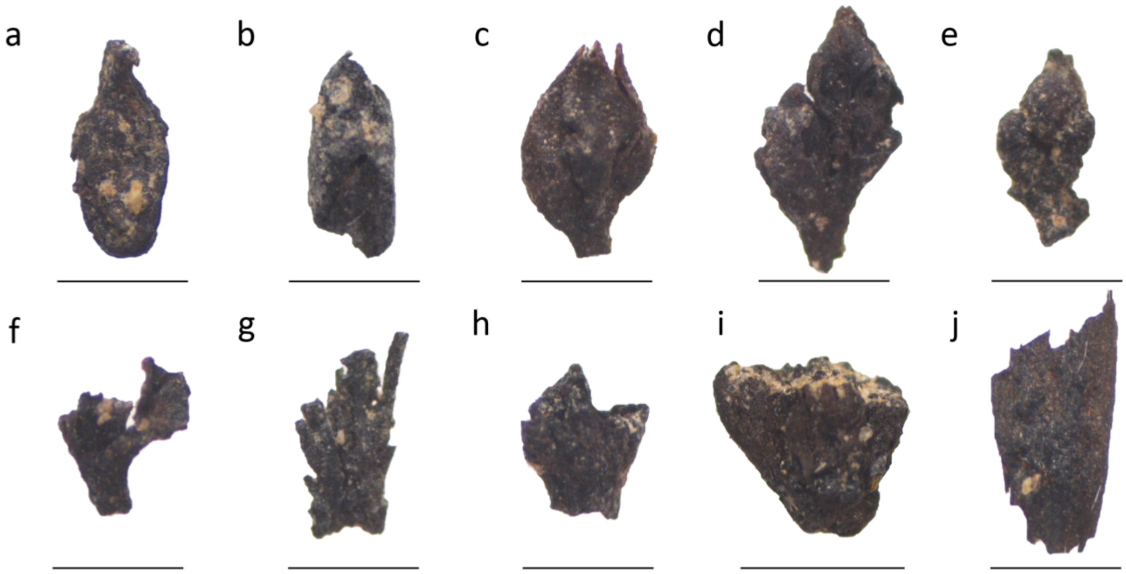


Figure 17. Macrobotanical remains from Vaharvo Timbo. a) charred *Sesamum* cf. *malabaricum* seed, b) charred *Digitaria* sp. caryopsis, c) charred cf. *Dactyloctenium aegyptium* inflorescence, d-e) charred Poaceae inflorescences, f-i) charred Poaceae spikelet bases, and j) charred Poaceae glume. Scale bars 1 mm in a-h and j, 2 mm in i.

Table 26. Phytolith and soil pH analyses from sediment samples from Vaharvo Timbo. Phytolith concentration is expressed in millions per g of AIF (Acid Insoluble Fraction). - = sample not analysed.

	Dep 1	Dep 2	Dep 3	Dep 4	Pit S	Pit N1	Pit N2
Phytoliths							
Grass LC inflorescence	7	-	-	-	.	-	.
Grass LC leaf/culm	44	-	-	-	.	-	1
Grass LC undetermined	3	-	-	-	.	-	0
Grass bulliform	7	-	-	-	.	-	2
Grass SC panicoid	7	-	-	-	.	-	2
Grass SC chloridoid	4	-	-	-	1	-	.
Grass SC pooid	5	-	-	-	.	-	.
Grass SC undetermined	4	-	-	-	.	-	1
Arecaceae	1	-	-	-	.	-	.
Dicot	.	-	-	-	.	-	1
Undetermined	65	-	-	-	3	-	4
Unidentified	17	-	-	-	3	-	4
Total phytoliths	164	-	-	-	7	-	15
Phytolith concentration	0	-	-	-	0	-	0
Soil pH	8.44	8.39	8.41	8.70	8.57	8.29	8.60

Loteshwar

Macrobotanical remains were analysed from six archaeological contexts, and a total of eight samples were analysed for microbotanical remains and soil pH.

The majority of the recovered macrobotanical remains are from the Anarta contexts (Table 27, Fig. 18). The assemblage is dominated by charred caryopses of small millets, mostly bristly foxtail (*Setaria verticillata* (L.) P.Beauv.) and yellow foxtail, including one hulled grain of yellow foxtail. Other taxa include possible little millet (cf. *Panicum sumatrense* Roth), browntop millet, *Digitaria* sp. and possible jungle rice (*Echinochloa* cf. *colona* (L.) Link.). Due to poor preservation, several grains could only be identified at the level of SEB group (*Setaria*, *Echinochloa* and *Brachiaria*) or simply as undetermined small millets. Small millet inflorescences were also preserved mineralised, including *B. ramosa*, *P. sumatrense* and SEB type. A whole pseudocarp and fragments of mineralised Job's tears were also found. Other grass remains included crowfoot grass caryopses, several fragmented caryopses of C_3 cereals (including free-threshing wheat, identified as *Triticum* cf. *aestivum*), a *Triticum* sp. glume base and the involucre base of an unidentified grass. The macrobotanical assemblage also consisted of domestic sesame (*Sesamum indicum* L.), *Papaver* sp. (poppy), a small seed of horsegram (*Macrotyloma uniflorum* (Lam.) Verdc.) and two taxa from the Solanaceae family: *Lycium* sp. and cf. *Solanum* sp. Finally, numerous unidentified species of sedges, parenchymatic tissue and weed taxa such as *Trianthema* spp. and *Chenopodium* sp. were encountered.

Table 27. Macrobotanical remains from Loteshwar. + = present.

	Dep 1	**Dep 2**	**Dep 3**	**Pit 1**	**Pit 3**	**Ash 2**
Sediment volume (l)	240	75	50	135	160	80
Aizoaceae						
Trianthema portulacastrum	6	.	.	2	.	2
Trianthema triquetra	2	.	.	.	.	.
Amaranthaceae						
Chenopodium sp.	11	1	.	1	16	18
Cyperaceae	9	1	2	10	5	2
Fabaceae						
Macrotyloma uniflorum	.	.	.	.	.	1
Papaveraceae						
Papaver sp.	1	.	.	1	1	1
Pedaliaceae						
Sesamum indicum	.	.	.	32	.	.
Poaceae						
Chloridoideae						
Dactyloctenium aegyptium caryopsis	3	1	.	.	1	2
Panicoideae						
Brachiaria ramosa caryopsis	1	.	.	.	.	.
B. ramosa mineralised inflorescence	6	.	1	.	2	.
B. ramosa mineralised lemma	2	.	.	.	.	.
Coix lacryma-jobi pseudocarp	+	+	+	>1	+	+
Digitaria sp. caryopsis	1	.	.	.	.	.
Echinochloa cf. *colona* caryopsis	1	.	.	.	.	.
cf. *Panicum sumatrense* caryopsis	2	1	.	1	.	4
P. sumatrense mineralised lemma	.	.	.	.	.	1
Setaria pumila caryopsis	8	.	.	.	1	3
S. pumila caryopsis (hulled)	.	.	.	.	.	1
Setaria verticillata caryopsis	9	2	.	8	2	10
SEB type caryopsis	7	.	.	.	.	7

	Dep 1	Dep 2	Dep 3	Pit 1	Pit 3	Ash 2
SEB type mineralised inflorescence	3	1	.	1	1	1
small millet undet. caryopsis	1	1	.	1	2	2
Pooideae						
Triticum cf. *aestivum* caryopsis	.	.	.	1	.	.
Triticum sp. glume base	.	.	.	1	.	.
Cerealia undet. caryopsis	.	.	.	.	1	1
Poaceae undet. involucre base	.	1	.	.	.	.
Solanaceae						
Lycium sp.	.	.	.	.	1	.
cf. *Solanum* sp.	4	1	.	4	1	1
Parenchyma fragments	+	.	.	+	.	+

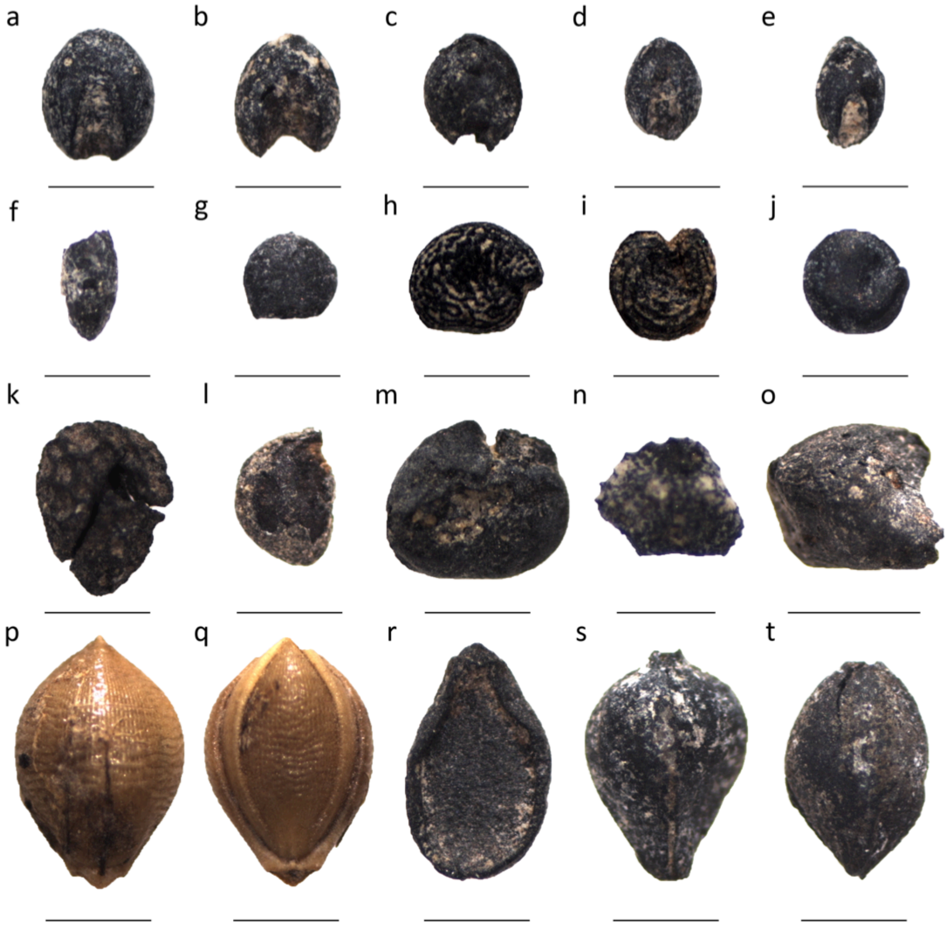


Figure 18. Macrobotanical remains from Loteswar. a) charred *Brachiaria ramosa* caryopsis, b) charred *Setaria pumila* caryopsis, c) charred *Echinochloa* cf. *colona* caryopsis, d) charred *S. verticillata* caryopsis, e) charred cf. *Panicum sumatrense* caryopsis, f) charred *Digitaria* sp. caryopsis, g) charred cf. *Solanum* sp. seed, h) charred *Trianthema portulacastrum* seed, i) charred *T. triquetra* seed, j) charred *Chenopodium* sp. seed, k) charred *Papaver* sp. seed, l) charred *Lycium* sp. seed, m) charred *Macrotyloma uniflorum* seed, n) charred *Dactyloctenium aegyptium* caryopsis, o) half charred *Triticum* cf. *aestivum* caryopsis, p-q) dorsal and ventral view of a mineralised inflorescence of *B. ramosa*, r) charred *Sesamum indicum* seed, s-t) charred Cyperaceae seeds. Scale bars 1 mm in a-m and p-t, 0.5 mm in n, 2 mm in o.

Sediment samples had very high phytolith concentrations (Table 28). Among the grass short cells, panicoid morphotypes predominated in all Anarta samples, whereas samples from the mixed and Mesolithic levels had more pooids. In all the samples leaf/culm morphotypes were the main grass long cells. The single-cell assemblage further included dicotyledon types and tabular scrobiculated cones from sedge achenes. Silica skeletons typically occurring in the internal parts of small millet inflorescences (*Panicum*/*Setaria* and *Echinochloa* types) were recovered, some showing characteristic threshing marks as described by Cummings (2007) (Fig. 19). Starch grains were very scarce in sediment samples. Soil pH values were slightly alkaline throughout the sequence, particularly in samples Pit 3, Dep 2 and Dep 3 (Table 28).

Table 28. Phytolith, starch grain and soil pH analyses from sediment samples from Loteshwar. Phytolith concentration is expressed in millions per g of AIF (Acid Insoluble Fraction). Starch concentration is expressed in grains per g of original sediment.

	Dep 1	Dep 2	Dep 3	Pit 1	Pit 2	Pit 3	Ash 1	Ash 2
Phytoliths								
Grass LC inflorescence	27	18	64	30	22	19	23	15
Grass LC leaf/culm	68	43	271	48	59	47	50	60
Grass LC undetermined	2	11	7	11	8	9	2	13
Grass bulliform	12	11	4	6	1	5	4	9
Grass SC panicoid	67	36	14	98	86	58	86	73
Grass SC chloridoid	43	51	24	35	40	40	56	75
Grass SC pooid	48	56	32	54	69	55	43	47
Grass SC undetermined	47	37	25	69	48	55	60	21
Cyperaceae	1	1	.	1	4	2	.	3
Dicot	7	15	11	.	3	1	1	2
Undetermined	36	55	65	25	31	32	29	33
Unidentified	5	5	16	1	2	.	7	8
Total phytoliths	363	339	534	378	373	323	361	359
Phytolith concentration	6.3	0.6	0.7	12.6	15.1	3.9	23.1	29.3
Starch grains								
Type 1b	.	1	1	.	.	1	1	.
Type 1c	.	.	1	.	.	2	1	.
Type 2	.	.	.	1	.	.	.	.
Type 4	.	.	1	.	2	.	1	.
Type 8	.	.	.	.	2	.	.	.
Unidentified	.	1	.	.	1	.	.	.
Total starch grains	.	2	3	1	5	3	3	.
Starch concentration	0	5	8	2	13	7	7	0
Soil pH	8.38	8.88	8.88	8.25	8.42	8.88	8.32	8.34

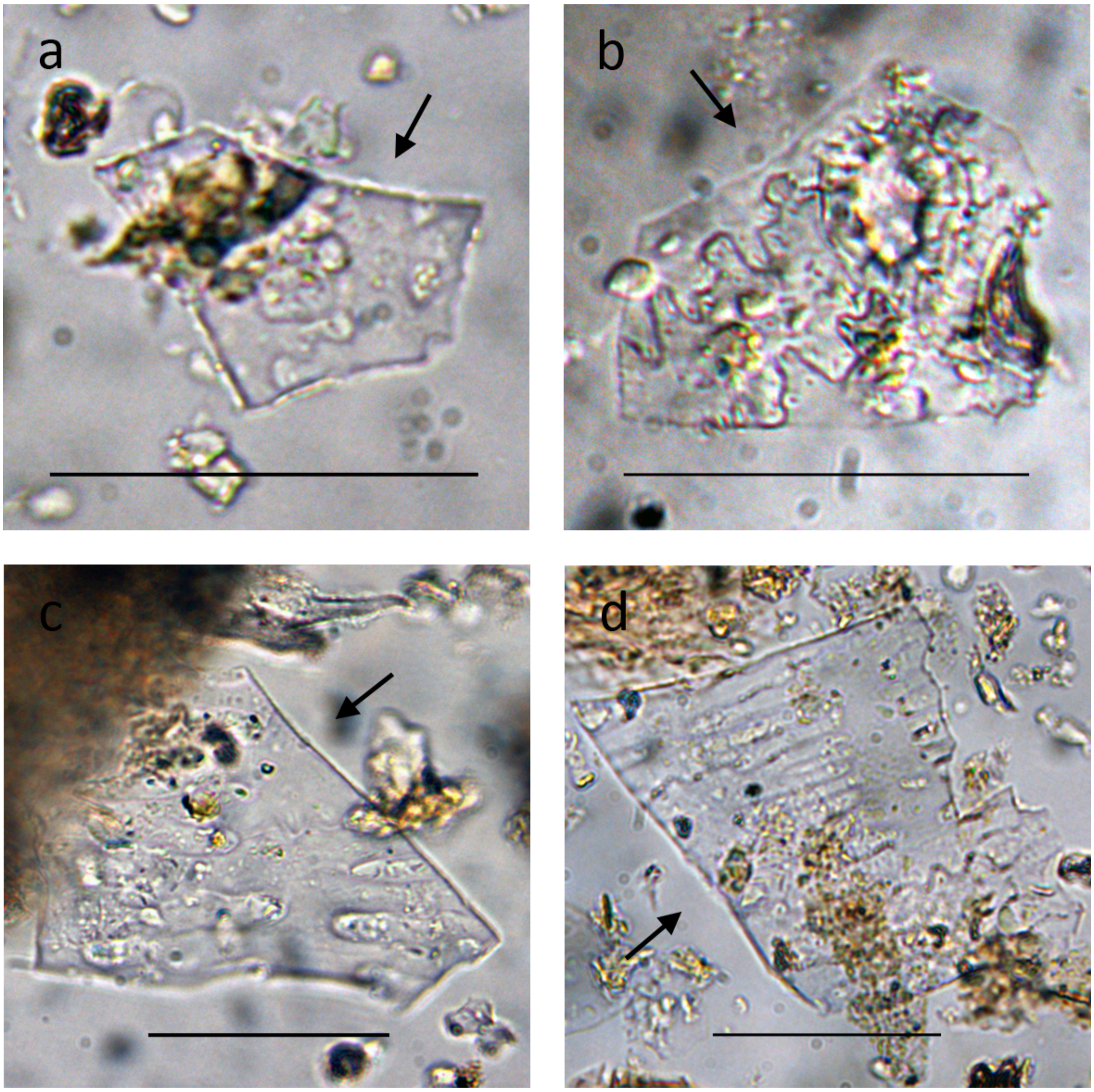


Figure 19. Silica skeletons from small millet internal inflorescence parts with potential threshing sledge marks (marked with arrows) recovered from Loteshwar. a-b) *Panicum*/*Setaria*-type inflorescences, c-d) *Echinochloa*-type inflorescences. Scale bars 50 µm.

Datrana IV

Macrobotanical remains were analysed from nine archaeological contexts, and a total of ten samples were analysed for microbotanical remains and soil pH.

Charred seeds and fruits were scarce (Table 29). The macrobotanical assemblage includes wild seeds and grains –crowfoot grass, sedges and Caryophyllaceae–, a weed usually associated with small millet cultivation (*Chenopodium* sp.) and a barley rachis (Fig. 20).

Table 29. Macrobotanical remains from Datrana IV.

	DTR 9	DTR 10	DTR 11	DTR 12	DTR 13	DTR 25	DTR 30	DTR 34	DTR 44
Sediment volume (l)	60	20	20	20	80	80	40	60	100
Amaranthaceae									
Chenopodium sp.	.	.	.	.	1	.	.	.	.
Caryophyllaceae	1	.	.	.	.	.	.	.	.
Cyperaceae	5	.	.	.	.	.	.	.	.
Poaceae									
Dactyloctenium aegyptium	.	.	.	.	1	1	.	.	.
Hordeum sp. rachis	.	.	.	.	1	.	.	.	.

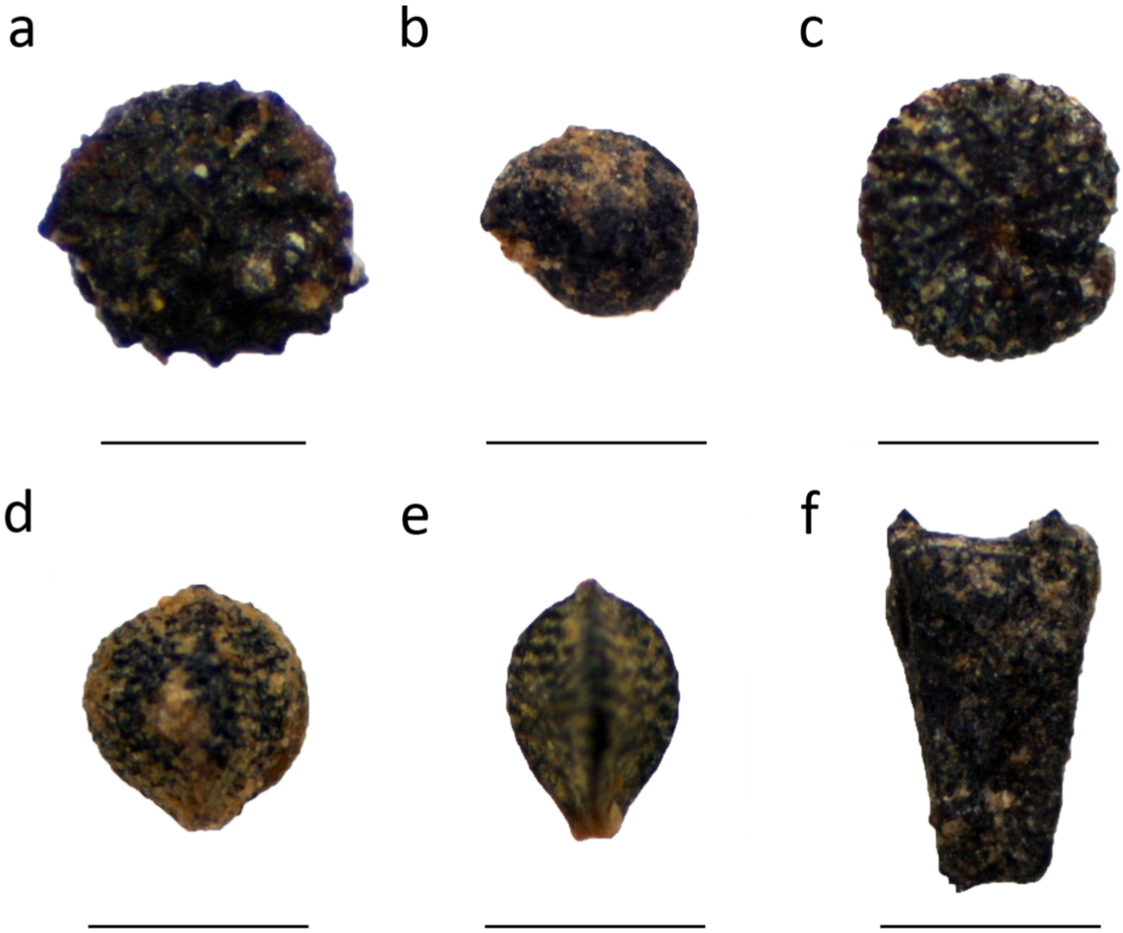


Figure 20. Macrobotanical remains from Datrana IV. a) *Dactyloctenium aegyptium* caryopsis, b) *Chenopodium* sp. seed, c) Caryophyllaceae seed, d-e) Cyperaceae seeds, f) *Hordeum vulgare* rachis. Scale bars 0.5 mm in a and 1 mm in b-f.

All phytolith samples were quick-scanned at 200x but, due to the extreme scarcity of phytoliths, only two samples were fully scanned at 630x (Table 30). Some phytoliths showed signs of chemical dissolution, but this trait was not generalised. Soil pH values were moderately high throughout the sequence (Table 30), indicating the presence of slightly alkaline soils.

Table 30. Phytolith, starch grain and soil pH analyses from sediment samples from Datrana IV. Phytolith concentration is expressed in millions per g of AIF (Acid Insoluble Fraction). Starch concentration is expressed in grains per g of original sediment. - = sample not analysed.

	DTR 9	**DTR 10**	**DTR 11**	**DTR 12**	**DTR 13**	**DTR 25**	**DTR 27**	**DTR 30**	**DTR 34**	**DTR 44**
Phytoliths										
Grass LC inflorescence	3	-	-	.	-	-	-	-	-	-
Grass LC leaf/culm	24	-	-	8	-	-	-	-	-	-
Grass LC undetermined	5	-	-	1	-	-	-	-	-	-
Grass bulliform	4	-	-	2	-	-	-	-	-	-
Grass SC panicoid	6	-	-	1	-	-	-	-	-	-
Grass SC chloridoid	2	-	-	2	-	-	-	-	-	-
Grass SC pooid	4	-	-	2	-	-	-	-	-	-
Grass SC undetermined	6	-	-	2	-	-	-	-	-	-
Dicot	2	-	-	.	-	-	-	-	-	-
Undetermined	78	-	-	37	-	-	-	-	-	-
Unidentified	26	-	-	9	-	-	-	-	-	-
Total phytoliths	166	-	-	64	-	-	-	-	-	-
Phytolith concentration	0	-	-	0	-	-	-	-	-	-
Starch grains										
Type 1b	4	.	2	.	.	.	.	2	2	.
Type 1c	.	.	1	.	.	.	.	1	.	.
Type 2	1	.	.	.	.	1	.	.	.	.
Type 4	.	.	1	.	.	1	.	.	1	.
Type 8	1	.	.	.	.	.	.	.	1	.
Unidentified	.	1	.	.	.	.	.	1	.	.
Total starch grains	6	1	4	.	.	2	.	5	4	.
Starch concentration	14	2	11	0	0	5	0	13	10	0
Soil pH	8.61	8.55	8.59	8.46	8.46	8.63	8.47	8.56	8.34	8.49

Shikarpur

Macrobotanical remains were analysed from nine fire-related contexts, and a total of 11 samples were analysed for microbotanical remains.

Charred macroremains were comparatively abundant but generally poorly preserved (Table 31; Fig. 21). Charred grass remains included 31 grains of small millets, of which 22 belonged to the general SEB type (*Setaria*, *Echinochloa* and *Brachiaria*) (Fig. 21a) and nine were identified no further than small millets due to severe damage. Chaff remains from rice (Fig. 21b) and barley were also found. Other recovered grasses included half a charred grain of Job's tears (Fig. 21c), 10 mineralised full inflorescences of browntop millet (Fig. 21d-e), two crowfoot grass caryopses and four partial wheat/barley caryopses. Pulses were also present and identified as mung bean/black gram (Fig. 21f). Morphometric analyses were not conclusive, but the generally small seed size (average 1.15 x 0.87 mm) suggests a wild species of *Vigna* (Fuller and Harvey

2006). Moreover, leaf fragments from an unidentified member of the Fabaceae were recovered from four contexts. Other finds included several weeds (*Trianthema* sp. and *Chenopodium* sp.) (Fig. 21g–h), six sedges (Cyperaceae) and several parenchyma fragments from tubers.

Table 31. Macrobotanical remains from fire-related contexts from Shikarpur. + = present.

	Ash 1	**Ash 2**	**Ash 3**	**Pit 1**	**Pit 2**	**BA 1**	**BA 2**	**Hearth 1**	**Hearth 2**
Sediment volume (l)	20	40	20	60	20	20	10	30	20
Aizoaceae									
Trianthema sp.	1	1	.	2	.	.	.	29	1
Amaranthaceae									
Chenopodium sp.	1	1	.	1	.	.	20	.	.
Cyperaceae	.	1	.	1	2	1	1	.	.
Fabaceae									
Vigna sp.	1	1	.	10	2	.	3	.	2
Leaf fragments	.	+	.	+	.	.	.	+	+
Poaceae									
Chloridoideae									
Dactyloctenium aegyptium	.	.	.	1	.	.	1	.	.
Ehrhartoideae									
Oryza sp. spikelet base	.	.	.	.	1	.	.	.	.
Panicoideae									
Brachiaria ramosa (mineralised)	.	.	.	10	.	.	.	.	.
SEB type caryopsis	1	1	.	16	2	1	.	.	1
Small millet indet. caryopsis	.	1	.	4	2	.	.	1	1
Coix lacryma-jobi caryopsis	.	.	.	1	.	.	.	.	.
Pooideae									
Hordeum vulgare rachis	.	.	.	.	1	.	.	.	.
Cerealia indet. caryopsis	.	1	.	.	2	.	.	.	1
Cerealia indet. chaff	.	.	.	3	.	.	.	.	1
Solanaceae									
cf. *Solanum* sp.	.	.	.	.	1	.	.	.	.
Parenchyma fragments	+	+	.	+	+	.	.	+	+

Figure 21. Macrobotanical remains from fire-related contexts from Shikarpur. a) charred caryopsis of a SEB type small millet, b) charred spikelet base of *Oryza* sp., c) half charred caryopsis of *Coix lacryma-jobi*, d) dorsal and e) ventral view of a mineralised inflorescence of *Brachiaria ramosa*, f) charred seed of *Vigna* sp., g) charred grains of *Trianthema* sp., and h) charred grains of *Chenopodium* sp. Scale bars 1 mm in a–f and 2 mm in g–h.

Fire-related contexts had very high phytolith concentrations (Table 32). Among the grass short cells, panicoid morphotypes predominated in all samples. Leaf/culm morphotypes were the main grass long cells. The single-cell assemblage further included dicotyledons, palms and sedges. Silica skeletons typically occurring in the external parts of small millet inflorescences were recovered (Fig. 22). Starch grains were scarce in fire-related contexts.

Table 32. Phytolith and starch grains analyses from fire-related contexts from Shikarpur. Phytolith concentration is expressed in millions per g of AIF (Acid Insoluble Fraction). Starch concentration is expressed in grains per g of original sediment.

	Ash 1	**Ash 2**	**Ash 3**	**Pit 1**	**Pit 2**	**BA 1**	**BA 2**	**Hearth 1**	**Hearth 2a**	**Hearth 2b**	**Oven**
Phytoliths											
Grass LC inflorescence	25	23	5	20	17	16	15	14	10	4	49
Grass LC leaf/culm	38	88	28	18	62	55	44	33	52	19	48
Grass LC undetermined	11	6	7	3	19	21	4	15	6	12	13
Grass bulliform	.	3	11	3	4	21	6	7	18	5	6
Grass SC panicoid	128	117	68	135	100	104	89	86	87	94	116
Grass SC chloridoid	25	31	24	44	36	44	34	28	30	42	40
Grass SC pooid	32	40	33	28	24	38	33	33	31	18	31
Grass SC undetermined	66	39	31	48	67	41	74	60	46	56	58
Cyperaceae	.	.	1	.	.	.	.	2	.	.	.
Arecaceae	.	.	.	.	1	.	.	.	.	.	.
Dicot	.	3	2	3	4	1	1	.	.	1	1
Undetermined	14	37	93	22	24	32	38	24	53	52	20
Unidentified	.	1	.	.	.	1	.	.	.	.	.
Total phytoliths	339	388	303	324	358	374	338	302	333	303	382
Phytolith concentration	5.6	4.4	0.1	10.8	8.5	1.2	7.2	0.6	0.8	0.3	3.9
Starch grains											
Type 1a	.	.	.	.	.	.	.	4	1	.	.
Type 1b	.	1	1	2	.	.	.	2	3	3	1
Type 1c	.	2	.	2	.	1	.	.	1	.	.
Type 2	.	.	1	1	1	1	.	.	.	2	1
Type 3	.	.	.	1	1	.	.	.	.	.	.
Type 4	3	2	.	2	.	1	4	.	1	.	.
Total starch grains	3	5	2	8	2	3	4	6	6	5	2
Starch concentration	7	12	5	20	5	7	10	15	15	13	5

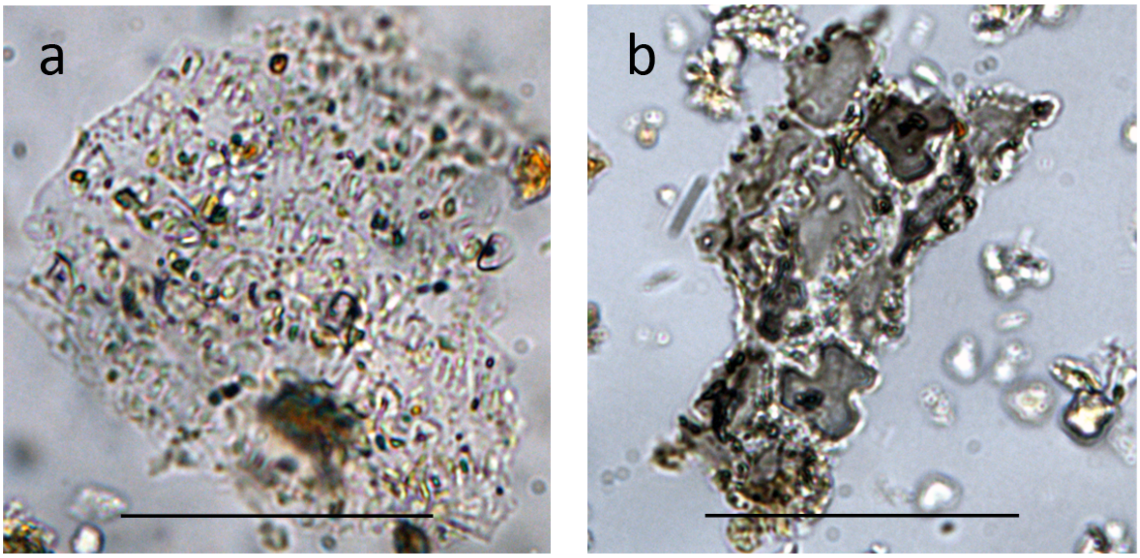


Figure 22. Silica skeletons from small millet external inflorescence parts recovered from Shikarpur. Scale bars 50 µm.

Geometric morphometrics

GM analyses were carried out exclusively with macrobotanical remains from SKP because the presence of *S. italica*/*B. ramosa* caryopses at other sites was minimal. After close examination, 15 SEB type caryopses from SKP were deemed suitable for the implementation of GM. The remaining seven grains lacked at least one of the homologous anatomical features required for the landmark configuration implemented in the study. A PCA and a Discriminant Analysis were conducted with the charred modern and archaeological caryopses in order to assess the morphological affinities of the latter group.

The PCA reflects the group differentiation between *S. italica* (negative end of the axis of PC1) and *B. ramosa* (positive end) (Fig. 23). The archaeological caryopses have a broad distribution, mostly overlapping with *B. ramosa* or occupying a more negative position on the axis (outside the distribution of *B. ramosa*); however, three seeds are located in the overlapping zone between *B. ramosa* and *S. italica*, around the zero value of the axis. PC2 does not portray group differentiation.

The Discriminant Analysis (Table 33) yielded one discriminant function, significant at $p \leq 0.05$, which provides a fairly good discrimination among the modern charred caryopses: 90.2% of the original cases are correctly classified, and 78.7% when cross-validation is employed. Based on Mahalanobis distances from modern group centroids, the analysis classifies 14 of the archaeological specimens as *B. ramosa* and one individual as *S. italica*.

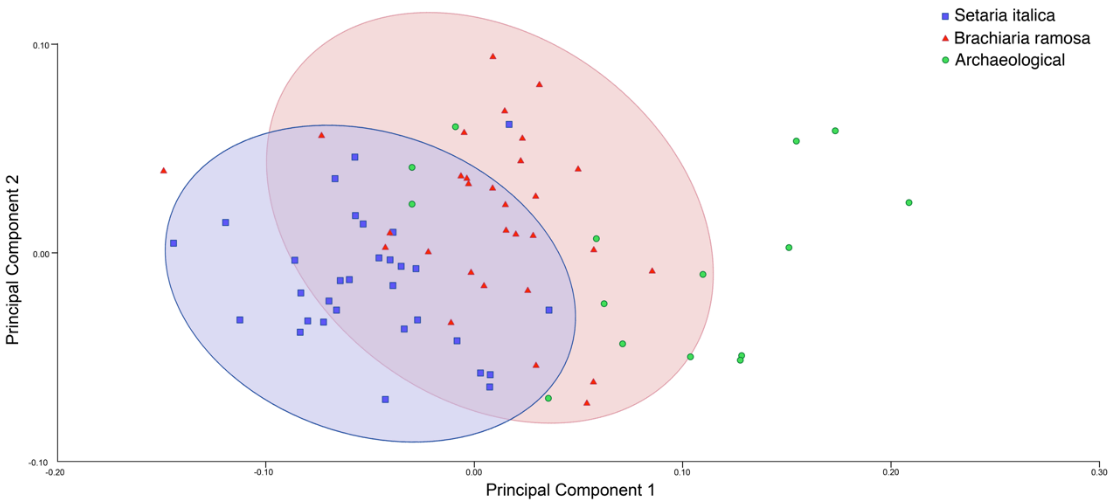


Figure 23. PC1 and PC2 scatterplot of the Principal Components Analysis (PCA) of charred modern *Setaria italica* and *Brachiaria ramosa* caryopses and archaeological specimens from Shikarpur.

Table 33. Results of the Discriminant Analysis on the Procrustes coordinates of charred modern *Setaria italica* and *Brachiaria ramosa* caryopses and archaeological specimens. D^2 = Squared Mahalanobis distance.

Specimen	**1st group**	**D^2**	**2nd group**	**D^2**
Archaeological #1	*S. italica*	0.278	*B. ramosa*	10.292
Archaeological #2	*B. ramosa*	1.153	*S. italica*	14.099
Archaeological #3	*B. ramosa*	1.89	*S. italica*	16.45
Archaeological #4	*B. ramosa*	1.733	*S. italica*	1.863
Archaeological #5	*B. ramosa*	0.379	*S. italica*	4.266
Archaeological #6	*B. ramosa*	7.523	*S. italica*	29.418
Archaeological #7	*B. ramosa*	0.293	*S. italica*	4.58
Archaeological #8	*B. ramosa*	0.186	*S. italica*	5.064
Archaeological #9	*B. ramosa*	15.997	*S. italica*	44.632
Archaeological #10	*B. ramosa*	14.689	*S. italica*	42.428
Archaeological #11	*B. ramosa*	0.077	*S. italica*	8.756
Archaeological #12	*B. ramosa*	0.352	*S. italica*	10.72
Archaeological #13	*B. ramosa*	0.247	*S. italica*	4.77
Archaeological #14	*B. ramosa*	25.408	*S. italica*	59.624
Archaeological #15	*B. ramosa*	1.189	*S. italica*	2.53

5.3.2. Grinding stones

Phytolith and starch data from the four sites are presented all together in a comparative approach rather than site-by-site. The results from the comparison between control samples and grinding stones are presented first.

Control samples

At VHV, LTS and DTR the sediment samples analysed to understand the general microbotanical input of the sites were also used as control samples for the grinding stones, whereas at SKP control samples were collected separately. Therefore, only the results of control samples from SKP are presented here (Table 34). For the results of the analyses of control samples from LTS, VHV and DTR se Tables 26, 28 and 30.

Samples with <100 encountered phytoliths were excluded from the similarity analysis. Only a few samples were available from VHV and LTS, and therefore they were analysed and plotted together (Fig. 24). Samples from SKP were analysed and plotted independently (Fig. 25). The analyses confirmed that most grinding stones do not cluster with their corresponding control sample, except for samples LTS_GS1a, LTS_GS7b and SKP_Hand4, which were therefore excluded from subsequent analyses.

Starch grains were very scarce (0-6 grains) in most control samples, with the exception of some samples from SKP that contained up to 54 grains (Tables 26, 28, 30 and 34). Control samples generally presented lower starch concentration than grinding stones.

Table 34. Phytolith and starch grain analyses from control samples from Shikarpur. Phytolith concentration is expressed in millions per g of AIF (Acid Insoluble Fraction). Starch concentration is expressed in grains per g of original sediment.

	Control 1	**Control 2**	**Control 3**	**Control 4**	**Control 5**	**Control 6**	**Control 7**	**Control 8**	**Control 9**	**Control 10**	**Control 11**
Phytoliths											
Grass LC inflorescence	25	19	18	2	20	5	25	11	17	11	16
Grass LC leaf/culm	35	23	34	30	28	12	27	30	35	41	36
Grass LC undetermined	13	34	13	7	5	4	2	2	12	11	7
Grass bulliform	1	22	12	5	17	8	7	9	7	11	5
Grass SC panicoid	98	82	97	64	78	74	70	102	91	87	85
Grass SC chloridoid	25	21	20	15	34	31	20	33	29	40	33
Grass SC pooid	34	32	19	26	30	43	35	28	20	19	26
Grass SC undetermined	60	29	44	61	37	57	61	34	50	59	53
Cyperaceae	.	.	.	.	.	.	.	.	.	3	.
Arecaceae	.	2	.	.	.	2	.	.	.	.	.
Dicot	.	5	1	3	2	2	.	1	2	2	3
Undetermined	27	66	52	87	58	60	66	54	40	38	39
Unidentified	1	.	.	.	.	.	.	.	.	.	.
Total phytoliths	319	335	310	300	309	298	313	304	303	319	306
Phytolith concentration	1.8	0.8	1.5	0.3	0.6	0.7	0.6	0.6	1.1	1.4	0.4
Starch grains											
Type 1a	.	.	.	.	.	.	20	.	.	.	.
Type 1b	.	1	3	1	1	3	1	1	1	.	1
Type 1c	.	1	.	.	.	1	.	1	1	.	.

	Control 1	Control 2	Control 3	Control 4	Control 5	Control 6	Control 7	Control 8	Control 9	Control 10	Control 11
Type 2	4	51	2	.	2	1	9	6	.	.	51
Type 4	.	.	.	.	.	1	.	1	.	.	2
Type 8	.	.	.	.	.	.	.	1	.	.	.
Unidentified	2	.	.	.	.	.	.	.	.	.	.
Total starch grains	6	53	5	1	3	6	30	10	2	0	54
Starch concentration	15	138	12	2	7	15	71	25	5	0	140

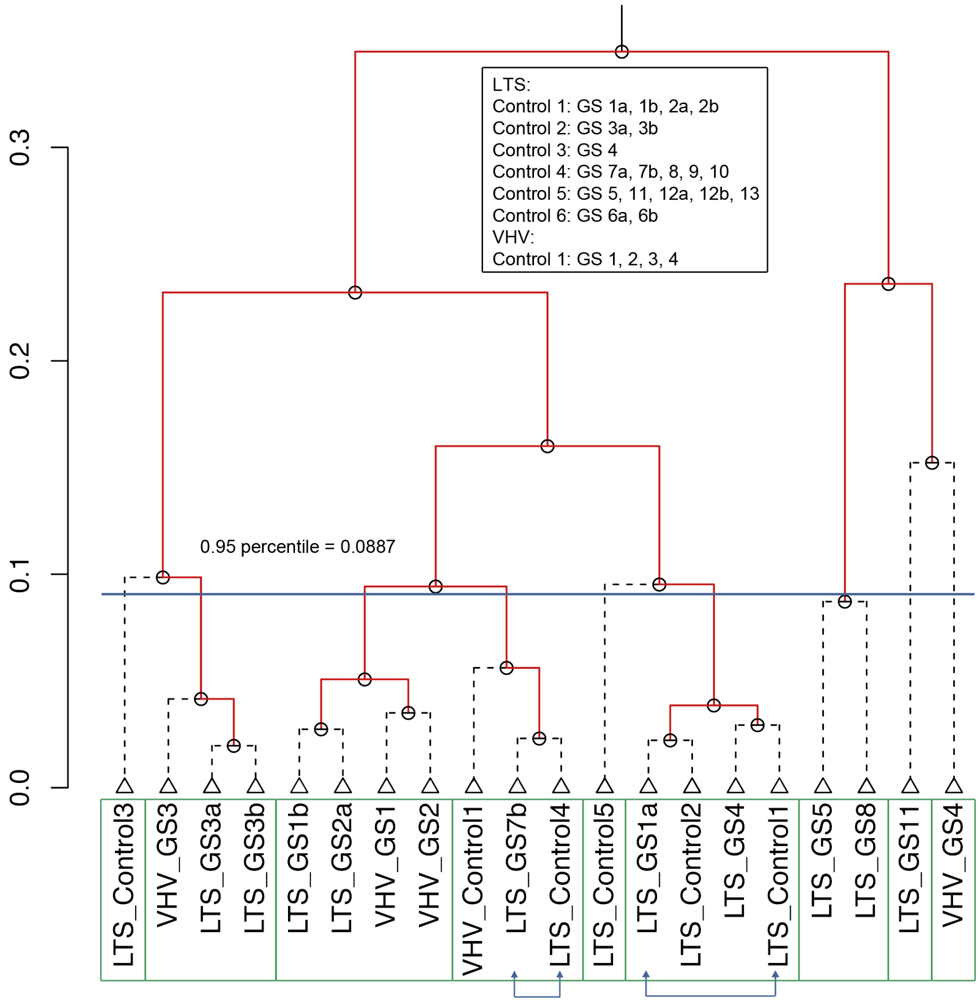


Figure 24. Dendrogram of the similarity analysis of grinding stones and control samples from Vaharvo Timbo and Loteshwar. The blue line marks the 0.95 percentile of the index score, which defines the sample clusters (green boxes). The blue arrows point to grinding stones clustered with their control sample.

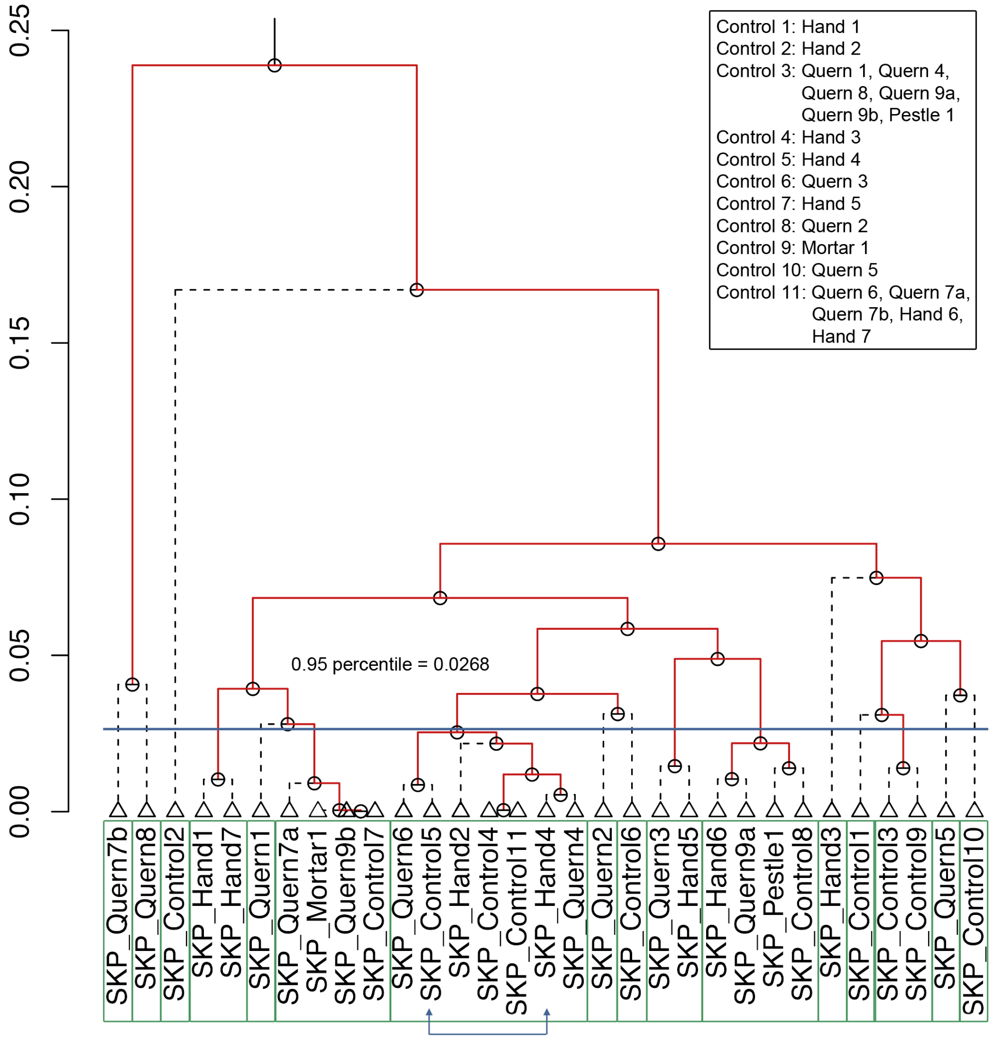


Figure 25. Dendrogram of the similarity analysis of grinding stones and control samples from Shikarpur. The blue line marks the 0.95 percentile of the index score, which defines the sample clusters (green boxes). The blue arrows point to grinding stones clustered with their control sample.

Grinding stones

Phytoliths were observed in all the samples from SKP, absent from all samples from DTR and variable in samples from VHV and LTS (Tables 35, 36, 37 and 38). At DTR, all phytolith samples were quick-scanned at 200x but, due to the extreme scarcity of phytoliths, only five of them were fully scanned at 630x. Samples from VHV showed a medium correlation (R^2=0.63) between the total number of phytoliths and the initial sample weight (samples <0.3 g are sterile), whereas samples from LTS did not show any correlation (Fig. 26a). Grasses dominated the phytolith assemblage in all samples, with Panicoideae being the most common grass subfamily in VHV, LTS_AP and, especially, SKP (Fig. 27a). Non-grass phytoliths –including sedges (Cyperaceae) and dicotyledons– were marginally present in all sites, and palms (Arecaceae) were observed only in samples from VHV and SKP. Undetermined and unidentified phytoliths were also present in all sites, being an important part of the assemblage from VHV.

Table 35. Phytolith analyses from grinding stones from Vaharvo Timbo. Phytolith concentration is expressed in millions per g

	GS 1	**GS 2**	**GS 3**	**GS 4**	**GS 5**	**GS 6**	**GS 7**	**GS 8**	**GS 9**	**GS 10**	**GS 11**	**GS 12**	**GS 13**	**GS 14**
Phytoliths														
Grass LC inflorescence	5	3	6	.	.	.	.	.	.	.	.	.	.	.
Grass LC leaf/culm	46	53	48	35	.	3	2	.	.	.	.	3	1	.
Grass LC undetermined	12	5	7	3	.	.	.	.	.	.	.	.	.	.
Grass bulliform	4	15	31	7	.	.	2	.	.	.	.	1	.	.
Grass SC panicoid	17	17	16	19	.	2	2	.	.	.	1	.	2	.
Grass SC chloridoid	17	12	24	12	.	.	.	.	.	.	.	.	.	.
Grass SC pooid	25	20	17	5	.	1	.	.	.	.	.	.	.	.
Grass SC undetermined	17	4	9	4	.	.	.	.	.	.	.	.	.	.
Cyperaceae	.	.	1	.	.	.	.	.	.	.	.	.	.	.
Arecaceae	1	.	2	.	.	.	.	.	.	.	.	.	.	.
Dicot	7	5	.	1	1	.	.	.	1	.	.	.	1	.
Undetermined	102	180	143	76	.	9	9	.	3	.	1	7	1	.
Unidentified	97	67	49	31	.	3	1	.	1	.	.	4	1	.
Total phytoliths	350	381	353	193	1	18	16	0	5	0	2	15	6	0
Phytolith concentration	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 36. Phytolith and starch grain analyses from grinding stones from Loteshwar. Phytolith concentration is expressed
Fraction). Starch concentration is expressed in thousands per g of original sediment.

	GS 1a	GS 1b	GS 2a	GS 2b	GS 3a	GS 3b	GS 4	GS 5	GS 6a	GS 16b	GS 17a	GS 17b	GS 18	GS 19
Phytoliths														
Grass LC inflorescence	24	5	10	1	11	5	19	9	.	3	3	13	4	
Grass LC leaf/culm	66	17	39	.	99	66	66	33	.	17	1	56	22	
Grass LC undetermined	10	1	12	.	13	20	16	15	.	.	.	18	22	
Grass bulliform	11	9	8	.	97	220	2	7	.	1	.	4	15	
Grass SC panicoid	72	32	64	.	50	45	68	33	.	2	.	43	38	
Grass SC chloridoid	19	41	54	.	42	24	29	27	.	.	.	32	12	
Grass SC pooid	54	28	49	.	35	48	61	39	.	.	.	33	50	
Grass SC undetermined	34	15	37	.	31	38	37	14	.	2	.	30	15	
Cyperaceae	1	.	.	.	.	.	1	1	.	.	.	3	.	
Arecaceae	.	.	.	.	.	.	.	.	.	.	.	.	.	
Dicot	3	2	5	.	.	.	7	23	.	.	.	15	35	
Undetermined	63	58	46	1	75	79	41	107	1	3	.	66	90	
Unidentified	8	12	3		12	13	3	8	1	2	.	43	7	
Total phytoliths	365	220	327	2	465	558	350	316	2	30	4	356	310	1
Phytolith concentration	3.6	0.1	2.4	0	0.2	0.1	8.1	0.5	0	0	0	1.1	0.4	
Starch grains														
Type 1a	8	13					1			2				3
Type 1b	1	1	2	4	2	3	4	4	3	4	2	2	3	
Type 1c	4	1	1	1	1				2	2		2		
Type 2	7	1	11	5	4	5	3	7	5	2	3	10	5	
Type 3		1		1			6		2	1	1			
Type 4							1		2					

	GS 1a	GS 1b	GS 2a	GS 2b	GS 3a	GS 3b	GS 4	GS 5	GS 6a	GS 16b	GS 17a	GS 17b	GS 18	GS 19
Type 5						1							1	
Type 7		1						1	1		1	1		
Type 9									1					
Unidentified	7	18	1		1	2	6	2	3	1		2		
Total starch grains	27	36	15	11	8	11	21	14	19	12	7	17	9	5
Starch concentration	4.4	8.3	3.7	4.9	3.4	5.2	2.7	1.5	5.9	3.9	0.4	2.1	1.6	6.

Table 37. Phytolith and starch grain analyses from grinding stones from Datrana IV. Phytolith concentration is expresse
Fraction). Starch concentration is expressed in thousands per g of original sediment. - = sample not analysed.

	GS 1	GS 2	GS 3	GS 4a	GS 4b	GS 5	GS 6a	GS 6b	GS 7	GS 8	GS 9	GS 10	GS 11a	GS 11b	GS 12a
Phytoliths															
Grass LC inflorescence	-	-	-	.	-	-	-	-	-	-	.	.	-	-	
Grass LC leaf/culm	-	-	-	3	-	-	-	-	-	-	.	1	-	-	
Grass LC undetermined	-	-	-	.	-	-	-	-	-	-	.	1	-	-	
Grass bulliform	-	-	-	3	-	-	-	-	-	-	.	1	-	-	
Grass SC panicoid	-	-	-	2	-	-	-	-	-	-	.	3	-	-	
Grass SC chloridoid	-	-	-	1	-	-	-	-	-	-	.	.	-	-	
Grass SC pooid	-	-	-	5	-	-	-	-	-	-	.	4	-	-	
Grass SC undetermined	-	-	-	1	-	-	-	-	-	-	.	.	-	-	
Dicot	-	-	-	.	-	-	-	-	-	-	.	1	-	-	
Undetermined	-	-	-	6	-	-	-	-	-	-	.	5	-	-	
Unidentified	-	-	-	8	-	-	-	-	-	-	.	3	-	-	
Total phytoliths	-	-	-	29	-	-	-	-	-	-	0	19	-	-	
Phytolith concentration	-	-	-	0	-	-	-	-	-	-	0	0	-	-	
Starch grains															
Type 1a	1	.	1	.	.	.	8	.	.	.	1	.	.	.	
Type 1b	2	2	1	3	.	.	44	.	.	1	1	1	.	2	
Type 1c	.	1	.	.	.	1	.	2	.	2	.	.	.	1	
Type 2	.	1	.	.	1	2	2	.	.	.	1	.	.	2	
Type 3	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Type 4	.	1	1	.	.	.	.	.	.	1	.	.	1	.	
Type 5	.	.	1	.	.	.	1	.	.	.	2	.	.	.	
Type 7	.	.	.	.	.	.	.	.	.	.	.	.	.	.	

	GS 1	GS 2	GS 3	GS 4a	GS 4b	GS 5	GS 6a	GS 6b	GS 7	GS 8	GS 9	GS 10	GS 11a	GS 11b	GS 12a
Type 8	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Type 9	.	.	.	.	.	.	1	.	.	.	.	.	.	.	
Type 14	.	.	.	.	1	.	.	.	.	.	.	.	.	.	
Unidentified	.	13	.	.	1	.	.	1	.	.	.	.	1	.	
Total starch grains	3	5	4	3	2	3	56	2	0	4	5	1	1	5	
Starch concentration	0.7	0.8	0.3	0.1	0.1	0.3	4.1	0.3	0	0.1	0.8	0.1	0.4	0.3	0.

Table 38. Phytolith and starch grain analyses from grinding stones from Shikarpur. Phytolith concentration is expressed
Fraction). Starch concentration is expressed in thousands per g of original sediment.

	Quern 1	Quern 2	Quern 3	Quern 4	Quern 5	Quern 6	Quern 7a	Quern 7b	Quern 8	Quern 9a	Quern 9b	Hand 1	Hand 2	Hand 3
Phytoliths														
Grass LC inflorescence	5	6	21	22	18	10	17	14	7	7	19	16	13	4
Grass LC leaf/culm	10	10	29	17	10	6	6	8	6	15	10	20	21	32
Grass LC undetermined	2	9	4	6	14	3	4	.	.	1	2	7	8	9
Grass bulliform	6	5	9	6	2	5	8	9	7	10	12	10	3	52
Grass SC panicoid	111	101	102	105	79	67	84	78	78	84	57	100	102	16
Grass SC chloridoid	31	34	53	44	33	61	48	32	40	34	41	31	32	8
Grass SC pooid	39	28	37	46	56	51	39	59	68	51	42	39	37	6
Grass SC undetermined	54	69	45	32	70	57	75	76	54	62	76	51	35	8
Cyperaceae	1	.	3	.	1	.	.	.	.	.	.	.	.	.
Arecaceae	.	.	.	.	.	.	.	.	.	.	.	.	.	3
Dicot	.	4	1	2	.	2	.	.	2	2	.	.	1	4
Undetermined	40	38	28	18	24	37	30	31	41	38	50	35	47	194
Unidentified	.	.	.	.	3	.	1	.	.	.	.	1	.	22
Total phytoliths	299	304	332	298	310	299	312	307	303	304	309	310	299	358
Phytolith concentration	4.6	4.2	3.1	1.7	4.4	1.9	3.1	2.1	4.5	4.1	1.9	3.6	1.1	0
Starch grains														
Type 1a	.	.	89	.	41	1	.	.	15	.	10	.	.	.
Type 1b	1	1	.	3	18	.	8	3	4	2	1	15	19	1
Type 1c	.	1	.	.	2	.	1	.	.	.	.	5	4	.
Type 2	3	.	4	20	5	11	11	4	17	18	13	8	19	5
Type 3	.	.	1	.	1	.	9	2	.	.	2	1	3	1

	Quern 1	Quern 2	Quern 3	Quern 4	Quern 5	Quern 6	Quern 7a	Quern 7b	Quern 8	Quern 9a	Quern 9b	Hand 1	Hand 2	Hand 3
Type 4	1	.	.	.	1	.	1	.	.	.	3	2	.	1
Type 5	1	1	1	1		5	2	1	1	5	.	.	2	.
Type 7	1	.	2	.	.	.	.	.	1			1	2	
Type 8	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Unidentified	.	2	1	.	1	2	1	2	7	.	.	.	1	1
Total starch grains	7	5	98	24	69	19	33	12	45	25	29	32	50	9
Starch concentration	0.3	0.2	1.9	0.2	2	0.3	0.7	0.2	0.4	0.4	1.6	0.6	0.5	0.4

Starch grains were present in all but two samples (Tables 36, 37 and 38), ranging in number between 1 and 230, and their quantities do not show any correlation with the initial sample weight (Fig. 26b). Panicoideae grains (particularly from small millets, Type 1a) predominated at all sites, followed by Faboideae (Type 2), which were present mostly in LTS_AP and SKP (Fig. 27b). Small amounts of Triticeae (Type 4) and cf. Triticeae (Types 3 and 8) grains were also present in all sites, as well as unidentified tuberous plants (Types 7 and 9). Finally, a single starch grain from the ginger family (Type 14) was encountered at DTR.

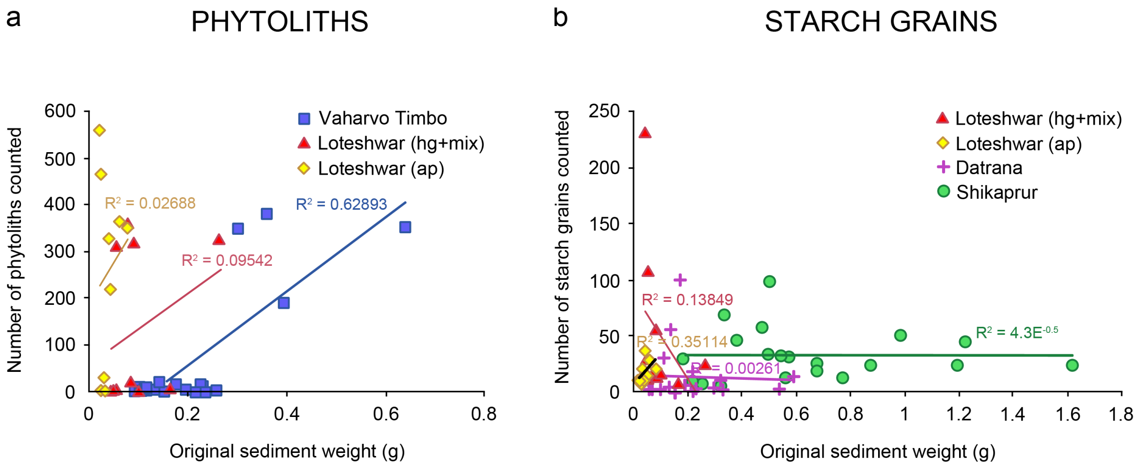


Figure 26. Total number of plant microremains counted per grinding stone against the initial sediment weight. a) phytolith samples from Vaharvo Timbo, Loteshwar and Shikarpur, and b) starch samples from Loteshwar, Datrana IV and Shikarpur.

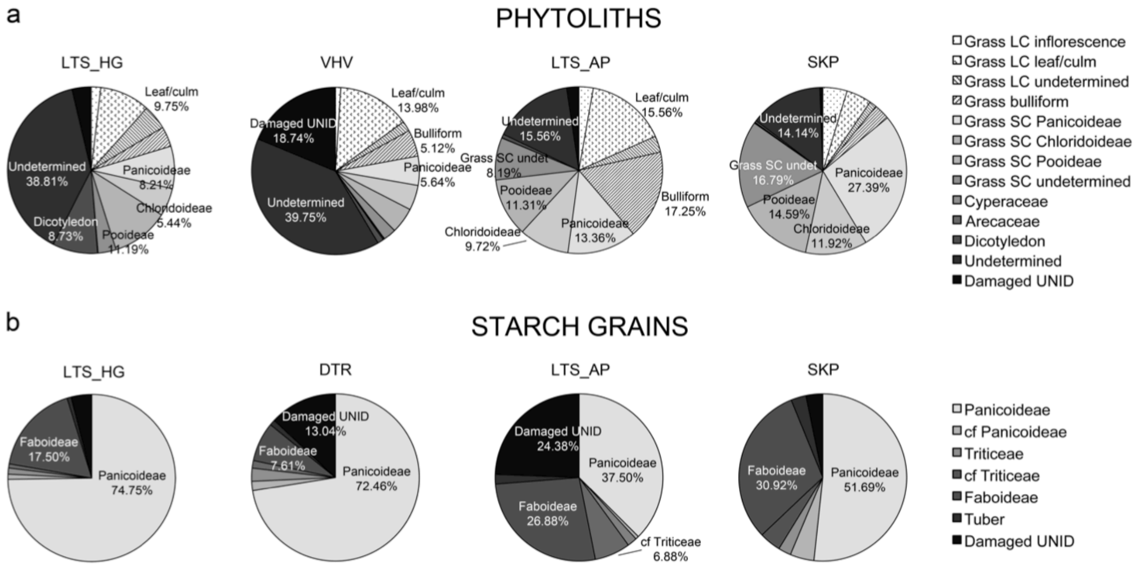


Figure 27. Percentages of microbotanical remains recovered from grinding stones. a) phytolith samples from Vaharvo Timbo, Loteshwar and Shikarpur, and b) starch samples from Loteshwar, Datrana IV and Shikarpur. Only those categories representing >5% of the assemblage are indicated in the charts.

For the PCA, only samples with >100 identified phytoliths (n=31) were plotted, excluding those samples clustered with their corresponding control sample in the similarity analysis. Samples from the HG and MIX deposits from LTS were plotted together due to the low number of samples from each context. SKP clearly separated from VHV and LTS, with the exception of sample SKP_Hand3 (Fig. 28a). Samples from the AP deposits from LTS were also differentiated from VHV and LTS_HG.

The PCA with the starch samples shows no differences in the starch assemblage composition between LTS and DTR, whereas samples from SKP had a different range of distribution, exhibiting the most positive values for PC1 (Fig. 28b).

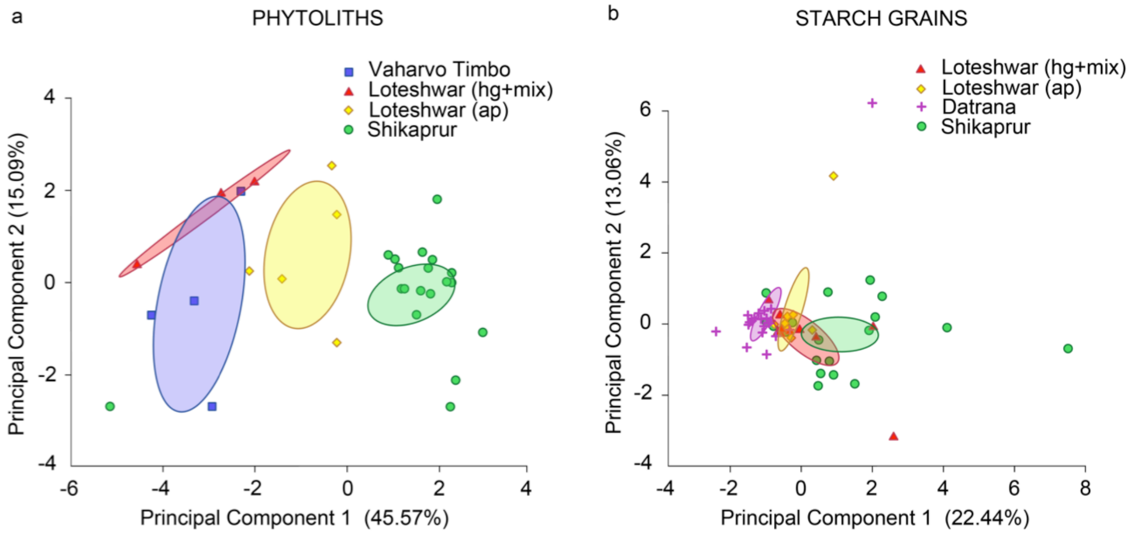


Figure 28. PC1 and PC2 scatterplots of the Principal Component Analyses (PCAs) of microbotanical samples from grinding stones. a) phytolith samples from Vaharvo Timbo, Loteshwar and Shikarpur, and b) starch samples form Loteshwar, Datrana IV and Shikarpur.

The only site where phytoliths and starch grains were recovered from all the grinding stones is SKP, and therefore the indices of compositional similarity to identify groups of tools were analysed only in this site. Sample SKP_Hand3 was excluded due to the taphonomical processes that affected the phytolith assemblage, which resulted in the preferential preservation of certain morphotypes more resistant to dissolution, such as parallelepipedals (Table 38), and its classification as an outlier in the PCS (Fig. 28a). In general, the grinding tools were grouped in three clusters, with two querns (SKP_Quern3 and SKP_Quern5) remaining outside of any cluster (Fig. 29). Grinding stones identified in each of the clusters come from a variety of archaeological contexts, and grinding stones recovered from the same context were not necessarily grouped in the same cluster (Fig. 30).

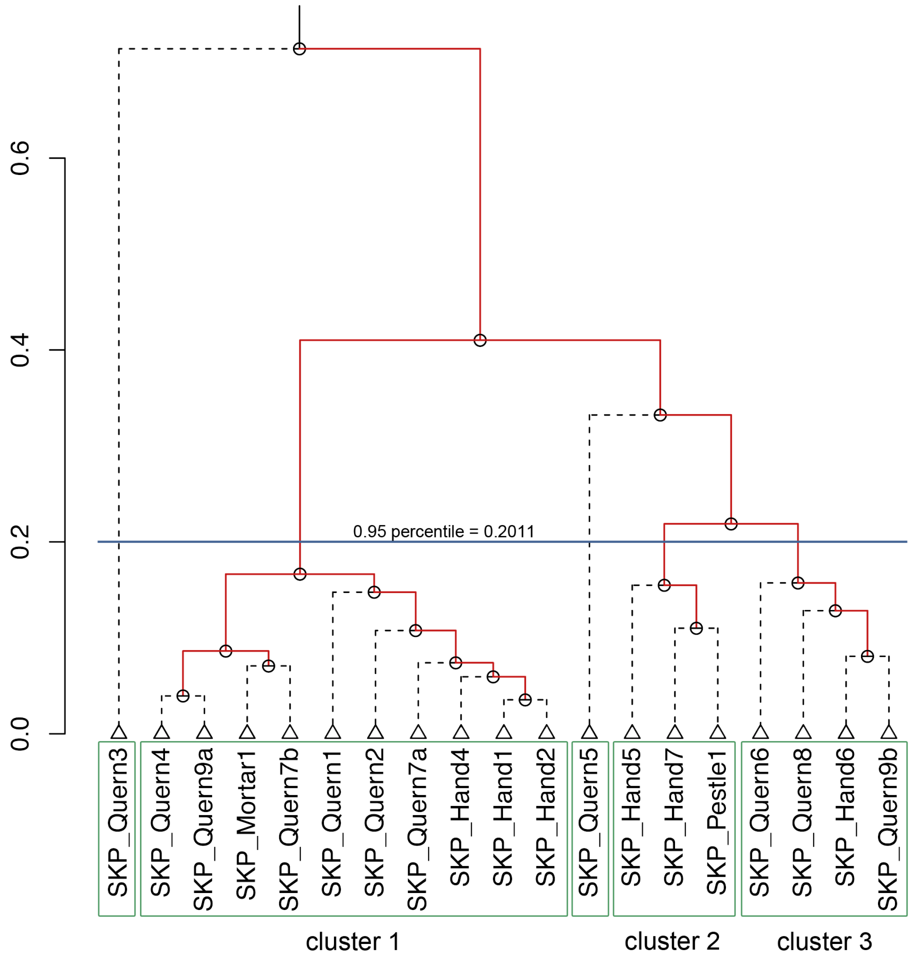


Figure 29. Dendrogram of the similarity analysis of grinding stones from Shikarpur. The blue line marks the 0.95 percentile of the index score, which defines the sample clusters (green boxes).

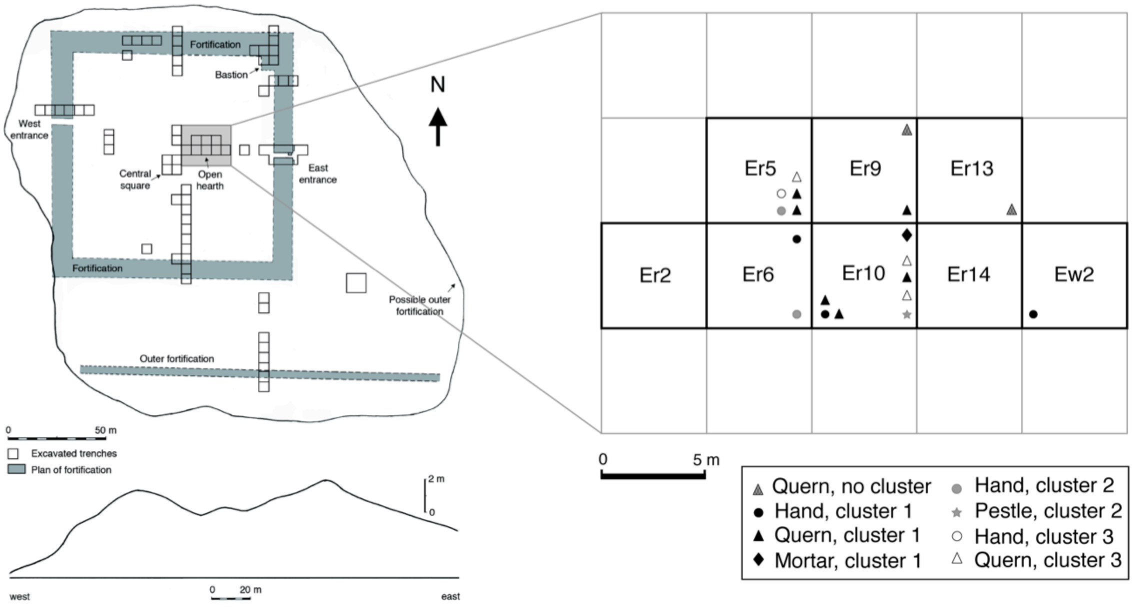


Figure 30. Spatial representation of the similarity analysis of grinding stones from Shikarpur. (site plan modified after Gadekar et al. 2014b).

6. Discussion

This chapter deals with the discussion of the main results of this thesis and it is organised according to the research questions presented in Chapter 2. Only the main findings are discussed; a more detailed discussion for the results of each study is available in the research papers.

6.1. What were the subsistence strategies of the inhabitants of northern Gujarat during the Holocene?

The main aim of this thesis was to understand how and why plant-related subsistence strategies changed throughout the Holocene in northern Gujarat. Three phases can be distinguished: hunting and gathering, low-level food production (plant cultivation) and intensive food production (farming). Data about plant gathering during the early-mid Holocene comes from VHV and the Mesolithic deposits from LTS; data about incipient plant cultivation during the mid-Holocene comes from DTR and the Anarta deposits from LTS; and data about the emergence of urban farming societies in the late Holocene comes from SKP and published archaeobotanical research in Harappan Gujarat. Finally, this part of the discussion focuses on the case for a centre of primary plant domestication in northern Gujarat.

6.1.1. Hunting and gathering during the early-mid Holocene

Palaeoclimatic models show a slow but constant weakening of the Indian Summer Monsoon after the early Holocene wet phase, ca. 10,000 to 7000 years ago, with certain degree of variability at a regional level (Gasse et al. 1996; Gupta et al. 2006; Hu et al. 2008; Liu et al. 2003; Overpeck et al. 1996; Wei and Gasse 1999). Preliminary data from interdunal depressions in the vicinity of VHV and LTS suggests that perennial water bodies existed until ca. 7000 years ago (NoGAP's unpublished data), as opposed to present day conditions where most depressions dry up during the winter (Conesa et al. 2014b).

The similar temporal and ecological ranges, and the comparable lithic assemblages of Mesolithic VHV and LTS (Gadekar et al. 2014a and C. Gadekar pers. comm.), suggest that these sites were frequented by groups of hunter-gatherers having similar economic practices. The archaeobotanical record from VHV is poor but the presence of *Digitaria* sp., crowfoot grass and spikelet bases from at least four different species suggests the gathering of wild grasses. Palm and sedge phytoliths indicate further exploitation of wild plants, including palms (e.g. *Phoenix sylvestris* (L.) Roxb.) (Barh and Mazumdar 2008; Davis and Johnson 1987; de Zoysa 1992; Khare 2007; Pandey et al. 2007), wild sesame and taxa from the more humid interdunal areas.

The archaeobotanical evidence from Mesolithic LTS shows a higher presence of dicot phytoliths than the evidence from the Anarta deposits, suggesting that hunter-gatherers exploited woody plants more than agro-pastoral people. The relatively high presence of pooid morphotypes –mainly rondels– is also interesting. Previous palaeoecological research in Gujarat suggests phases of higher winter precipitation during the Holocene (Prasad et al. 2007; Singh et al. 2007), which might have facilitated a higher presence of pooid grasses. The pooid morphotypes, however, may also derive from a so far unidentified rondel-producing panicoid grass, as in other areas of the world (e.g. *Panicum turgidum* Forssk. in West Africa, Radomski and Neumann 2011: Table 3). Indeed, several species of Panicoideaea were exploited in Mesolithic LTS, as suggested by Panicoideae starch grains. Moreover, the starch assemblage further indicates the exploitation of wild pulses.

Overall, the archaeobotanical evidence from Mesolithic LTS and VHV suggests the exploitation of a wide range of plants originating from (semi)permanent water bodies that created marshy microenvironments in the dune-interdune area. When combined with the zooarchaeological analysis from LTS (Patel 2009), these data show that hunter-gatherers inhabiting this region during the early-mid Holocene were relying on a broad-spectrum economy that exploited a diverse set of microenvironments.

6.1.2. The origins of food production during the mid-Holocene

The current regime of interdunal water availability was established ca. 7000 years ago and the local human populations had to adapt to new ecological settings, characterised by reduced water availability during the pre-monsoon season (Conesa et al. 2014b). Zooarchaeological data advocates for the adoption of semi-nomadic pastoralism (*sensu* Khazanov 1984: 19) from neighbouring herders (Fuller 2006) or as a locally developed process of cattle domestication (Patel 2009). Plant remains from Anarta LTS and DTR suggest that livestock was complemented with the cultivation of local small millets and probably other *kharif* crops, such as Job's tears, horsegram and sesame. The presence of weeds associated with cultivation (*Trianthema* spp. and *Chenopodium* sp.) supports the hypothesis that these crops were not simply gathered.

The integration of millet cultivation and semi-nomadic pastoralism has been (and still is) a successful subsistence strategy for populations in semi-arid regions worldwide, including for instance the Central Eurasian steppes during the Final Bronze Age and the Early Iron Age (Chang et al. 2003; Lightfoot et al. 2014; Murphy et al. 2013; Svyatko et al. 2013) or present-day FulBe groups in the Sahel (Thébaud and Batterbury 2001). The cultivation of fast-maturing small millets, harvested 60-90 days after sowing (Weber and Fuller 2008), is compatible with the seasonal migration cycles of mobile pastoral groups, enabling them to take advantage of several ecological niches (Di Cosmo 1994). Semi-nomadic agro-pastoral groups inhabiting northern Gujarat during the mid-Holocene would have scheduled plant-related activities according to the highly seasonal monsoon regime, maximising mobility during periods of low resource availability.

During years of scarce yields, wild grasses could have been gathered to supplement the cultivated grains. The presence of crowfoot grass in the macrobotanical assemblage from LTS and DTR suggests such a possibility, and it would also explain the relatively high presence of saddle phytoliths in sediments and grinding stones at LTS. Crowfoot grass is widely distributed throughout the tropics, subtropics, and warm temperate regions of the Old World (Manidool 1992) and it is generally considered a weed. Ethnography from modern Rajasthan reports its consumption as a famine crop, either alone, mixed with semi-ground pulses to prepare Keech or ground with millet for bread-making (www.hort.purdue.edu).

During the pre-monsoon season, gathering of plant resources collected from the marsh interdunal depressions, such as sedges and tubers, would have increased to complement the dwindling grains. To overcome pre-monsoon scarcity, semi-nomadic groups in northern Gujarat could have also traded with neighbouring Harappan communities, and the minor presence of winter crops (wheat/barley and poppy seeds) at LTS and DTR can be interpreted as such. The small presence of sheep/goat remains at LTS seems to reinforce this interpretation (Patel 2009). Further evidence for exchange and/or trade, in this case outside the Indus Valley, was highlighted by the presence of *Musa* sp. phytoliths in a previous study from LTS (García-Granero 2011; García-Granero et al. in press).

6.1.3. The establishment of urban farming communities during the late Holocene

With the advent of settled urban life in the mid-third millennium BC mobility was no longer a viable strategy to face resource scarcity. Instead, Harappan settlements had to develop a more intensive land-use strategy that involved a diversification of animal resources (compared to mid-Holocene semi-nomadic groups) and an intensification of certain plant resources. Moreover, the enhanced trade with Harappan centres in the Indus Valley probably provided access to food as well as other resources (Bahn and Ajithprasad 2008; Bhan et al. 2005; Gadekar et al. 2014b; Kenoyer 1984, 1991, 1997; Possehl 2002; Wright 2010).

The analysis of faunal remains from SKP and neighbouring Bagasra suggests the exploitation of cattle for secondary products, especially milk and traction (Chase 2010, 2014). Moreover, sheep and goat began to be locally raised and commonly consumed (Chase et al. 2014b), and –possibly domestic– pig (*Sus* sp.) appeared in the faunal record (Chase 2010, 2014). The relative diversification on animal exploitation strategies contrasts with a specialisation of agricultural practices. The plant-related subsistence strategy of the inhabitants of SKP was generally based on the cultivation of local summer crops, mostly small millets (*B. ramosa* and some other taxa, as shown by the GM analysis) and a morphologically wild *Vigna* sp. This cereal-legume intercropping pattern is repeated throughout the Urban and Post-Urban Harappan archaeobotanical record in Gujarat (Fuller 2006a, 2011; Reddy 1997; Weber 1999), suggesting that it was the strategy put in place by Harappan populations to maximise productivity by improving the soil through nitrogen enrichment. The use of animal traction would have also enabled the cultivation of larger extensions of land.

Wheat and barley, which were staple crops in the core Harappan areas, are scarcely present at SKP and other Harappan settlements in Gujarat (with the exception of Kanmer, where the interpretation of their presence is problematic; see Section 3.4.4). At SKP, macrobotanical evidence is limited to one barley rachis and a few fragmentary wheat/barley grains. Pooideae phytoliths were only marginally observed in all analysed contexts and tools, and characteristic wheat/barley chaff phytoliths (Rosen 1992) were completely absent. The best evidence for wheat/barley consumption comes from Triticeae starch grains, which were recovered from grinding stones. This minor presence of big grain, C_3 cereals at SKP and other Harappan settlements in Gujarat might represent a local, small-scale cultivation (cf. Bhan 1994) or, most likely, the trading between Harappan settlements set in different ecological regions.

6.1.4. Was northern Gujarat a centre of plant domestication?

The local character of the prehistoric crop package in Gujarat suggests the existence of an indigenous plant domestication process (Fuller 2006, 2011; Fuller and Murphy 2014; Purugganan and Fuller 2009). Cultivation of small millets and tropical pulses was well established in the region by the Urban Harappan period (Fuller and Madella 2002). The archaeobotanical evidence from VHV, LTS and DTR reveals a long and continuous history of gathering and pre-domestication cultivation of at least three different plant groups: small millets, pulses and sesame. The cultivation is unequivocal from the archaeobotanical record, but defining northern Gujarat as a primary centre of domestication requires an assessment of the 'domestic' character of these plants. Some of the morphological and genetic traits that characterise a plant as 'domestic' are the loss of seed dispersal mechanisms, the loss of germination inhibition, changes in seed size, and the appearance of seasonality control (Fuller and Allaby 2009).

Germination inhibition (loss of seed dormancy) and changes in seed size would occur during pre-domestication cultivation and should therefore be the first observed archaeobotanically, especially in the case of size change. However, South Asian small millets do not show an increase in seed size after domestication and most of them are still found wild or as weeds nowadays (Fuller 2011: Table A5). The small millets recovered from LTS and later Harappan settlements in Gujarat are no exception to this, hindering the possibility of making inferences on their domestication status *sensu stricto*. A similar case can be made for pulses, which were recovered at LTS from the macro (horsegram) and microbotanical (Faboideae starch) assemblages, suggesting exploitation since the seventh millennium BC. Tropical pulses are commonly found in Harappan settlements in Gujarat and Rajasthan, and wild stands of *Macrotyloma* sp. and *V. radiata* are still present in the region (Fuller and Harvey 2006).

The native character of these plants and their long-term presence (hundreds to thousands of years) in the archaeological records, including the occurrence of other taxa considered associated weeds, all advocate for northern Gujarat as a centre of small millet and pulses (probably horsegram) domestication. Dating the origins of small millet and horsegram exploitation and cultivation in northern Gujarat is however difficult because of the challenging archaeological deposits. The lack of clear stratigraphy and significant pre- and post-depositional taphonomic processes at LTS, as in most Anarta sites, created a scant macrobotanical assemblage.

Genetic evidence indicates that sesame was domesticated in South Asia (Bedigian 2003), but the exact centre of domestication is unknown. The seeds of domestic sesame from Anarta LTS are among the earliest recovered in South Asia (see Fuller 2003b for a review). The presence of wild sesame seeds at VHV suggests that the plant was already exploited by hunter-gatherer groups during the early-middle Holocene, and possibly became locally domesticated during the mid-Holocene. However, further evidence and a more robust chronology are needed to establish northern Gujarat as *the* centre of sesame domestication.

6.2. What do plant remains tell us about the social organisation of the inhabitants of northern Gujarat?

The scarcity of archaeobotanical remains at VHV and Mesolithic LTS hampers the possibility of making inferences about the social organisation of the hunter-gatherer groups that occupied northern Gujarat during the early-mid Holocene. On the contrary, plant remains recovered from Anarta LTS, DTR and SKP inform on aspects of the daily life of their inhabitants. In particular, it is possible to understand how agricultural production was organised in terms of labour-force at LTS and SKP through the composition of their weed assemblages. Moreover, lithic and archaeobotanical evidence from DTR suggests that craftsmanship and food acquisition were specialised activities that took place separately either at a micro (site) or a local (northern Gujarat) scale. Finally, archaeobotanical data from LTS, DTR and SKP (as well as other neighbouring Harappan settlements) advocate for the consumption of certain foodstuffs (e.g. wheat and barley) as a marker of Harappan identity in Gujarat.

6.2.1. The organisation of agricultural production

Human activities related to food production and transformation can be communal, household-based or centralised (Fuller and Stevens 2009). In northern Gujarat, small millets were probably harvested in multiple episodes as immature spikelets to avoid major seed loss (Fuller and Allaby 2009). Inflorescence structure in small millet species can sometime be loose, requiring cutting at the base of the plants that results in the incorporation of a large quantity of weeds and the need for labour-intensive crop processing (Reddy 1997).

At LTS and SKP, most weeds are similar in size to small millets, thus suggesting that the macrobotanical assemblages derive from the by-products of the final crop processing (Fuller et al. 2014b; Harvey and Fuller 2005; Jones 1987, 1992; Reddy 1997). Initial crop-processing activities –drying, threshing, sieving and first winnowing– probably took place in the fields immediately after harvesting (Kimata et al. 2000; Reddy 1997). Grains would have been stored hulled to protect them against humidity, fungi, insects and rodents (Bouby et al. 2005; Reddy 1997), as suggested by the weed assemblage and the recovery of several mineralised inflorescences. Final crop processing –de-husking, second winnowing and grinding– would have been carried out on site on a daily basis, as suggested by the abundance of millet chaff phytoliths and the microbotanical evidence from grinding stones.

The need for labour-intensive initial crop processing would have required the participation of a considerable group of people during a relatively short period, whereas final crop processing would have been carried out throughout the year to meet daily food requirements. At LTS, initial crop-processing activities were probably carried out communally, involving most of the social group (e.g. extended family). The relatively small size of the trench opened in 2009 (16 m^2) does not allow for the identification of spatial patterns, and therefore it is not possible to understand whether final crop-processing activities were carried out communally or at household level.

At SKP, on the contrary, agricultural production might have been a centralised effort controlled/organised by the settlement’s elites, as suggested by the existence of socioeconomic differences –highlighted by the faunal analysis (Chase 2014)– between the residents of the walled enclosure and their neighbours outside of the walls. All the samples analysed in this study come from the walled area, and therefore broad spatial differences cannot be assessed using the current archaeobotanical data. However, the similarity analysis performed on the grinding stones made apparent that there was no spatial specialisation in the final food-processing stages within the walled area, thus suggesting that the final stages of food processing (e.g. grinding) were carried out at household level, and not centralised in a particular area of the settlement.

6.2.2. Craft specialisation and the acquisition of food

The exploitation of lithic resources was an important aspect of prehistoric resource exploitation strategies and adaptation. Research has mostly focused on technological and spatial aspects of lithic factory sites, often overlooking how these sites were integrated within local socio-ecological dynamics in terms of food acquisition and consumption. Archaeobotanical evidence from DTR suggests that the inhabitants of this lithic blade workshop consumed mostly small millets. The scarcity of phytoliths indicates that either a) crops were processed in other areas of the site or b) they were not processed on site but acquired de-husked. De-husked millets are more prone to be affected by pests when stored for long periods of time (Bouby et al. 2005; Reddy 1997) and therefore, if this was the case, food would have been acquired in a 'ready-to-consume' form.

The first hypothesis is concomitant with a well-structured division of working space for diverse routine daily activities. The inhabitants of DTR would engage not only on specialised craftsmanship but also on food production. Monsoon-adapted small millets could have been cultivated in the large interdunal depression adjacent to the dune. It is worth highlighting that the area excavated in 2010 was chose because of its highest concentration of surface lithic material, and it is thus possible that this represents the workshop area while other daily routines were carried out elsewhere.

The second hypothesis posits a situation in which food was obtained through exchange with local millet-producing communities, an example of which could be represented by the inhabitants of LTS. This model implies a high level of interaction between the occupants of DTR and the native populations of northern Gujarat, a situation in which two communities would occupy the same ecological but different economic niches, carrying out complementary activities: food production and specialised craftsmanship.

At present we lack enough evidence to favour one hypothesis over the other. Moreover, they are not mutually exclusive: plant foodstuffs could have been acquired through on site production and also traded with local populations. In any case, it seems clear that craftsmanship and food acquisition were independent but somehow integrated activities at DTR.

6.2.3. The role of food in shaping Harappan identities

As we have seen, the lack of well-defined residential contexts (LTS, DTR and SKP), as well as the small excavated areas (LTS and DTR), hamper the possibility of understanding the spatial distribution and social significance of food-related activities. However, inferences can be made at a broader scale. In particular, the diet of the inhabitants of mid-late Holocene Gujarat informs about their food choices beyond climatic and ecological constraints. Wheat and barley were not the main staples at LTS, DTR and SKP, but their presence is a constant in these and other contemporaneous occupations in Gujarat. C_3 cereals are not adapted to northern Gujarat ecological settings (neither 4000 years ago nor at present) and their cultivation would have been possible only on exceptionally wet years or by irrigation, and it would have required an enormous investment in terms of time and labour. Most likely, wheat and barley cultivated in the Indus Valley were acquired via the extensive trade networks operating between Gujarat and the Harappan urban centres (Bahn and Ajithprasad 2008; Bhan et al. 2005; Kenoyer 1997). A possibly similar picture seems to be emerging from recent archaeobotanical research in Haryana, where a mixture of small millets, rice and barley formed the staple of the diet, with a small proportion of wheat used only occasionally (J. Bates pers. comm.).

The consumption of wheat and barley in Gujarat cannot be explained by nutritional parameters, since monsoon-adapted small millets are, in many aspects, nutritionally superior (Hulse et al. 1980; Rachie 1975). Therefore, their consumption must be related to cultural preferences as part of the area of Harappan influence. Wheat and barley would have been produced along the Indus and traded to the peripheral regions, playing a key role in defining Harappan identities in those areas unsuitable for their cultivation. As such, these crops can be considered as a prestige food (Curet and Pestle 2010; van der Veen 2003). Wheat and barley were not necessarily used to create or reinforce class identity –as hypothesised by Madella (2014) for rice– but to express membership to the Harappan sphere (cf. Twiss 2012).

A modern-day comparison with this hypothesised situation is found in traditional agro-pastoral societies of the same area. Subsistence in a traditional compound at Jandhala village (Patan district, North Gujarat) is based on the local cultivation of pearl millet (or *bajra*), which is milled for flour and consumed as roti (Indian flatbread) with cooked vegetables or curries (pers. observation). Roti made of bread wheat, purchased as flour from a nearby market, is only consumed on special occasions, such as festivities or celebrations, highlighting its exceptionality over daily millet consumption.

We can envisage a similar role of food as a structuring factor of social life during mid-late Holocene Gujarat. Locally produced small millets would have been consumed on a daily basis, whereas wheat and barley would have been acquired for the celebration of special events (i.e. feasts). Whether wheat and barley were differently consumed by elites and non-elites at Harappan settlements in Gujarat cannot be assessed under the light of the current evidence, but it is certainly a possibility worth exploring in the future.

6.3. How can a multi-proxy approach help answering these questions?

An integrated multi-proxy approach, in which several botanical proxies and a broad-spectrum sampling strategy are used together, is an extremely powerful strategy to explore diet and plant use strategies in past societies. This study has shown how effective this method can be and how the information obtained can be enhanced even in archaeological contexts with important taphonomic issues.

The scarcity of charred remains in northern Gujarat, linked to the dry-wet cycles caused by the monsoon climate of this region and the high salinity of the soils, highlights the difficulty of assessing the plant use strategy solely based on the macrobotanical evidence. The few data gathered from macroremains show that small millets appear together with common millet weeds, such as *Trianthema* spp. and *Chenopodium* sp., suggesting that small millets were being cultivated and not simply gathered.

The evidence from phytoliths and starch grains also suggests that small millets were staples for the inhabitants of northern Gujarat. Moreover, the presence of millet inflorescence silica skeletons highlights that small millet processing was taking place on site. The abundance of Type 1a starch grains (small millet) and the scarcity of inflorescence silica skeletons in grinding stones implies that these tools were used to mill clean small millet grains for flour and not for de-husking –cereals were probably de-husked with other tools, such as wooden pestles (Kimata et al. 2000; Reddy 1997). The use of millets as flour was possibly related to bread making, which might have complemented the whole grain food.

The presence of Type 1c starch grains (big millet) seems to suggest that big millets were also consumed in northern Gujarat. The presence of African millets in South Asia during the third millennium BC seems unlikely (Fuller 2003), and it is possible that Type 1c morphologies are from Job's tears, also recovered macrobotanically as charred grains (SKP) and mineralised psuedocarps (LTS). This plant is still a minor food and fodder crop in some parts of South Asia (Arora 1977), and it is very likely that it was also consumed during the mid-late Holocene.

The combined botanical evidence demonstrates that pulses also played an important role in the diet of the inhabitants of northern Gujarat. At SKP, the presence of Fabaceae leaf fragments in fire-related contexts might suggest that the wild *Vigna* grains had entered the archaeobotanical record as fuel, either directly or via animal dung (Lancelotti and Madella 2012). However, the significant presence of Faboideae starch grains on grinding stones makes clear that pulses were part of the people's diet. Similarly, at Anarta LTS pulses are very scarce in the macrobotanical assemblage (n=1), but once again their abundance as starch from grinding stones advocates for their dietary importance. Moreover, the presence in all sites of sedge nutlet phytoliths from grinding stones suggests, despite being scarce, that these nutlets may have been processed in small quantities for human consumption. Tuberous plants also appear in the archaeobotanical assemblages and they were probably consumed both whole (charred parenchyma) and ground (starch grains from grinding tools).

Finally, the evidence from DTR highlights the need for taking into account the effect of taphonomic processes when interpreting archaeobotanical assemblages, as well as the benefits of a multi-proxy approach when studying past plant exploitation strategies. In this study, the integration of charred macroremains, phytoliths and starch grains helped overcoming taphonomic biases, thus offering a broad picture of food acquisition strategies.

7. Conclusions

This chapter presents the main conclusions of this thesis and the future perspectives stemming from this research. Only broad conclusions are highlighted; conclusions relevant exclusively to a particular study are available in the research papers.

7.1. Main conclusions

The conclusions of the analysis of archaeobotanical remains from four archaeological occupations in northern Gujarat can be summarised as follows:

1. Hunter-gatherer groups inhabiting northern Gujarat during the early-mid Holocene exploited a wide range of wild plants originating from areas with (semi)permanent water bodies, including grasses, pulses, sedges, tubers and sesame. When combined with the zooarchaeological data, archaeobotanical evidence shows that these groups relied on a broad-spectrum economy.
2. The progressive weakening of the Indian Summer Monsoon ca. 7000 years ago compelled human populations to adopt semi-nomadic cattle pastoralism and plant cultivation, which resulted in the domestication of several small millet species, pulses and sesame. Agricultural production was probably carried out communally, with most of the social group (e.g. extended family) involved in the activity.
3. The evidence from DTR suggests the existence of local-scale (northern Gujarat) economic specialisation. According to this hypothesis, two communities would occupy the same ecological but different economic niches, carrying out complementary activities: food production (Anarta agro-pastoralists) and specialised craftsmanship (lithic blade workshop at DTR).
4. With the advent of urban settlements during the late Holocene some of the inhabitants of northern Gujarat developed a more intensive land-use strategy involving a cereal-pulse intercropping agricultural system. Agricultural production might have been centralised by the elites, but the final food-processing stages were carried out daily at household level.
5. The consumption of wheat and barley in northern Gujarat during the third millennium BC seems related to cultural preferences as part of the area of Harappan influence. These crops would have been produced in areas connected to the water dynamics of the Indus and traded to peripheral regions, playing a key role in defining Harappan identities in those areas unsuited for their cultivation. In northern Gujarat, locally produced small millets would be consumed on a daily basis, whereas wheat and barley would be acquired for the celebration of special events (i.e. feasts).
6. From a methodological perspective, an integrated multi-proxy approach, in which several botanical proxies and a broad-spectrum sampling strategy are

used together, is the best possible way to explore diet and plant use strategies in past societies.

7.2. Future perspectives

This last section presents questions that have been left partly unanswered and proposes ideas for expanding the research carried out as part of this thesis.

7.2.1. Reference collections

The experimental work with modern *S. italica* and *B. ramosa* showed the usefulness of GM to distinguish among archaeological small millet charred caryopses, and their potential to understand the biogeographical history of these critical crops in arid and semi-arid regions worldwide. When compared to traditional methods, the GM approach presents several advantages: a) it enables an objective, quantitative approach for the analysis of shape change; b) it can be applied when the overall morphology of the caryopsis has been deformed during the charring process; and c) it can be applied on old imagery, even when the original seeds are no longer available for analysis. Future work will include the GM analysis of other *Setaria* spp. native to South Asia and the putative wild ancestor of *S. italica*, *S. viridis*. Moreover, the analysis of more archaeological specimens from northwestern South Asia and other regions of Eurasia will allow for the understanding of the biographical history of *S. italica*, including the existence of alternative domestication centres and its time and route of dispersion.

The work carried out on reference material also highlighted the potential of phytoliths to identify small millets at genus level. Moreover, a preliminary morphometric appraisal of long cells from the internal inflorescence parts (upper lemma and upper palea) carried out as part of this thesis showed encouraging perspectives for future research. In particular, the linear morphometric parameters used by Zhang et al. (2011) to distinguish between foxtail millet and green foxtail long-cell phytoliths can be successfully applied to identify small millets at species level.

7.2.2. Plant domestication processes in northern Gujarat

The evidence from VHV, LTS and, to a lesser extent, DTR clearly suggests the existence of a local process of plant domestication in northern Gujarat. However, these are the only pre-Harappan archaeological occupations in Gujarat where a systematic sampling strategy for macro and microbotanical remains has been put in place. Moreover, radiocarbon dating has been carried out only in a few sites, and the chrono-cultural ascription of certain sites is not devoid of controversy (see Section 3.3.3). Therefore, more systematic archaeobotanical research and a more robust chronology are needed to establish the exact timing and characteristics of plant domestication processes in Gujarat.

7.2.3. The social context of food in Harappan Gujarat

The evidence for the presence of a ruling class or elite during Harappan times is not conclusive (Madella 2014). However, zooarchaeological research at Bagasra and SKP highlighted the existence of dietary differences between the inhabitants of the walled area of the settlements and their neighbours outside the walls, which led Chase (2010, 2014) to suggest the existence of social differentiation. Specifically targeted archaeobotanical research could address this issue, but so far this has not been the case. Future research should take into account spatial variation in the distribution of archaeological remains, and not only temporal shifts (e.g. Weber 1999).

In relation to the social context of food, an interesting pattern seems to be emerging from recent archaeobotanical research in so-called 'peripheral' areas of the Indus Civilisation. In order to bind the presence of wheat and barley in Gujarat (and wheat in Haryana) to sociocultural choices, we first need to understand whether these crops were locally produced or imported from the Indus Valley. Considering the relatively poor preservation of macrobotanical remains, phytoliths are the best proxy to study crop-processing activities. However, most archaeological sites were excavated during the 20th century and phytolith analyses were not envisaged when designing sampling strategies. A possible alternative approach is the application of isotope analyses on available macrobotanical remains (Fiorentino et al. 2015). In particular, the use of strontium isotopes is providing interesting insights to evaluate local versus distant land-use models (e.g. Bogaard et al. 2014; Chase et al. 2014b), which could potentially answer questions related to the trading of food along the Harappan area of influence.

7.2.4. Informing future policies on land management in semi-arid regions

Understanding how human societies adapted to environmental and climatic variability in the past is fundamental to face present and future climatic events, particularly in highly vulnerable arid and semi-arid regions (Brooks et al. 2009; Costanza et al. 2007). Archaeological research in marginal areas has revealed how humans reacted to changing ecological conditions by integrating short-term coping mechanisms and long-term adaptive strategies such as innovation, enhanced social networks, increased mobility and, ultimately, migration (e.g. An et al. 2005; Dillehay and Kolata 2004; Kuper and Kröpelin 2006; Rosen and Rivera-Collazo 2012; Spielmann et al. 2011).

Modern irrigation techniques, including water mining, were introduced in northern Gujarat 50 years ago to enhance soil productivity, resulting in water table dropping and soil deterioration. The environmental costs of modern agriculture contrast with the low environmental impact and long-term sustainability of traditional subsistence strategies in this region. In this perspective, the study of long-term subsistence strategies can inform on how past societies faced environmental degradation and uncertainty in water availability, while providing examples of sustainable land use strategies. Moreover, this long-term knowledge can then be used to inform policy-makers and successfully face future climatic events, not only in northern Gujarat but also in arid and semi-arid areas worldwide.

The study of archaeobotanical remains has broadened our understanding on plant-related subsistence strategies in northern Gujarat. However, in order to effectively inform policy-makers this evidence has to be integrated with archaeological, historical and palaeoecological data at regional level (see e.g. Marchant and Lane 2014 for East Africa). Therefore, the next stage of this research will be to integrate archaeobotanical data in a multi-disciplinary perspective to reach a wider audience beyond archaeology (and beyond academia) and to help designing sustainable land use strategies in northern Gujarat and other marginal areas.

III. Resum

1. Presentació

Aquesta tesi s'ha dut a terme en el marc del projecte NoGAP (North Gujarat Archaeological Project), un acord de col·laboració entre el grup de recerca CaSEs (Complexity and Socio-Ecological Dynamics) del Departament d'Arqueologia i Antropologia de la Institució Milà i Fontanals del Consell Superior d'Investigacions Científiques (IMF-CISC, Barcelona), i el Departament d'Arqueologia i Història Antiga de la Maharaja Sayajirao University of Baroda (MSUB, Vadodara, Índia). Les mostres arqueològiques analitzades com a part d'aquesta tesi doctoral provenen de tres excavacions desenvolupades dins el marc del projecte NoGAP (Loteswar al 2009, Datrana IV al 2010 i Vaharvo Timbo al 2011), i una excavació del Departament d'Arqueologia i Història Antiga de la MSUB (Shikarpur al 2012). El treball de laboratori es dugué a terme majoritàriament al laboratori BioGeoPal de la IMF-CSIC.

Aquesta tesi es presenta com a compendi de sis articles publicats a revistes de reconegut prestigi internacional. Alguns dels articles són metodològics i d'altres es centren en un cas d'estudi, però tots tenen una mateixa finalitat: entendre el paper dels recursos vegetals en la subsistència de les poblacions que ocuparen el Gujarat del Nord durant l'holocè. Dos d'aquests articles versen sobre la identificació de mills petits (el principal cultiu al Gujarat del nord durant la prehistòria) al registre arqueològic mitjançant l'estudi de col·leccions de referència de plantes modernes, i estan publicats a *Archaeological and Anthropological Sciences* (Madella et al. 2013) i *Vegetation History and Archaeobotany* (García-Granero et al. enviat per publicació a). Els altres quatre articles discuteixen els resultats de l'anàlisi de les restes arqueobotàniques dels quatre jaciments mencionats, i estan publicats a *Vegetation History and Archaeobotany* (García-Granero et al. 2015), *Current Anthropology* (García-Granero et al. en premsa), *Archaeological and Anthropological Sciences* (García-Granero et al. enviat per publicació b) i de nou *Vegetation History and Archaeobotany* (García-Granero et al. enviat per publicació c).

Aquesta tesi està organitzada en dues parts principals: la Introducció (Capítols 1-4) i la Discussió (Capítols 5-7). La Introducció inclou la Presentació de la tesi (Capítol 1), les Preguntes de la Recerca (Capítol 2), el Marc de la Recerca (Capítol 3) i els Materials i Mètodes emprats (Capítol 4); mentre que la Discussió inclou els Resultats Principals (Capítol 5), la Discussió d'aquests resultats (Capítol 6) i les Conclusions (Capítol 7). Els sis articles que formen part d'aquesta tesi es presenten a continuació, ja sigui en format final (articles publicats) o adaptats a l'estil de la resta de la tesi (articles encara en procés de revisió/publicació). Finalment, s'inclouen una sèrie d'apèndixs amb les dades en brut de les anàlisis arqueobotàniques.

2. Preguntes de la Recerca

L'objectiu d'aquesta tesi doctoral és respondre tres preguntes independents però altament interconnectades:

1. Quines eren les estratègies de subsistència dels habitants del Gujarat del Nord durant l'holocè?
2. Què ens diuen les restes arqueobotàniques sobre l'estructura social dels habitants del Gujarat del Nord?
3. Com pot ajudar una perspectiva *multi-proxy* a respondre aquestes preguntes?

3. Marc de la Recerca

Aquest capítol està format per quatre seccions que presenten el marc teòric, geogràfic, arqueològic i arqueobotànic d'aquesta recerca.

3.1. Marc teòric

L'estudi de les estratègies de subsistència permet entendre la relació entre allò natural i allò cultural, definit mitjançant la teoria de sistemes socioecològics (SESs, per les seves sigles en anglès). La teoria de SESs postula que el processos humans (culturals) i ecològics (naturals) no són independents sinó que estan altament interrelacionats (Adger 2000; Collins et al. 2011; Cote i Nightingale 2012; Cumming 2008; Haberl et al. 2006; Redman et al. 2004; van der Leeuw i Aschan-Leygonie 2001). Un SES és un sistema complex caracteritzat per diferents graus de resiliència, definida com la capacitat del sistema d'ajustar-se a pertorbacions (Janssen et al. 2007; Folke 2006; Widlok et al. 2012). A més a més, l'estudi dels SESs s'ha d'enfocar des d'una perspectiva multiescala, ja què les interaccions entre les societats i el medi es dóna a múltiples escales temporals i espacials (Anderies i Hegmon 2011; Barton et al. 2010). L'arqueologia ofereix una perspectiva multiescalar de llarg termini perfecta per a l'estudi de SESs (Barton et al. 2010; Redman 2005; Schoon et al. 2011). Conceptes com ara resiliència, robustesa, sostenibilitat o vulnerabilitat han estat recurrentment utilitzats en la literatura arqueològica de les darreres dues dècades. La recerca arqueològica inspirada en la teoria de SESs s'ha enfocat principalment en l'estudi de estratègies sostenibles d'explotació dels recursos (p.e. Barton et al. 2010; Campbell i Butler 2010; Ellis i Wang 1997; Glaser 2007; Marchant i Lane 2014; Smith 2009; Spielmann et al. 2011) i les respostes de les societats humanes a la variabilitat climàtica (p.e. Anderies i Hegmon 2011; Costanza et al. 2007; Dillehay i Kolata 2004).

El major canvi que han patit les estratègies de subsistència durant la història de la humanitat és la transició de societats caçadores-recol·lectores-pescadores a societats agrícoles-ramaderes. Els processos d'emergència de producció d'aliments han estat intensament estudiats durant els darrers 100 anys, però l'aplicació de noves tècniques (com ara la genètica) i noves perspectives teòriques està causant un canvi en la forma d'entendre aquests processos. D'entre els nous paradigmes, els més rellevants són: a) la relació entre l'adopció de plantes domèstiques i la complexitat social no és linear sinó complexa (Fuller et al. 2012a; Layton et al. 1991; Smith 2001); b) la transició a la producció d'aliments és un procés coevolutiu entre plantes i humans (Diamond 2002; Jackson 1996; Purugganan i Fuller 2009); c) les plantes foren domesticades de forma independent a diversos centres arreu del món, i paral·lelament a diverses localitats en cadascun d'aquests centres (Brown et al. 2008; Fuller et al. 2011, 2012a); d) els processos de domesticació foren el resultat d'una sèrie de pressions selectives inconscients (Diamond 2002; Fuller i Allaby 2009; Fuller et al. 2012b, 2014a; Purugganan i Fuller 2011); e) aquests processos es van allargar durant al menys 1000-2000 anys (Fuller i Allaby 2009); f) no existeix una dicotomia entre societats caçadores-recol·lectores-pescadores i societats agrícoles-ramaderes, hi ha una complexa frontera entre l'adquisició intensiva d'aliments i la producció a baixa escala (Smith 2001); i g) malgrat la importància dels canvis mediambientals per entendre els processos d'emergència de producció d'aliments a nivell regional (p.e. Bar-Yosef 2011), estudiar els canvis socials associats és fonamental per entendre aquests processos a nivell local.

L'estudi de les estratègies de subsistència és en certa manera l'estudi dels processos d'adquisició (producció i distribució) i transformació (preparació, consum i disposició) d'aliments (Goody 1982: 37). L'arqueobotànica estudia aquests processos i té el potencial d'identificar la seva importància a nivell social (Palmer i van der Veen 2002). Les implicacions socials de l'organització de treball durant l'adquisició d'aliments han estat àmpliament estudiades (p.e. Fuller i Stevens 2009; Fuller et al. 2014b), però el rerefons dels processos de transformació d'aliments ha rebut molta menys atenció, principalment degut a la dificultat d'identificar-los arqueològicament (Twiss 2012).

3.2. Marc geogràfic

El Gujarat, al nord-oest de l'Índia, està format per l'illa de Kachchh, la península de Surastra i la zona continental, que està dividida en dues zones (Gujarat del Nord i Gujarat del Sud) pel riu Mahi. El Gujarat del Nord és un ecotò semiàrid (400-600 mm de precipitació anual) situat entre el desert del Thar i la zona subhumida del Gujarat del Sud. Les precipitacions varien considerablement intra i interanualment, afectant la disponibilitat de recursos i, conseqüentment, les poblacions que depenen d'ells. La majoria de les precipitacions es concentren durant el monsó (entre juny i setembre), i les sequeres perllongades són un fenomen comú. El recés del desert del Thar fa uns 7000 anys va provocar que al Gujarat del Nord quedés un paisatge "fossilitzat" caracteritzat per dunes estabilitzades i zones interdunals on s'acumula la pluja del monsó durant gran part de l'any, oferint aigua per al desenvolupament d'activitats agrícoles i ramaderes.

Tradicionalment, l'agricultura al Gujarat del Nord es desenvolupa durant la campanya d'estiu (*kharif*) aprofitant les pluges del monsó (Reddy 1997). La introducció de tècniques modernes d'irrigació als anys 1960 ha permès cultivar durant la campanya d'hivern (*rabi*), però alhora ha causat una forta degradació mediambiental i una sobreexplotació dels recursos hídrics (Gupta i Deshpande 2004; Kavalanekar et al. 1992; Pearce 2004). Els costos mediambientals de l'agricultura moderna contrasten amb el baix impacte ecològic de les estratègies de subsistència tradicionals que perviuen avui en dia, tant pel que fa a l'agricultura (Singh 2010) com pel que fa a la ramaderia (Salpeteur et al. en premsa).

No hi ha un registre peleoecològic exhaustiu de l'àrea d'estudi, però l ainvestigació en curs dins el projecte NoGAP suggereix que les zones interdunals estaven permanentment inundades fins fa 7000 anys (dades no publicades). Aquestes dades coincideixen amb models paleoclimàtics, que estableixen un afebliment del monsó després d'una fase humida entre 10,000 i 7000 anys abans del present (Gasse et al. 1996; Gupta et al. 2006; Hu et al. 2008; Liu et al. 2003; Overpeck et al. 1996; Wei i Gasse 1999).

3.3. Marc arqueològic

El registre arqueològic del Gujarat del Nord està intrínsecament lligat a la vall de l'Indus. Les primeres evidències d'activitat agrícola-ramadera en aquesta regió provenen del jaciment de Mehrgarh (Baluchistan, actual Pakistan), on plantes i animals domesticats al Proper Orient, així com d'altres domesticats localment, apareixen al registre arqueològic a finals del vuitè mil·lenni aC (Costantini 2008; Fuller 2006a). Aquestes plantes i animals, provinent principalment del sud-oest asiàtic, conformarien la base de la subsistència del grans centres urbans que sorgiren a la vall de l'Indus entre el 3300 i el 1300 aC (Kenoyer 1991; Possehl 2002; Wright 2010). L'esplendor de la Civilització de l'Indus es donà durant la seva fase urbana (Urban Harappan, 2600-1900 aC), en la qual apareixen trets característics com ara l'ús de l'escriptura, el desenvolupament d'arquitectura monumental, l'establiment de xarxes comercials de llarga distància, etc. (Kenoyer 1991: 334; Possehl 1990: 268; Sonawane 2002: 159).

Al Gujarat s'han trobat més de 500 jaciments arqueològics amb els trets diferencials de la Civilització de l'Indus, principalment de la fase urbana (Chase et al. 2014a; Possehl 1992). L'excavació d'alguns d'aquests jaciments demostra que estaven principalment destinats a la manufactura de bens de consum de diversos materials (com ara coure, ivori, pedres semiprecioses, etc.) que després comerciaven amb els grans centres urbans de la vall de l'Indus (Sonawane 2002).

Durant l'holocè inicial i mitjà el Gujarat del Nord va ésser ocupat per grups de caçadors-recol·lectors (CR) i agricultors-ramaders (AR). Les ocupacions de CR es caracteritzen per la presència d'indústria microlítica i l'absència de ceràmica. El començament de l'ocupació de CR durant l'holocè està datat a principis del vuitè mil·lenni aC a Datrana IV (dades no publicades, comunicació personal de P. Ajithprasad). D'altra banda, el final de l'ocupació de CR al Gujarat del Nord és un punt de controvèrsia: mentre que alguns autors defenen que continuà fins a finals del tercer mil·lenni aC (Misra 1973; Sonawane 2000), d'altres qüestionen la integritat estratigràfica dels jaciments d'on provenen aquestes datacions (Patel 2009).

Les ocupacions d'AR, caracteritzades per la presència de ceràmica, apareixen al Gujarat del Nord al quart mil·lenni aC. La majoria de jaciments AR contenen ceràmica de tradició Anarta, però a Datrana IV es troba ceràmica Pre-Prabhas (Ajithprasad 2002, 2011). La importància de les activitats ramaderes per a aquestes poblacions sembla clara (Ajithprasad i Sonawane 2011; Patel 2009), però fins ara el paper dels recursos vegetals no havia estat avaluat (Sonawane 2000: 143).

3.4. Marc arqueobotànic

A l'hora d'estudiar les estratègies de subsistència al passat, les restes arqueobotàniques més comunament analitzades són les granes, els fitòlits i els midons. Malgrat que les restes macro (granes) i microbotàniques (fitòlits i midons) es poden recollir dels mateixos contextos arqueològics, els estudis arqueobotànics no acostumen a integrar les dades d'aquestes dues línies d'evidència. L'anàlisi integrada de granes, fitòlits i midons presenta diversos avantatges: més plantes hi estan representades anatòmica i taxonòmicament i es poden entendre millor els processos tafonòmics, tant deposicionals com postdeposicionals.

Els estudis previs d'estratègies de subsistència al Gujarat s'han centrat principalment en l'estudi de restes macrobotànics de jaciments de la Civilització de l'Indus. La recerca arqueobotànica duta a terme a jaciments de Saurashtra (com ara Rodji, Oriyo Timbo i Babar Kot – Reddy 1997; Weber 1999) va permetre identificar l'existència d'un sistema de cultiu diferent a l'establert a la vall de l'Indus durant la Civilització de l'Indus. A l'Indus predominen els cultius provinents del sud-oest asiàtic (com ara el blat, l'ordi o els pèsols), mentre que al Gujarat predominen cultius locals (com ara els mills petits i les lleguminoses tropicals) (Fuller i Madella 2002).

4. Materials i Mètodes

Aquest capítol presenta els materials analitzats en aquesta tesi i els mètodes emprats per al seu estudi.

4.1. Col·leccions de referència

En primer lloc, es desenvoluparen col·leccions de referència de plantes modernes basades en recerca etnobotànica i arqueobotànica prèvia al Gujarat i altres parts d'Àsia del Sud (Arora 1977; Fuller 2001, 2002, 2003a, 2005, 2006a, 2006b, 2011; Fuller i Boivin 2009; Fuller i Madella 2002; Fuller et al. 2001, 2004; Gupta i Sharma 1971; Kashyap i Weber 2010; Kimata et al. 2000; Lancelotti 2010; Parmar et al. 2012; Patel et al. 2013; Pokharia et al. 2011, 2014; Reddy 1997; Singh 2010; Tengberg 1999; Weber 1998, 1999; Webber i Fuller 2008; Webber i Kashyap 2013; Weber et al. 2011). Les col·leccions de referència s'estudiaren de dues maneres: a) mitjançant l'ús de la morfometria geomètrica per identificar les diferències entre les granes carbonitzades de *Setaria italica* (L.) P.Beauv. i *Brachiaria ramosa* (L.) Stapf., i b) mitjançant una anàlisi morfològica i morfomètrica de les restes microbotàniques de diverses espècies de plantes.

4.2. Contextos arqueològics

Els materials analitzats en aquest estudi provenen de quatre excavacions arqueològiques dutes a terme entre el 2009 i el 2012 al Gujarat del Nord: Vaharvo Timbo, Loteshwar, Datrana IV i Shikarpur. Les mostres arqueobotàniques es recolliren sistemàticament durant les quatre excavacions, incloent la flotació de sediments per a l'anàlisi de restes macrobotàniques (1.470 litres de sediment), el mostreig de sediments per a l'anàlisi de restes microbotàniques (47 mostres) i el pH del sòl (25 mostres), i la recollida d'eines de mòlta per al mostreig i anàlisi de restes microbotàniques (67 eines de mòlta per a un total de 80 mostres).

Vaharvo Timbo (23º 33' 17.05"; 71º 48' 12.01") forma part d'un complex de cinc dunes on es documenta ocupació de CR al voltant d'una gran zona interdunal (Balbo et al. 2013: Fig. 7c). Els membres del projecte NoGAP hi excavaren dues trinxeres l'any 2011. Els materials analitzats en aquesta tesi provenen exclusivament de la trinxera I, on l'ocupació de CR ha estat datada aproximadament entre el 5600-5000 aC.

Loteshwar (23º 36′ 1.8″ N; 71º 50′ 11.8″ E) fou excavat en primera instància pel Departament d'Arqueologia i Història Antiga de la MSUB a principis dels anys 1990 (IAR 1995a). En base a les restes faunístiques, es diferencià una primera ocupació de CR (7168-4703 aC) i una ocupació posterior d'AR (Anarta, 3681-2243 aC), que basaven la seva subsistència en l'explotació del zebú (Patel 2009). A la trinxera excavada pels membres del projecte NoGAP l'any 2009 també es documentà un nivell de CR i un altre d'AR, amb una capa de materials barrejats entre ells.

Datrana IV (23º 46' 41.7" N, 71º 07' 26.2" E) també fou excavat pel Departament d'Arqueologia i Història Antiga de la MSUB a principis dels anys 1990 (IAR 2000a, 2000b). En aquest jaciment també s'identificaren ocupacions de CR i AR (Pre-Prabhas), però la trinxera excavada pel NoGAP l'any 2010 només revelà l'ocupació d'AR, datada aproximadament entre el 3300-3000 aC.

El Departament d'Arqueologia i Història Antiga de la MSUB va excavar Shikarpur (N 23º 14' 15", E 70º 40' 39") entre els anys 2007 i 2013 (Bhan i Ajithprasad 2008). Aquest jaciment urbà, envoltat per una muralla de 130 x 110 m, va estar ocupat principalment durant la fase Urban Harppan (2600-1900 aC). Les mostres analitzades en aquest estudi foren recollides durant la campanya de l'any 2012, en la qual s'excavaren nivells pertanyents a la Fase II (2200-1900 aC).

4.3. Procediments de laboratori

Les mostres provinents de la flotació foren garbellades i separades en les fraccions de 2 mm, 1 mm, 0.5 mm i 0.25 mm. Les restes faunístiques (ossos i conquilles) i vegetals (carbons i granes) majors de 0.5 mm foren triades i recollides amb un estereoscopi Leica EZ4 D.

El mostreig de restes microbotàniques d'eines de mòlta es dugué a terme seguint el protocol de raspallat en sec i humit proposat per Chandler-Ezell i Pearsall (2003). Els residus resultants es processaren al laboratori BioGeoPal per a extreure fitòlits i midons conjuntament combinant els protocols proposats per Horrocks (2005) i Madella et al. (1998).

Els consumibles de laboratori (com ara els guants) poden contenir grans de midó que podrien contaminar les mostres arqueològiques (Crowther et al. 2014). Per aquesta raó, un total de 12 mostres de consumibles utilitzats durant el mostreig i processament de les mostres arqueològiques s'analitzaren per identificar la presència de possibles contaminants.

4.4. Anàlisis

Les restes macrobotàniques s'identificaren comparant-les amb la col·lecció de referència del laboratori BioGeoPal i amb literatura publicada (Cappers i Bekker 2013; Cappers et al. 2009; Neef et al. 2012). A més a més, el mètode de morfometria geomètrica aplicat a llavors modernes de *S. italica* i *B. ramosa* (veure Secció 4.1) s'utilitzà per identificar granes de mills petits de Shikarpur.

Les restes microbotàniques s'analitzaren a 200x i 630x magnificacions amb un microscopi Leica DM 2500 equipat amb llum polaritzada i una càmera Leica DF 470 per microfotografia. La concentració de fitòlits es calculà en base al pes de la fracció indissoluble en àcid (AIF, per les seves sigles en anglès) seguint la fórmula proposada per Albert i Weiner (2001), mentre que la concentració de midons es calculà en base al pes inicial de la mostra. Els resultats de les anàlisis microbotàniques foren explorats amb estadística multivariant utilitzant el software R (R Development Core Team 2014).

Les mostres de control de laboratori també s'analitzaren a 200x i 630x magnificacions amb el microscopi Leica DM 2500. Finalment, el pH del sòl fou analitzat a mostres de Vaharvo Timbo, Loteshwar i Datrana IV amb un instrument Combo pH & EC HI98129 by HANNA® per entendre si l'alcalinitat o acidesa del sòl havia afectat la integritat del registre arqueobotànic.

5. Resultats Principals

Aquest capítol presenta els resultats principals d'interès general. Els resultats que incumbeixen exclusivament un dels estudis es poden trobar als articles.

5.1. Col·leccions de referència

L'anàlisi de granes de *S. italica* i *B. ramosa* mitjançant la morfometria geomètrica demostrà que aquestes dues espècies poden ser clarament diferenciades utilitzant aquest mètode. D'altra banda, l'anàlisi dels fitòlits de mills petits il·lustrà el seu potencial per distingir aquestes plantes a nivell de gènere i diferenciar-ne distintes parts de les plantes. A més a més, l'anàlisi de midons de diverses espècies posà de manifest la seva utilitat per distingir entre diferents subfamílies de plantes.

5.2. Mostres de control del laboratori

De les 12 mostres de laboratori analitzades, només una (provinent d'una marca de guants de làtex) contenia un nombre significant de grans de midó. Donat que aquests guants havien estat utilitzats per processar les mostres de Vaharvo Timbo, no es pot descartar que els midons trobats a aquestes mostres hagin estat transferits des dels guants. Conseqüentment, els resultats de l'anàlisi de midons d'aquest jaciment es consideren invàlids i han estat exclosos de la secció posterior.

5.3. Mostres arqueològiques

A Vaharvo Timbo es trobaren poques granes, incloent sèsam silvestre i vàries espècies de poàcies silvestres. El regsitre fitolític és relativament pobre, tant a les mostres de sediment com a les eines de mòlta, però es documenta la presència de gramínies, ciperàcies i palmes. El pH del sòl és lleugerament alcalí a tota la seqüència estratigràfica.

A Loteshwar la majoria de les granes es trobaren als nivells Anarta, incloent sèsam domèstic, vàries espècies de mills petits, una llavor d'una lleguminosa tropical, alguns fragments de blat/ordi, ciperàcies i males herbes relacionades amb el cultiu del mill. Els fitòlits, abundants tant a les mostres de sediment com a les eines de mòlta, provenen principalment de poàcies panicoides (subfamília que inclou els mills petits). Els midons, escassos a les mostres de sediment però abundants a les eines de mòlta, provenen principalment de poàcies panicoides i, a les mostres Anarta, també de lleguminoses. El pH del sòl és lleugerament alcalí a tota la seqüència estratigràfica.

A Datrana IV es trobaren poques granes, incloent una poàcia silvestre, ciperàcies, raquis d'ordi i males herbes. Els fitòlits eren virtualment absents, tant a les mostres de sediment com a les eines de mòlta. Els midons, escassos a les mostres de sediment però abundants a algunes eines de mòlta, provenen principalment de poàcies panicoides. El pH del sòl és lleugerament alcalí a tota la seqüència estratigràfica.

A Shikarpur es trobaren abundants granes, incloent mills petits (principalment *B. ramosa*, segons l'anàlisi amb morfometria geomètrica), llegums tropicals, alguns fragments de blat/ordi, raquis d'ordi i arròs, ciperàcies i males herbes relacionades amb el cultiu del mill. Els fitòlits, abundants tant a les mostres de sediment com a les eines de mòlta, provenen principalment de poàcies panicoides. Els midons, escassos a les mostres de sediment però abundants a les eines de mòlta, provenen principalment de poàcies panicoides i lleguminoses.

6. Discussió

Aquest capítol presenta la discussió dels resultats principals. La discussió detallada dels resultats de cadascun dels estudis es pot trobar als articles.

6.1. Quines eren les estratègies de subsistència dels habitants del Gujarat del Nord durant l'holocè?

Dades preliminars de zones interdunals properes a Loteshwar i Vaharvo Timbo suggereixen que fins fa 7000 anys algunes zones interdunals retenien aigua durant tot l'any, creant zones pantanoses idònies per a les poblacions de CR. El registre arqueobotànic de Vaharvo Timbo és relativament pobre, però es documenta la presència de diverses plantes silvestres, incloent sèsam, poàcies, ciperàcies i palmes. Les restes arqueobotàniques de l'ocupació de CR de Loteshwar també indica l'explotació de poàcies i, en certa mesura, lleguminoses.

El canvi del règim monsònic fa uns 7000 anys forçà les poblacions humanes a adoptar la ramaderia seminòmada del zebú i el cultiu de plantes. El registre arqueobotànic de les ocupacions d'AR de Loteshwar i Datrana IV indica que el cultiu bàsic durant l'holocè mitjà eren els mills petits, amb una menor aportació del sèsam i les lleguminoses. A més a més, aquestes poblacions també consumien blat i ordi, probablement adquirit mitjançant el comerç amb poblacions de la vall de l'Indus.

Amb l'adveniment de la vida urbana sedentària a l'holocè tardà, les poblacions humanes s'especialitzaren en el cultiu intercalat de mills petits (principalment *B. ramosa*) i lleguminoses (*Vigna* sp.). El blat i l'ordi també es consumien però, com passava durant l'holocè mig, probablement no es produïen localment sinó que s'adquirien des de la vall de l'Indus.

6.2. Què ens diuen les restes arqueobotàniques sobre l'estructura social dels habitants del Gujarat del Nord?

L'escassetat de restes arqueobotàniques a les ocupacions de CR no ens permet fer inferències sobre la seva organització social. D'altra banda, el registre arqueobotànic de les ocupacions d'AR ens informa de aspectes de la vida diària dels seus ocupants més enllà de la seva dieta. Les activitats relacionades a la producció i transformació d'aliments es poden fer de forma comunal, a nivell familiar o de forma centralitzada (Fuller i Stevens 2009). L'evidència de Loteshwar i Datrana IV suggereix que la producció agrícola durant l'holocè mig es duia a terme probablement de forma comunal, mentre que l'evidència de Shikarpur indica la possible existència d'una producció centralitzada per les elits, malgrat que la transformació final d'aliments es feia a nivell familiar.

6.3. Com pot ajudar una perspectiva *multi-proxy* a respondre aquestes preguntes?

Aquest estudi ha demostrat l'efectivitat d'una perspectiva *multi-proxy* a l'hora d'estudiar estratègies de subsistència en el passat. El cas més il·lustratiu és el de les lleguminoses que, malgrat ser escasses al registre macrobotànic, estaven ben representades al registre microbotànic (midons) d'eines de mòlta, assenyalant la seva importància en la dieta de les poblacions humanes. A més a més, l'anàlisi *multi-proxy* ha permès identificar que el blat i l'ordi eren consumits però no produïts localment, així com la presència d'algunes plantes no preservades al registre macrobotànic, com ara les palmes.

7. Conclusions

Aquest capítol presenta exclusivament les conclusions generals i les perspectives futures d'aquesta recerca. Les conclusions que incumbeixen exclusivament un dels estudis es poden trobar als articles.

7.1. Conclusions principals

Les conclusions de l'anàlisi de restes arqueobotàniques de quatre jaciments arqueològics al Gujarat del Nord es poden resumir de la següent manera:

1. Els grups de caçadors-recol·lectors que habitaren el Gujarat del Nord durant l'holocè inicial-mitjà explotaren una gran varietat de plantes silvestres que creixien a zones pantanoses, incloent gramínies, lleguminoses, ciperàcies, tubercles i sèsam. Combinada amb dades zooarqueològiques, l'evidència arqueobotànica demostra que aquests grups tenien una economia d'ampli espectre.
2. L'afebliment progressiu del monsó fa uns 7000 anys forçà les poblacions humanes a adoptar la ramaderia seminòmada i el cultiu de plantes, que donà com a resultat la domesticació de diverses espècies de mills petits, lleguminoses i sèsam. La producció agrícola es duia a terme probablement de forma comunal, involucrant la majoria del grup d'agricultors-ramaders.
3. L'evidència de Datrana IV suggereix l'existència d'especialització econòmica a escala local (Gujarat del Nord). Segons aquesta hipòtesi, dues comunitats

ocuparien el mateix nínxol ecològic però diferents nínxols econòmics, duent a terme activitats complementàries: la producció d'aliments (poblacions agrícoles-ramaderes Anarta) i l'artesania especialitzada (talla lítica a Datrana IV).

4. Amb l'adveniment de les societats urbanes a l'holocè final, els habitants del Gujarat del Nord intensificaren l'ús del sòl mitjançant un sistema de cultiu intercalat de cereals i lleguminoses. És possible que la producció agrícola estigués centralitzada per part de les elits, però les etapes finals del processat d'aliments es duia a terme diàriament a nivell domèstic.
5. El consum de blat i ordi al Gujarat del Nord durant el tercer mil·lenni aC sembla lligat a preferències culturals com a part de l'àrea d'influència Harappa. Aquests cultius haurien estat distribuïts des d'àrees irrigades de la vall de l'Indus, jugant un paper clau en la definició d'una "identitat Harappa". Al Gujarat del Nord, els mills petits produïts localment es consumirien diàriament, mentre que el blat i l'ordi s'adquiririen per a celebrar esdeveniments especials.
6. Des d'un punt de vista metodològic, una aproximació *multi-proxy*, on s'integren l'anàlisi de diverses restes botàniques i una estratègia de mostreig d'ampli espectre, és la millor manera d'estudiar la dieta i les estratègies de subsistència de societats del passat.

7.2. Perspectives futures

Aquesta darrera secció examina aquelles qüestions que han quedat parcialment sense resposta i, alhora, proposa idees per expandir la recerca duta a terme com a part d'aquesta tesi doctoral.

En primer lloc, l'estudi de la col·lecció de referència de plantes es pot expandir en dues direccions: a) estudiant la història biogeogràfica de *S. italica* mitjançant l'aplicació de morfometria geomètrica a un major nombre d'espècies de mills petits i l'anàlisi de més restes arqueològiques tant d'Àsia del Sud com d'altres àrees d'Euràsia, i b) identificant trets diagnòstics a nivell d'espècie als mills petits mitjançant l'aplicació de morfometria lineal a fitòlits de les parts internes de la inflorescència utilitzant els paràmetres desenvolupats per Zhang et al. (2011). En segon lloc, malgrat l'evidència provinent de Vaharvo Timbo, Loteshwar i Datrana IV, més recerca arqueobotànica sistemàtica i un millor marc cronològic són necessaris per mirar d'entendre els processos de domesticació de les plantes al Gujarat del Nord. En tercer lloc, la recerca arqueobotànica pot ajudar a respondre preguntes relacionades amb l'organització social de les poblacions Harappa al Gujarat, com ara l'existència d'elits i el paper del menjar en la definició d'una "identitat Harappa". Finalment, el següent pas d'aquesta recerca serà integrar les dades arqueobotàniques amb dades arqueològiques, històriques i paleoecològiques a nivell regional per ajudar a desenvolupar estratègies sostenibles d'ús del sòl al Gujarat del Nord i altres àrees àrides i semiàrides arreu del món.

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V. Research Papers

Madella M, Lancelotti C, García-Granero JJ (2013) Millet microremains – an alternative approach to understand cultivation and use of critical crops in Prehistory. Archaeol Anthropol Sci. doi: 10.1007/s12520-013-0130-y

Archaeol Anthropol Sci
DOI 10.1007/s12520-013-0130-y

ORIGINAL PAPER

Millet microremains—an alternative approach to understand cultivation and use of critical crops in Prehistory

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Received: 11 December 2012 / Accepted: 5 February 2013

Abstract The term "millets" is used to identify several genera of grasses (Poaceae), most of which belong to the subfamily Panicoideae. Millets are one of the major food sources in arid and semi-arid areas of the world and they have been important crops in the prehistory of Africa and Eurasia. In this paper, we discuss phytoliths and starch grains from two of the less studied major millets (*Pennisetum glaucum* and *Sorghum bicolor*) as well as from some small millet species that are not normally considered of much importance (so-called forgotten millets: *Digitaria ciliaris*, *Echinochloa colona*, *Echinochloa frumentacea*, *Brachiaria ramosa*, *Setaria pumila* and *Setaria verticillata*). The preliminary results of this study on phytolith morphology, both at single and joined (silica skeletons) morphotypes, and starch grains show great potentials for the identification of different genus or species on the basis of microremains.

Keywords Millets · Small millets · Phytoliths · Starch grains · Plant microfossils · Morphology

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Introduction

Millets are one of the major food sources in arid and semi-arid areas of the world. The term "millets" is used to identify several genera of grasses (Poaceae), most of which belong to the subfamily Panicoideae, with the notable exception of finger millet (*Eleusine coracana* (L.) Gaertn.) and teff (*Eragrostis tef* (Zucc.) Trotter), which belong to the Chloridoideae. The most commonly cultivated species are broomcorn millet (*Panicum miliaceum* L.), foxtail millet (*Setaria italica* (L.) P. Beauv.), pearl millet (*Pennisetum glaucum* (L.) R. Br.), finger millet and sorghum (*Sorghum bicolor* (L.) Moench.). Broomcorn and foxtail millet are relatively common in the archaeobotanical record of Asia and Europe and have received much attention over the past years (Austin 2006; Crawford 2009; Fujita et al. 1996; Hu et al. 2008; Hunt et al. 2008; Jacob et al. 2008a, 2008b; Li et al. 1995; Lu 2002; Lu et al. 2009a, b; Marinval 1992; Motuzaite-Matuzeviciute et al. 2012; Nasu et al. 2007; Nesbitt and Summers 1988; Song et al. 2012; Yang et al. 2012a, b; Zhang et al. 2010, 2011; Zhao 2011; Zohary and Hopf 2000). On the contrary, pearl millet and sorghum are less studied, albeit a few recent publications are dealing specifically with these species (D'Andrea et al. 2001; Jain and Bal 1997; Lux et al. 2002; Out and Madella 2013; Spangler et al. 1999; Tripathi et al. 2012a, b; Weber 1998).

Apart from these, there are a few so-called minor millets; the most well-known of which normally include: Indian barnyard millet (*Echinochloa frumentacea* Link.), Japanese barnyard millet (*Echinochloa esculenta* (A. Braun) H. Scholz), kodo millet (*Paspalum scrobiculatum* L.), little millet (*Panicum sumatrense* Roth ex Roem. & Schult.), Guinea millet (*Brachiaria deflexa* (Schumach.) H. Scholz), browntop millet (*Brachiaria ramosa* (L.) Stapf.) and fonio millet (*Digitaria exilis* Stapf.). A few more species, notably teff and Job's tears (*Coix lacrima-jobi* L.), are sometimes considered part of the millets group. All these species are widely used across Africa, Asia and Europe as food and fodder or as secondary crop products.

Archaeologically, millet macro-remains (charred seeds) present two main problems for their recovery and identification: one depositional and one post-depositional. Carbonisation is necessary for the preservation of the grains. Even when carbonisation takes place, it needs to be within a set of temperature and oxidation conditions for the grains to be preserved; indeed, millet charring conditions are more restrictive when compared with other cereals (Märkle and Rösch 2008; Yang et al. 2011). Secondly, the millet small grain size makes the recovery difficult, even when a systematic flotation strategy is set in place. Adding to these preservation and recovery drawbacks, charred millet grains of some species are difficult to set apart, for instance domestic *S. italica* and the weed *B. ramosa* (Fuller 2006). Therefore, the archaeobotanical record is currently very scarce (for Africa, see for example, van der Veen 1999 and references therein; for Asia in general, see Weber and Fuller 2008 and references therein and Fuller 2006, 2007, 2011; Fuller et al. 2007).

Plant microremains or plant microfossils are an array of microscopic plant remnants such as phytoliths, starch grains, pollen grains, fibres, druses and other crystalline deposits. In this paper, when we discuss microremains we intend specifically and only phytoliths and starch grains because these are the fossils that offer more solid bases for investigating dietary and economic significance of plants. This is especially true for those taxa where preservation (e.g. preservation of diagnostic parts, processing procedures, soft tissues, etc.) or recovery (e.g. seeds of small dimensions) might be an issue. The dietary and economic implications of phytoliths and starch grains are made possible by:

1. The vast amount of information from modern reference collections, which offer the possibility of identifying plant taxa as well as the plant different organs (for phytoliths, see Madella 2007 and Out and Madella 2013; for starch, see for example Ge et al. 2010 and Yang et al. 2012b);
2. The high preservation rate in a varied range of archaeological deposits (Madella and Lancelotti 2012; Torrence 2006, Table 1);
3. The possibility of identifying both crop processing and cooking procedures (e.g. Crowther 2012; Harvey and Fuller 2005; Henry et al. 2009);
4. The direct dietary evidence from human dental calculus (Fox et al. 1994, 1996; Hardy et al. 2009, 2012; Henry 2012; Henry and Piperno 2008; Henry et al. 2011; Piperno and Dillehay 2008) or indirect evidence from tools (e.g. Aranguren et al. 2007; García-Granero 2011; Kashyap and Weber 2010; Nadel et al. 2012; Radomski and Neumann 2011).

Size, shape and other features of starch granules can be diagnostic of the plant species in which they occur (ICSN 2011; Reichart 1913; Torrence 2006). Two main forms of starch are produced: transitory and storage starch. Transitory starch originates in leaves and it has very diminutive size (<5 μm) with little or none taxonomical information. For this reason, this type of starch has not received much attention in archaeology (Haslam 2004). Storage starch is deposited in plant storage organs, which are often consumed by humans (e.g. roots, tubers, fruits and seeds), and therefore it is valuable for studying the vegetal component of the diet (Torrence 2006). Phytoliths can have high taxonomic significance and are formed in the epidermal tissues of many plants of economic importance. Phytoliths and starch grains have been widely used to distinguish among different species of major cereals such as wheat, barley, rice or maize (Babot and Apella 2003; Ball et al. 1999, 2009; Dickau et al. 2007; Gu et al. 2013; Pearsall et al. 2004; Piperno 1984; Piperno and Pearsall 1993; Zarrillo et al. 2008). The analysis of phytolith assemblages has been shown to be useful to understand the consumption of both wild and domestic cereals, and has often been applied to the study of plant domestication processes (Albert and Henry 2004; Ranere et al. 2009; Rosen and Weiner 1994). However, it is only during the last few years that scholars have explored the possibilities offered by the analysis of millets microbotanical proxies. In millets, species of *Setaria* and *Panicum* have received much attention due to their major economic role in the prehistory of Eurasia. The recent study of reference material offered the possibility of identifying the differences existing between husk (glume, lemma and palea) phytoliths of *S. italica* and *P. miliaceum* (Lu et al 2005, 2009a, 2009b), and of *S. italica* and *Setaria viridis* (Zhang et al. 2011). Radomski and Neumann (2011) also investigated inflorescence phytoliths from West African grasses, including *Pennisetum*, *Sorghum* and *Digitaria* species. Finally, Tripathi et al. (2012a, b) studied the differences in phytoliths of sorghum and Johnson grass (*Sorghum halepense* (L.) Pers.) and the variability within pearl millet.

Krishna Kumari and Thayumanavan (1998), Mercader (2009) and Ge et al. (2010) carried out the first morphological analyses of starch grains of millets, while further studies come from Yang et al. (2012b). This morphometric analysis of starch grains from seven species from the genus *Setaria* and two species from the genus *Panicum* concluded that morphological features, rather than size, are the clue to identify and distinguish starch grains within these genera (Yang et al. 2012b).

Table 1 Millet species analysed in the current study and origin of the grain samples

Species	Vernacular name	Origin
Small millets		
Digitaria ciliaris (Retz.) Koeler	Southern crabgrass	USA
Echinochloa colona (L.) Link	Jungle rice	India
Echinochloa frumentacea Link	Billion-dollar grass	India
Brachiaria ramosa (L.) T.Q.Nguyen	Browntop millet	India
Setaria pumila (Poir.) Roem. & Schult.	Yellow foxtail millet	Afghanistan
Setaria verticillata (L.) P.Beauv.	Bristley foxtail millet	Turkey
Big millets		
Sorghum bicolor (L.) Moench ssp. *bicolor*	Grain sorghum	India
Pennisetum glaucum (L.) R.Br.	Pearl millet	India

Despite these important achievements over the past decade, the study of microbotanical remains of millets requires far more attention. Where phytoliths are concerned, only husk phytoliths have been considered so far and the analysis of phytoliths from other parts of the plants, such as the leaves and the culm, is essential for the understanding of past economic practices (e.g. Out and Madella 2013). Moreover, many millet species remain poorly investigated. Genera such as *Echinochloa* or *Digitaria* have received little or no attention despite their main role in regional economies. The study of these and other millet species can provide important clues about the use past use of small cereals, as well as their possible applications for future sustainable agriculture.

This study aims at exploring the potentials of taxonomic and anatomical variability at intra- and inter-specific level and to set the basis for morphometric analyses. We propose a preliminary approach on a first-level, systematic method to draw attention to a set of characteristics, in both inflorescence phytoliths and starch, which can be used to identify microremains from millets. We focus on the less studied of the major millets (*P. glaucum* and *S. bicolor*) as well as on some species that are not normally considered of much economic importance (so-called forgotten millets—see for instance Weber and Fuller 2008). The main reason for choosing these species lies in the gap of information created by the intensity of studies focused on few selected *taxa*. We consider that, for example, *Pennisetum* sp. and sorghum have been understudied in respect to the importance they hold today and held in the past (on sorghum, see National Research Council 1996, p. 127). Furthermore, most of the species considered in the present work were examined before, as they are currently collected wild, are extremely marginal crops (e.g. famine crops) or are regarded as infesters (weeds) of other grain crops. Widening our knowledge on these species and their importance in the past can help us in reconstructing the trajectories of domestication of minor cereals, understanding the relative importance of different grain crops under distinct climatic conditions and evaluating the range of subsistence strategies available to human populations.

Materials

For this study, we considered eight species of millets within the Panicoideae subfamily (Poaceae): six small millets and two big millets (see Table 1). All the samples studied for the present work were grown from seeds of the National Plant Germplasm System of the United States Department of Agriculture (USDA). The plants were cultivated from June to September 2010 in Kyoto (RIHN), under a humid subtropical climate (Köppen Cfa). There is an abundant ethnobotanical literature on the use of millets, and here following, we summarise the most significant.

Eurasian origin

Digitaria ciliaris (southern crabgrass) A widely distributed tropical weed used as fodder and considered palatable (Skerman and Riveros 1990, p. 348). Other species of *Digitaria* (e.g. *D. exilis* (Kipp. Stapf), *Digitaria iburua* Stapf, *Digitaria sanguinalis* (L.) Scop. and *Digitaria cruciata* (Nees ex Steud.) A. Camus) are cultivated in Africa as well as Central and East Asia. The grains of these plants are used to cook porridge, *couscous*, brew beer and grounded for making bread (van Wyk 2005, p. 175).

Echinochloa colona (jungle rice) It is used as fodder in Assam (Islam 2002), sometimes only in times of stress (Skerman and Riveros 1990, p. 370). Also, it is used to make hay and silage (National Research Council 1996, p. 267).

E. frumentacea (billion-dollar grass) It is cultivated in India, Southeast Asia and Africa as fodder and crop (Norman et al. 1995, p. 87; Skerman and Riveros 1990, p. 376). It is also used for short-term control of erosion in recently cleared and ploughed sandy soil as it grows rapidly (Skerman and Riveros 1990, p. 378).

B. ramosa (browntop millet) A weedy species in tropical Africa and Asia, possibly originally domesticated in southern India (Weber and Fuller 2008); it is sometimes cultivated in India as grain and forage crop, and rarely for birdseeds (Wipff and Thomson 2003). *Urochloa* (*Brachiaria*) sp. is reported to be used by Tonga people of Zambia during times of famines (National Research Council 1996, p. 259).

Setaria pumila (yellow foxtail millet) It is used as fodder in the Terai Region of Uttar Pradesh, India (Khanna 2002). It is cultivated in the Eastern Ghats of India and elsewhere is gathered wild (van Wyk 2005, p. 345).

Setaria verticillata (Bristley foxtail millet) The possible centre of domestication of this species might be southern India (Weber and Fuller 2008). Today, it is gathered wild for food consumption (Austin 2006). Topnaar people of Namibia use the seeds in porridges and to brew beer (van Wyk and Gericke 2000).

African origin

S. bicolor ssp. bicolor (grain sorghum) Domestication of this species first occurred in Africa, although there is still controversy concerning its focus and the exact date, which is estimated around the sixth–fifth millennium BP (Doggett 1988) although archaeological material from Africa has only been dated to 800–600 BC (Rowley-Conwy 1991). The most ancient presence of *S. bicolor* in India comes from the northwest and dates to the third millennium BP (Fuller 2003). The *S. bicolor* is the most cultivated of the three subspecies of sorghum, and it is widespread in Africa and South and Southeast Asia (Norman et al. 1995, p. 145). Sorghum is very resistant to drought and it is used to cook porridges, brew alcoholic beverages, bake unleavened breads and, sometimes, the grain is eaten boiled in a sort of couscous (van Wyk 2005, p. 352) or popped like corn for snacks (National Research Council 1996, p. 128). Moreover, the whole plant is used as fodder and building material, for fencing, for roof covering, for broom-making, etc. (National Research Council 1996, p. 128), which makes this species one of the most versatile crops of the world.

P. glaucum (pearl millet) The oldest evidence comes from Northern Ghana and is dated to early- to mid-second millennium BC (D'Andrea et al. 2001). However, domestication must have occurred earlier as domestic forms of this species, which is clearly of African origins, have been found in the Indian subcontinent in contexts dated to the end of the third millennium BC (Fuller 2003). Pearl millet is the sixth largest cereal crop of the world (National Research Council 1996) and has a large potential, as it is the most drought-tolerant amongst the cereals. India is the major producer of this cereal both in terms of cultivated area as well as production (Biddinger et al. 1981). Apart from being cultivated on large scale, it is still one of the major staple crops of traditional agriculture. In India, for example, it is sown around mid-May by the Kondareddis tribe of Andhra Pradesh in a mixed cropping system (Krishna Prasad et al. 2002). It is one of the main food crops (together with *Cyamopsis tetragonoloba* (L.) Taubert, *Hordeum vulgare* L., *Capparis decidua* (Forssk.) Edgew. and *Zea mays* L.) of the Banjara tribe of Rajasthan (Trivedi 2002).

Methods

Phytoliths samples were prepared and described according to the following procedure:

1. Tweezers and scalpel were used to separate the floral parts from the grains.
2. Glumes were cleaned in an ultrasonic bath to remove any dust or contaminant.
3. Glumes were soaked in bleach until they became transparent and subsequently rinsed with distilled water washes.
4. Glumes were then mounted on a microscope slide with distilled water and covered with a covering slip fixed at the four corners with transparent nail polish. With this technique, the preparations can be stored dehydrated and water can be added before further observations at the microscope.
5. Microphotographs were taken at ×630 magnifications with a Leica DM2500 microscope equipped with a Leica DFC490 camera.
6. Phytoliths morphology was described using the terminology established by the ICPN (Madella et al. 2005). Also, in the description of long cells, the noun *protuberance*(*s*) of the sides is used to identify the "waves" of the sides as we considered it more accurate; when describing the "wavy" interlocking pattern of the silica skeletons, we used *undulate*. In describing epidermal long cells, the sides are here considered the longer faces of the cells that join the cells between the rows (see Fig. 1). The edges of long cells are the short faces that joint the cells within a row (see Fig. 1).

We concentrated on the glumes as they tend to be the most resilient part of the spikelet but a further development of our catalogue will focus on the lemma as they seems to receive higher (but later) silicification rates

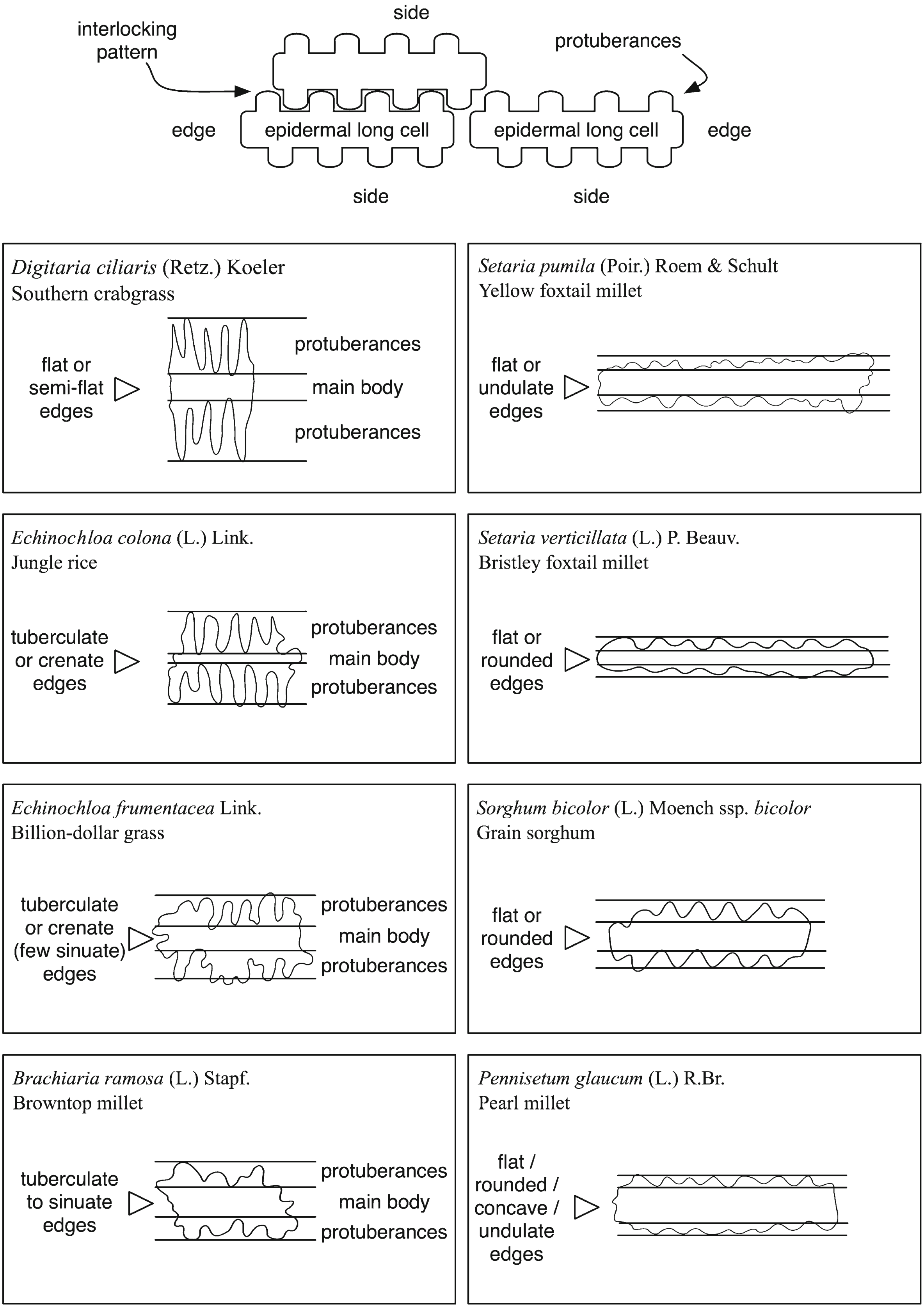


Fig. 1 *Top*, schematic drawing of the glumes long cells indicating the terminology used in this work. *Boxes*, line drawings of the glumes long cells from the eight species discussed in the text, highlighting the relationship between the main cell body and the protuberances as well as the characteristics of the edges of the cells

(Sangster et al. 1983). Starch samples were prepared and described according to the following procedure:

1. One levelled teaspoon of seeds was milled in an agate mortar.
2. The resulting powdered starch was mounted on a microscope slide with distilled water or DPX (a non-aqueous mounting medium) and covered with a covering slip.
3. Microphotographs were taken at ×630 magnifications with a Leica DM2500 microscope equipped with a Leica DFC490 camera.
4. The morphology of starch grains was described using the terminology established by the International Code for Starch Nomenclature (ICSN 2011, http://fossilfarm.org/ICSN/Code.html, accessed November 2012). Grain size was defined according to the classes established by Lindeboom et al. (2004): large (>25 μm), medium (10–25 μm), small (5–10 μm) and very small (<5 μm).

Results

Phytoliths

Despite the fact that only a small number of glumes (between 3 and 6) from three different specimens from the same population were analysed for each species, the inter-species (and partially the intra-species) phytolith production of the considered millets shows great diversity (Figs. 1, 2 and 3). Focusing on long cells, some characteristic traits can be identified both at single morphotypes level (on which morphometric analyses are currently undergoing) and at silica skeletons level.

D. ciliaris It has long cells with simple (never branched) deep and serrate/tuberculate side protuberances, height much greater than width. The main, central part of the body of the long cell has (mainly) the same or smaller size of the amplitude of the protuberances. Cell edges are truncated, flat or semi-flat. The silica skeletons have very serrated, zigzagging cell interlocking with flat or semi-flat edges between cells along the same row.

E. colona It has long cells with simple or branched/lobate and columellate/crenate/serrate side deep protuberances, height much greater than width. The main, central body of the long cell has generally a smaller (but up to the same) size of the amplitude of the protuberances. Cell edges are tuberculate or crenate. The silica skeletons have deeply undulate cell interlocking pattern, never (or extremely rarely) serrated.

E. frumentacea It has long cells with deep irregular side protuberances. The protuberances vary from (more rarely) simple to (very common) branched/lobate with the contour columellate/crenate/serrate/pilate. Height/width relationship is rather variable. The main, central body of the long cell is of similar size or greater size than the amplitude of the protuberances. Cell edges are tuberculate or crenate. The silica skeletons have deeply undulate cell interlocking pattern, never (or extremely rarely) serrated.

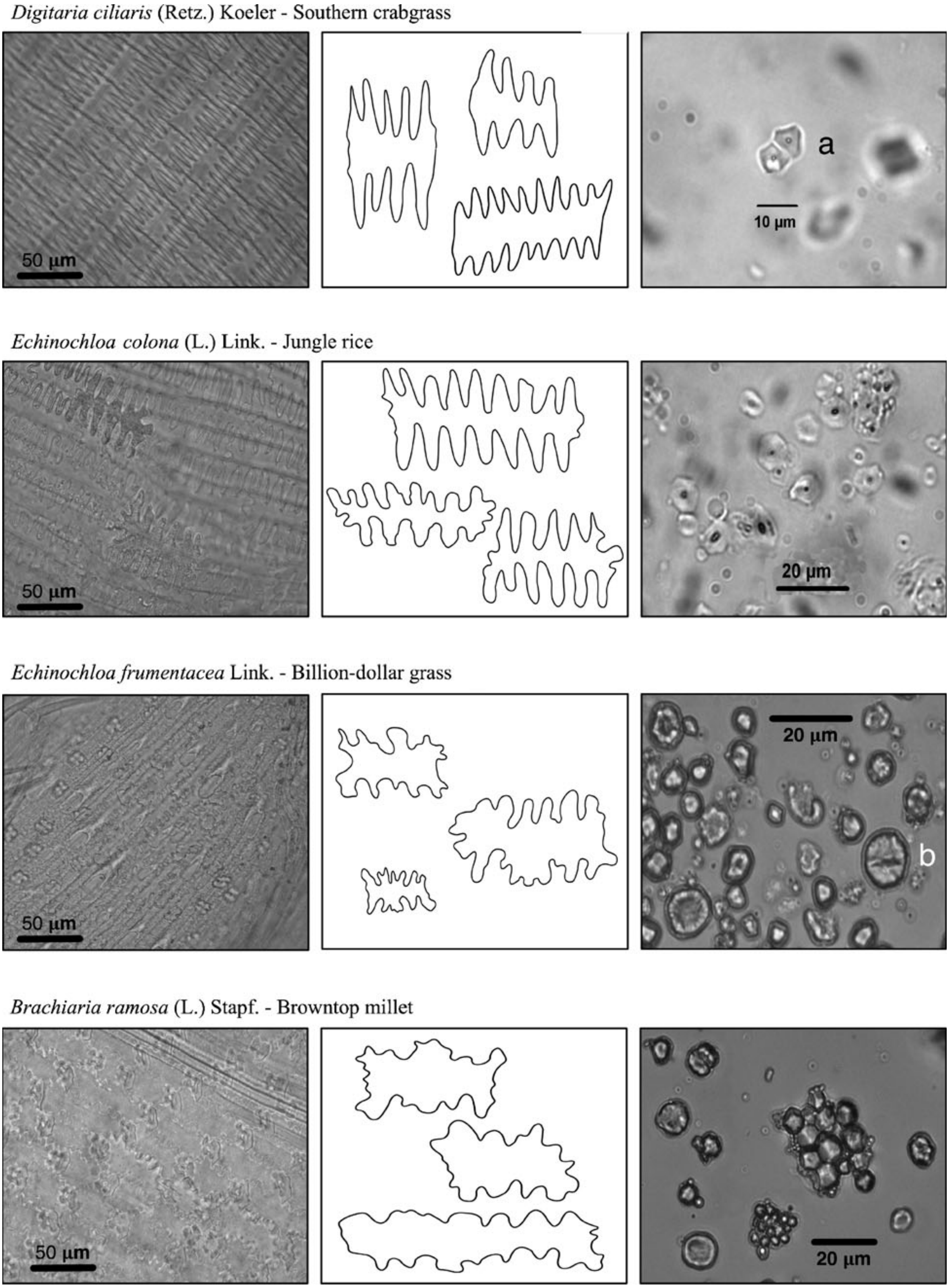
B. ramosa It has long cells with side sinuate to lobate (some crenate) protuberances, normally wider than higher or of similar width/height. The protuberances can be simple or divided. The main central body of the long cell is of similar size or greater size than the amplitude of the protuberances. Cell edges are similar to sides, sinuate to tuberculate/crenate. The silica skeletons have undulate to serrated cell interlocking pattern.

S. pumila It has long cells with side sinuate to lobate (some crenate) protuberances, normally of similar width/height or slightly higher than wider. The protuberances can be simple or divided. The main central body of the long cell is of similar size or greater size than the amplitude of the protuberances, with a scrobiculated surface. Cell edges are similar to sides, sinuate to tuberculate/crenate. The silica skeletons have undulate (rarely serrated) cell interlocking pattern.

S. verticillata It has long cells with side sinuate to lobate (some crenate) protuberances, normally wider than higher or of similar width/height. The protuberances are generally simple. The main central body of the long cell is of greater size (sometime similar size) than the amplitude of the protuberances. Cell edges rounded or rarely sinuate. The silica skeletons have mostly serrated and occasionally undulate cell interlocking pattern.

S. bicolor bicolor It has long cells with serrated (few crenate) protuberances, normally of similar width/height. The protuberances are simple. The main central body of the long cell is of greater size than the amplitude of the protuberances. Cell edges truncated, rarely rounded or gently concave. The silica skeletons have distinctive serrated (orthogonal zigzagging) cell interlocking pattern.

P. glaucum It has long cells with sinuate/lobate/crenate protuberances, of variable width/height. The protuberances are very rarely branched. The main central body of the long cell is of somewhat greater or similar size than the amplitude of the protuberances with a scrobiculated surface. Cell edges are from rounded to flat to concave. The silica skeletons have serrated to undulate cell interlocking pattern.



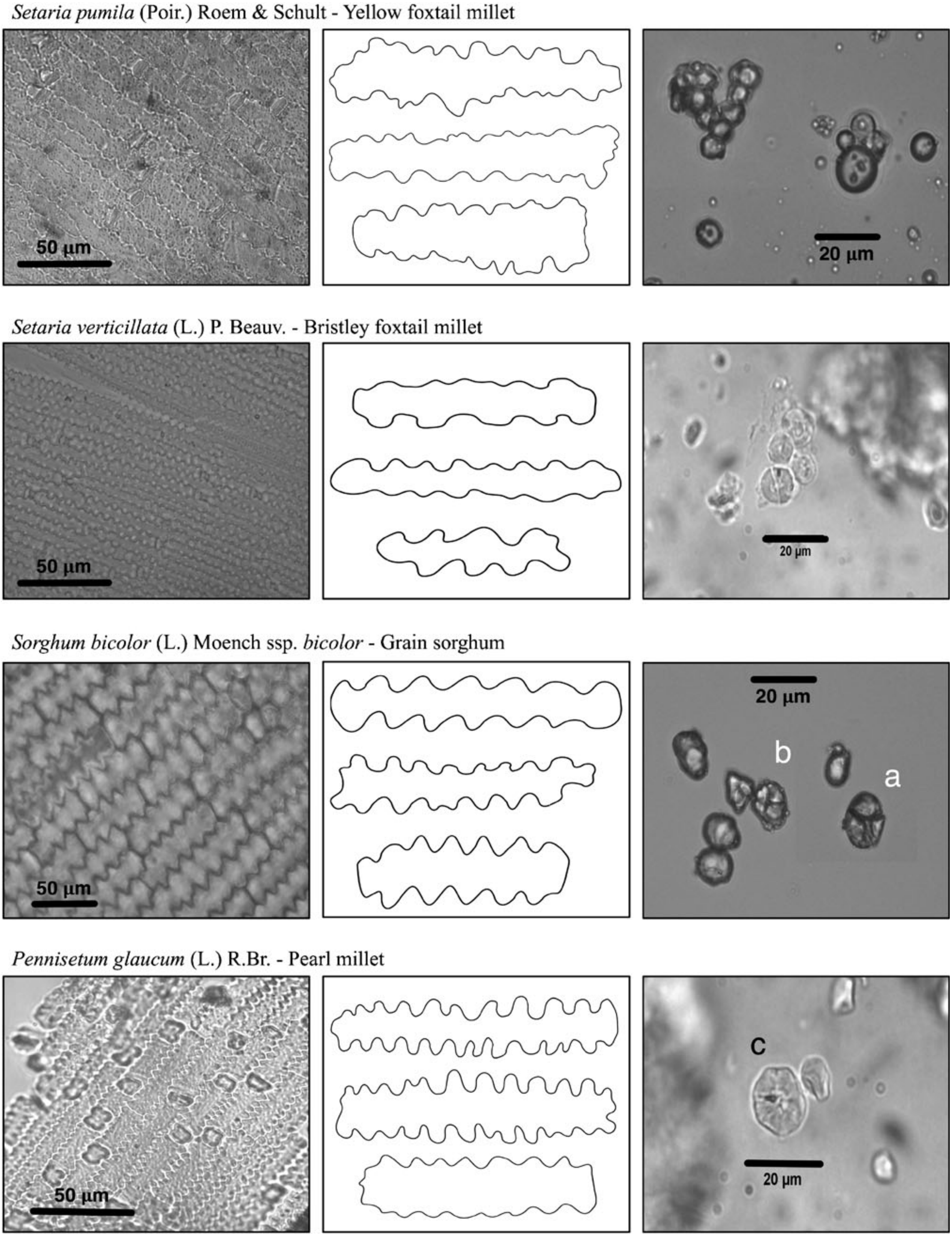
Digitaria ciliaris (Retz.) Koeler - Southern crabgrass

Echinochloa colona (L.) Link. - Jungle rice

Echinochloa frumentacea Link. - Billion-dollar grass

Brachiaria ramosa (L.) Stapf. - Browntop millet

Fig. 2 Comparative diagram of the glumes silica skeletons, long cells line drawings and seed starch grains from *D. ciliaris* (*a*, centric, circular hilum), *E. colona*, *E. frumentacea* (*b*, hilum with linear fissure) and *B. ramosa*


Setaria pumila (Poir.) Roem & Schult - Yellow foxtail millet

Setaria verticillata (L.) P. Beauv. - Bristley foxtail millet

Sorghum bicolor (L.) Moench ssp. *bicolor* - Grain sorghum

Pennisetum glaucum (L.) R.Br. - Pearl millet

Fig. 3 Comparative diagram of the glumes silica skeletons, long cells line drawings and seed starch grains from *S. pumila*, *S. verticillata*, *S. bicolor* (*a*, y-shaped hilum; *b*, stellate hilum) and *P. glaucum* (*c*, lines radiating from the starch grain centre)

Starch grains

Starch grains from the species within the Panicoideae subfamily are generally polyhedral or spherical (Ge et al. 2010; Mercader 2009; Yang et al. 2012a, b). Grain size varies widely within the Panicoids group, ranging from less than 5 μm to more than 30 μm (Ge et al. 2010). All the species considered for this study possess polyhedral starch grains, although with varying frequencies. Moreover, the species analysed here have constantly non-lamellated grains.

D. ciliaris It has very small-to-small in size (<10 μm) grains, with a polyhedral or spherical shape and with centric, circular hilum (Fig. 2, a).

E. colona It has very small-to-small in size (< μm) grains, with a polyhedral or spherical shape and with centric, circular hilum.

E. frumentacea It has very small-to-small in size (<10 μm) grains, with a polyhedral or spherical shape. The hilum can either be circular or have linear (Fig. 2, b) or stellate fissures.

B. ramosa It has very small-to-small in size (<10 μm) grains, with a polyhedral or spherical shape. The hilum can either be circular or have stellate or irregular fissures.

S. pumila It has very small-to-small in size (<10 μm) grains, with a polyhedral or spherical shape. The hilum can either be circular or have irregular fissures.

S. verticillata It has very small-to-small in size (<10 μm) grains, with a spherical shape, and with short lines that radiate from the centre towards the edges of the grains (Yang et al. 2012b).

S. bicolor bicolor It has medium to big in size grains, up to 30 μm, the biggest among Panicoids (see Ge et al. 2010; Mercader 2009). They have polyhedral or spherical shape, with y-shaped (Fig. 3, a) or stellate (Fig. 3, b) fissures of the hilum.

P. glaucum It has small to medium-sized (up to 15 μm) grains, with a polyhedral shape. Two types of grains can be identified: those with lines radiating from the centre to the edges of the grains (Fig. 3, c) and those with a centric, circular hilum.

Discussion

Phytoliths

Phytolith morphology, both at single and joined (silica skeletons) morphotypes, and starch grains from the eight taxa on which the current study focuses show great potential for the identification of different genus and/or species on the basis of microremains.

A first level of separation is that of two major groups highlighted by the general morphology of the glume phytoliths. A first group is the one with more compact long cell phytoliths with deeply incised sides (long protuberances): *D. ciliaris*, *E. colona*, *E. frumentacea*, *B. ramosa*. A second group has more elongated long cells with less extreme incisions of the sides (short protuberances) and much less (or absent) branching of the protuberances: *S. pumila*, *S. verticilla*, *S. bicolor bicolor*, *P. glaucum*.

At a second level of separation, the protuberances' morphology could help identifying lower rank groups. *D. ciliaris* has very distinctive glume epidermal long cells with exceptionally deep protuberances that in silica skeletons create a deeply, mostly orthogonal interlocking pattern not observed in any of the other taxa. *E. colona* also has long protuberances that can be sometime similar to *D. ciliaris*; however, the sides of these are often undulate and the interlocking pattern is definitively not orthogonal. *E. frumentacea* can be separated because of the even more undulate/branching protuberances giving the long cell an irregular aspect. In *B. ramosa*, the protuberances are less incised and very irregular. It is possible to observe a trend for the species *D. ciliaris*–*E. colona*–*E. frumentacea*–*B. ramosa* in which the protuberances become from long to short, from regular to irregular and from simple to branched/divided (see Fig. 2).

Long cell side patterns in *S. pumila* (scrobiculated surface) and *S. verticillata* (psilate surface) are rather similar but the protuberances of *S. verticillata* are more regular (Fig. 3) and, in the silica skeleton, show a low zigzagging (crenate) pattern sometime similar to *S. bicolor*. In this last species, however, the crenate pattern is much more evident. *P. glaucum* long cells are very similar to *S. bicolor* but the silica skeletons of *P. glaucum* has more rounded cell joints and the long cells have a scrobiculated surface.

Starch grains

Previous studies with modern starch material had analysed three of the species considered in this study: *E. colona* (Yang et al. 2012a), *S. pumila* (Yang et al. 2012b) and *S. bicolor* (Ge et al. 2010; Mercader 2009). The results from our analysis substantiate the conclusions of these studies. Small millets have very small-to-small grains, whereas the grains of *P. glaucum* and *S. bicolor* have wider diameters. An exception to this is *S. verticillata*, which grains can occasionally measure up to 15 μm in diameter. As stated by Yang et al. (2012b), the key to identify starch grains of small millets is on the basis of their surface features rather than on their size. Indeed, it is possible to observe certain variability in relation to surface typology (see Figs. 2 and 3). However, the high degree of intra-species variability examined in our samples cautions drawing definite conclusions on clear-cut separation of small millet starch grains with the current data. The size and shape of starch grains from the two big millets considered here, *S. bicolor* and *P. glaucum*, have sufficiently different morphological traits that allow easy differentiation. This is particularly relevant if we consider the rather similar morphology of the long cell phytoliths.

Conclusions

The development of a combined approach, in which phytoliths (single and silica skeletons) and starch grains are used to identify small and big millets, opens new possibilities for the archaeological detection of a very important group of grain crops. This study aimed at exploring the potentials of taxonomic and anatomical variability at intra- and inter-specific level and to set the basis for morphometric analyses. The preliminary results demonstrate sufficient variability to advocate the identification of groups and/or single taxon of millets on the basis of the morphological characteristics of phytoliths and starch grains.

Acknowledgments The work for this paper was partially carried out by MM while holding a Visiting Professorship at the Research Institute for Humanity and Nature (RIHN—Japan). Thanks are due to Prof. Yoichiro Sato for his support and help in Kyoto. The initial stage of the work benefited from discussions with Prof. DQ Fuller and Prof. S Weber. JJGG has worked while holding a JAE-Predoc PhD grant (Spanish National Research Council and European Social Fund) and CL while holding a fellowship from the Agriwestmed European Research Council project led by L. Peña-Chocarro. We are grateful to USDA for supplying the seeds for the experimental plants. Finally, we would like to acknowledge the comments from two anonymous reviewers that helped improving the original work.

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García-Granero JJ, Lancelotti C, Madella M (2015) A tale of multi-proxies: integrating macro- and microbotanical remains to understand subsistence strategies. Veget Hist Archaeobot 24, 121–133

Veget Hist Archaeobot (2015) 24:121–133
DOI 10.1007/s00334-014-0486-7

ORIGINAL ARTICLE

A tale of multi-proxies: integrating macro- and microbotanical remains to understand subsistence strategies

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Received: 31 December 2013 / Accepted: 30 August 2014 /

Abstract The integrated analysis of several proxies in order to answer a research question is a widespread approach in palaeoecology, but it is not well developed in archaeobotanical research. Applying a multi-proxy approach to archaeobotany has several advantages: a more diverse anatomical and taxonomical representation of the original plant input and a better understanding of taphonomic processes, both depositional and post-depositional. The aim of this paper is to show how a multi-proxy approach can enrich our understanding of plant-related subsistence strategies. Macro and microbotanical analyses were carried out on samples from Shikarpur, a Chalcolithic settlement in Kachchh, Gujarat, northwest India. This settlement is located in a semi-arid region with wet/dry cycles and highly saline soils that influence the preservation of charred remains, so that they do not offer the full picture of plant-related subsistence strategies. We show that the combination of different proxies is crucial to cross-validate the results and to gain a wider understanding of plant use strategies. The inhabitants of Shikarpur relied on a double-cropping system based on local small millets and pulses, and they also consumed cereals, tubers and sedges.

Keywords Multi-proxy · Phytoliths · Starch grains · Macrobotanical remains · Archaeobotany · Indus valley

Communicated by F. Bittmann.

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Introduction

Plants used and transformed by people can produce a diverse record that can be considered as a proxy of their choices and activities, and in certain cases of ecological conditions too. In a broad sense, the term ‘proxy’ is used to define a representative or intermediary. In palaeoclimatology, a proxy is defined as “a local record that is interpreted using physical or biophysical principles to represent some combination of climate-related variations back in time” (Folland et al. 2001, p. 130). Noise and possible biases make it necessary to calibrate and cross-validate proxies in order to obtain more accurate and reliable palaeoclimatic reconstructions. A multi-proxy approach is also commonly adopted in palaeoecological studies, particularly in palaeolimnology (Birks and Birks 2006 and references therein). In palaeoecology, a proxy is understood as a record of changes that can be measured or analysed to reconstruct past ecosystems and biotic responses to natural or human-caused changes (Birks and Birks 2006). Palaeoecological proxies include fossil organisms such as diatoms, phytoliths and pollen grains, as well as sediment characteristics which are measured through physico-chemical analyses.

Despite the fact that archaeobotany shares several methodological approaches with palaeoecology, the concept of proxy is not much theorised and, in general, the major evidence (proxy) is considered to be the charred remains record. This is due to (a) visibility, because charred remains can be seen by naked eye, (b) relatively easy methods of recovery either handpicked or by flotation, and (c) direct analysis without previous chemical processing.

An example of the single-proxy approach in archaeobotany, based on charred remains, is the study of plant-related subsistence strategies and agricultural practices. However, as a single-proxy approach, plant microremains offer a valuable alternative. Phytolith and starch grain analyses have made major contributions to the understanding of plant domestication processes worldwide (e.g. Piperno et al. 2009). Moreover, direct evidence of past human diet has been gained from plant microremains recovered from human dental calculus (Henry and Piperno 2008) or artefacts involved in food processing such as grinding stones (Piperno et al. 2004). Similarly to plant macroremains, phytoliths and starch grains have also been used to establish the practice of irrigated agriculture (Madella et al. 2009; Rosen and Weiner 1994), dry farming (Lu et al. 2009) and vegeculture (Barton and Denham 2011), as well as to study crop-processing activities (Harvey and Fuller 2005; Yang et al. 2013).

Although macro and microremains can be recovered from the same contexts, only a few studies have actively pursued an integration of data from both lines of evidence (Delhon et al. 2008; Dickau et al. 2012). The integrated analysis of charred macroremains, phytoliths and starch grains can widen the information spectrum at several levels:

Taxonomy

The combined use of macro- and microbotanical remains increases the number of taxa identified, independently of the preservation pathways. Microremains allow for the recognition of taxa from leaves (Out and Madella in press; Yang et al. 2013), roots and tubers (e.g. Chandler-Ezell et al. 2006) and fruits such as banana (Denham et al. 2003 for starch and Mindzie et al. 2001 for phytoliths). Charred seeds and related floral parts, on the other hand, are often strongly taxonomically diagnostic. For example, charred small millets can usually be identified to species level, whereas starch grains are, at best, diagnostic to genus level (Krishna Kumari and Thayumanaban 1998; Liu et al. 2011; Yang et al. 2012). The potential of phytoliths to differentiate between small millets has only started to be evaluated outside the two main genera, *Panicum* and *Setaria* (Madella et al. 2013 and references therein).

Anatomy

A multi-proxy approach allows for the identification of different plant parts, useful for both dietary and non-dietary investigation of plant use (Fig. 1). Plant parts seldom preserved in the macrobotanical record such as chaff of small grasses, leaves or culms can be identified from plant microremains (Lu et al. 2009; Madella et al. 2013; Out and Madella in press; Yang et al. 2013; Zhang et al. 2011).

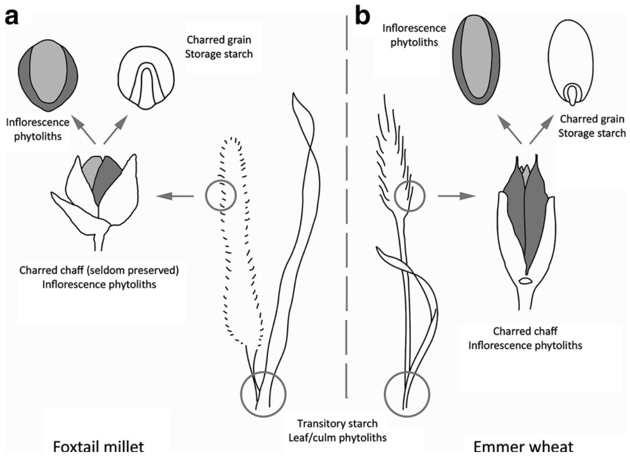

Fig. 1 Idealised drawings and examples of proxies (macro and microbotanical remains produced by different plant parts) from **a** *Setaria italica* (L.) P. Beauv. (foxtail millet), and **b** *Triticum turgidum* ssp. *dicoccon* (Schrank) Thell. (emmer wheat)

Taphonomy

Plants and plant parts are preferentially preserved depending on their intrinsic characteristics (soft vs. hard tissues), processing technique (roasting, boiling, etc.) and post-depositional settings (dry vs. wet environments, bioturbation, etc.). A multi-proxy approach offers the possibility to analyse a wider spectrum of plant residues, therefore allowing more precise evaluations of the original assemblages. Phytoliths are usually preserved regardless of the depositional conditions, since they are not dependent on fire for preservation as most macroremains are. Starch grains can be easily degraded by enzymes, bacteria and other organisms of the soil (Haslam 2004). However, when trapped in dental calculus or pores in artefacts they can be preserved for thousands of years in diverse environmental settings (Torrence 2006, Table 1). Starch taphonomy and preservation has been experimentally assessed in a set of tests by Lu (2003; in Haslam 2004).

To summarise, a multi-proxy approach offers the possibility of wider anatomical and taxonomical identification as well as overcoming some taphonomic effects, resulting in a more representative set of data from the original input. The aim of this paper is to illustrate how the analysis of multiple archaeobotanical proxies from the same archaeological contexts improves and enriches our understanding of plant use. The case study is from the Chalcolithic Harappan settlement of Shikarpur (ca. 2500–1500 BC), located

Table 1 Fire-related contexts analysed in this study. Phytoliths are expressed in concentration per g of AIF (Acid Insoluble Fraction). Starch grains are expressed in concentration per g of original sediment

ID	Description	Sediment vol. (l)	Phytoliths	Starch grains
Ash 1	Area with ash	20	5,611,441	7
Ash 2	Area with ash	40	4,396,082	12
Ash 3	Area with ash	20	117,241	5
Pit 1	Pit	60	10,822,431	20
Pit 2	Pit	20	8,518,178	5
BA 1	Area with burning activity	20	1,199,512	7
BA 2	Area with burning activity	10	7,191,799	10
Hearth 1	Fireplace	30	608,497	15
Hearth 2a	Fireplace, upper level (ashy)	20	792,819	15
Hearth 2b	Fireplace, lower level (compact)		274,166	13
Oven	Small oven delimited by brick, stone and clay plaster		3,880,028	5

in Kachchh, Gujarat, northwest India, at the fringe of the Indus valley. The paper discusses the evidence from integrated macro and microbotanical analyses from fire-related contexts and grinding stones.

Archaeobotanical background

Harappan subsistence strategies varied between the core area in the main Indus valley and the peripheries. In the Indus valley, subsistence relied on winter crops (*rabi*) such as *Triticum* spp. (wheat), *Hordeum vulgare* L. (barley), *Cicer arietinum* L. (chickpea), *Lens culinaris* Medik. (lentil) and *Pisum sativum* L. (pea). In the southern peripheral areas such as Gujarat, crops were mainly cultivated in summer (*kharif*), including large and small millets, *Oryza* sp. (rice) and tropical pulses such as *Vigna radiata* (L.) R. Wilczek (mung bean), *Vigna mungo* (L.) Hepper (black gram) and *Cajanus cajan* (L.) Huth (pigeon pea) (Fuller and Madella 2001).

Previous studies of plant-related subsistence strategies in Harappan Gujarat focused mostly on charred macroremains. Archaeobotanical research at Kanmer, a settlement in Kachchh occupied from the Early to the Post Urban Harappan Period (Pokharia et al. 2011), shows a switch from a predominance of winter crops, mainly barley, in the earlier phases towards a more diversified strategy at the end of the Harappan occupation, when the assemblage is dominated by summer crops. Plant remains from Rojdi, located in the Saurashtra peninsula in Gujarat, show the predominance of summer crops (millets and pulses) during both the Urban and Post Urban phases of occupation. Post Urban Harappan, 2nd millennium BC Oriyo Timbo has a plant assemblage dominated by summer crops, especially millets such as *Eleusine coracana* Gaertn. (finger millet), *Setaria* and *Panicum* spp. and to a minor extent, pulses (*V. mungo*) (Reddy 1997). In contemporary Babar Kot the crop assemblage additionally included winter pulses, such as *L. culinaris* or *Vicia* sp. (Reddy 1997).

Macrobotanical analyses from previous field seasons at Shikarpur by Chanchala and Saraswat show the presence of *Triticum aestivum* L. (bread wheat) and *Eleusine coracana* and *Setaria* sp. (small millets) (IAR 1995, 2002). However, Fuller (2003, 2006) questioned the presence of African crops such as *E. coracana* at Shikarpur and other Harappan settlements during the 3rd millennium BC. The author also pointed out the possible confusion between *Setaria* sp. and *Brachiaria ramosa* (L.) Stapf (browntop millet). Therefore, the identification of *E. coracana* and *Setaria* sp. at this settlement cannot be taken as conclusive.

Materials and methods

Shikarpur (N 23°14′15″, E 70°40′39″) is located in Kachchh, a semi-arid region with an average annual rainfall of ca. 400 mm, most of which falls during the monsoon period between June and September. The materials analysed for this study were collected during the 2012 field season, when the eastern part of the fortified area was excavated to expose the structures of occupational Phase II, Late Urban Harappan, ca. 2200–1900 BC (Bahn and Ajithprasad 2008).

A total of 923 l of sediment were floated of which 240 l from nine fire-related contexts such as hearths, ashy patches or areas with burning activity were analysed for this study. For each context, the sampling strategy consisted on collecting a minimum of 10 l of sediment for flotation and a 5 × 3 cm zip-lock bag of sediment for microremains extraction. Bucket flotation was carried out with a 0.25 mm mesh. It was not possible to collect a flotation sample from one oven due to a mishap during the excavation. A total of 11 phytolith and starch grain samples were analysed (Table 1).

Furthermore, 20 microremain samples were analysed from 18 grinding tools (Table 2). Quern 7 presented two used surfaces (a and b) which were sampled and analysed separately. Quern 9 was broken into two fragments (a and b), which were also separately sampled and analysed. In addition, 11 control samples from the same contexts of the grinding tools were checked to assess them for contamination, which was preliminarily appraised by checking differences in microremains concentration, where higher

Table 2 Grinding stones analysed in this study. Descriptive terms after Wright (1992). Phytoliths are expressed in concentration per g of AIF (Acid Insoluble Fraction). Starch grains are expressed in concentration per g of original sediment

ID	Description	Grinding stone		Control sample	
		Phytoliths	Starch grains	Phytoliths	Starch grains
Quern 1	Quern fragment	4,634,268	275	1,530,812	15
Quern 2	Saddle-shaped quern	4,182,827	156	1,199,512	138
Quern 3	Half saddle-shaped quern	3,090,134	1,940	725,916	12
Quern 4	Half saddle-shaped quern	1,683,901	201	1,530,812	15
Quern 5	Saddle-shaped quern	4,400,743	2,048	1,428,320	2
Quern 6	Half saddle-shaped quern	1,896,012	281	433,430	7
Quern 7a	Half saddle-shaped quern, face a	3,136,372	660	433,430	7
Quern 7b	Half saddle-shaped quern, face b	2,138,836	213	433,430	7
Quern 8	Saddle-shaped quern	4,511,346	368	1,530,812	15
Quern 9a	Basin grinding slab, fragment a	4,149,532	369	1,530,812	15
Quern 9b	Basin grinding slab, fragment b	1,912,030	1,571	1,530,812	15
Hand 1	Spherical handstone	3,596,088	591	1,820,230	15
Hand 2	Oval, irregular handstone	1,066,864	506	837,048	71
Hand 3	Bifacial, rectilinear handstone	23,493	411	282,607	25
Hand 4	Spherical handstone	2,191,360	263	607,404	5
Hand 5	Spherical handstone	2,052,040	1,206	649,305	0
Hand 6	Bifacial, rectilinear handstone	1,211,538	540	433,430	7
Hand 7	Bifacial, rectilinear handstone	1,224,839	148	433,430	7
Mortar	Boulder mortar	2,161,381	156	1,062,273	140
Pestle	Bipolar cylindrical pestle	12,316,703	1,206	1,530,812	15

concentrations were assumed for stone tools; further experiments on this issue are ongoing. Residue recovery consisted of a two-step process in which the outer layer of sediment was first dry brushed from the used surface(s) of the grinding stone (dry sample), and then the inner layer of sediment was brushed with deionised water (wet sample) (Hart 2011). Microbotanical remains were extracted from the wet sample with a combination of the methods described in Madella et al. (1998) and Horrocks (2005), adapted for small samples recovered from grinding stones (generally < 1 g). Loose sediments from fire-related contexts and control samples were processed using the same extraction protocol to allow for comparison. Phytoliths, both single cells and silica skeletons, and starch grains were observed at 200 and 630 magnifications with a Leica DM 2500 microscope equipped with a Leica DF 470 camera. Macroremains were identified using a Leica EZ4 D stereoscope. Taxonomical identification of all plant remains relied on the plant reference collection of the BioGeoPal Laboratory (CaSEs, Barcelona) and on relevant literature (Fuller and Harvey 2006; Madella et al. 2013; Neef et al. 2012). Phytoliths were described using the International Code for Phytoliths Nomenclature (ICPN—Madella et al. 2005), whereas starch grains were described according to the International Code for Starch Nomenclature (ICSN 2011).

Results

Fire-related contexts

Charred macroremains from Shikarpur were scarce and generally poorly preserved (Table 3; Fig. 2). Charred grass (Poaceae) remains included 31 grains of small millets, of which 22 belonged to the general SEB type (*Setaria*, *Echinochloa* and *Brachiaria*) (Fig. 2a) and nine were identified no further than *small millets* due to severe damage. Chaff from *Oryza* (Fig. 2b) and *Hordeum* were also found. Further recovered grasses included half a charred grain of *Coix lacryma-jobi* L. (Job's tears) (Fig. 2c) and 10 mineralised full inflorescences of *B. ramosa* (Fig. 2d-e). Pulses (Fabaceae) were also present, and 19 seeds morphologically comparable to *Vigna radiata* and *V. mungo* were found (Fig. 2f). Morphometric analyses were not conclusive, but the generally small seed size (average 1.15 × 0.87 mm) suggests a wild species of *Vigna* (Fuller and Harvey 2006). Moreover, leaf fragments

Table 3 Results of the macroremains analysis from fire-related contexts. + = present

	Ash 1	Ash 2	Ash 3	Pit 1	Pit 2	BA 1	BA 2	Hearth 1	Hearth 2
Aizoaceae									
Trianthema sp.	1	1	.	2	.	.	.	29	1
Amaranthaceae									
Chenopodium sp.	1	1	.	1	.	.	20	.	.
Cyperaceae									
cf. *Scirpus* sp.	.	1	.	1	2	1	1	.	.
Fabaceae									
Vigna sp.	1	1	.	10	2	.	3	.	2
Leaf fragments	.	+	.	+	.	.	.	+	+
Poaceae									
Panicoideae									
Brachiaria ramosa (min.)	.	.	.	10	.	.	.	.	.
SEB type	1	1	.	16	2	1	.	.	1
Small millet indet.	.	1	.	4	2	.	.	1	1
Coix lacryma-jobi	.	.	.	1	.	.	.	.	.
Oryza sp. spikelet base	.	.	.	.	1	.	.	.	.
Pooideae									
Hordeum vulgare rachis	.	.	.	.	1	.	.	.	.
Cerealia chaff	.	.	.	3	.	.	.	.	1
Parenchyma fragments	+	+	.	+	+	.	.	+	+

from an unidentified member of the Fabaceae were recovered from four contexts. Other finds included several weeds (*Trianthema* sp. and *Chenopodium* sp.) (Fig. 2g–h), six sedge grains and several parenchyma fragments from tubers.

The analysis of single-cell phytoliths (Table 4, Fig. 3a) showed a predominance of grass morphotypes (91.99 % Poaceae) over non-grass (1.51 %). Undetermined phytoliths, a group that includes non-diagnostic as well as unidentified phytoliths, accounted for 6.50 % of the single-cell phytoliths. The non-grass phytoliths were mainly morphotypes from dicotyledons and monocotyledons, such as palms (Arecaceae) and sedges (Cyperaceae) (Fig. 4a–c). Among grass phytoliths, long (elongated) cells and bulliforms offer anatomical information, whereas short cells are taxonomically diagnostic at subfamily level. Anatomical and taxonomical information is considered separately, so percentages presented below are calculated independently for the anatomically and the taxonomically diagnostic phytoliths. Leaf/culm phytoliths (bulliforms and psilate/sinuate elongated cells; 75.38 %) (Fig. 4d) outweigh inflorescence phytoliths (11.08 %) and anatomically non-diagnostic elongated cells (13.54 %). Short cell panicoid morphologies predominate (46.09 %) over chloridoid (15.42 %) and pooid (12.47 %), with non-attributable morphologies accounting for 26.02 % of the total. A total of 111 grass multi-cell phytoliths (silica skeletons) were encountered in the fire-related contexts, with 65 from leaves/culms, 44 from inflorescences and 2 anatomically non-diagnostic. Based on the morphology of elongated and short cells, 10 inflorescence silica skeletons were identified as panicoids. In particular, this silica skeleton morphology typically occurs in the external parts of the inflorescence (glumes, lower lemma and lower palea) of small millets (Fig. 5).

Starch grains were also scarce (n = 46) and only four morphotypes were identified (Table 4; Fig. 3a). The most common typology (52.17 %), further divided into three sub-types according to size, has a Panicoideae faceted polyhedral morphology. Type 1 grains are small (5-10 µm) to very small (<5 µm), characteristic of small millets (Fig. 6a) and rice, whereas Type 3 grains (>20 µm) occur mostly in big millets such as *Sorghum bicolor* (L.) Moench. (sorghum), *Pennisetum glaucum* (L.) R.Br. (pearl millet) and *C. lacryma-jobi* (Fig. 6b) (Madella et al. 2013 and references therein). Type 2 grains are of medium size (10–20 µm) and they can represent any of the previous taxa within the Panicoideae. The second-most frequent type (28.26 %) has discoidal grains, with a smooth surface and lamellae, characteristics of the tribe Triticeae (Pooideae, Poaceae) (Fig. 6c–d). Other finds include seven ovoid grains with a smooth surface, lamellae and a linear hilum diagnostic of the Faboideae (Fabaceae) (Fig. 6e–f); and two small grains that could belong to the Triticeae but which are also present in other taxa, and are therefore classified as cf. Triticeae.

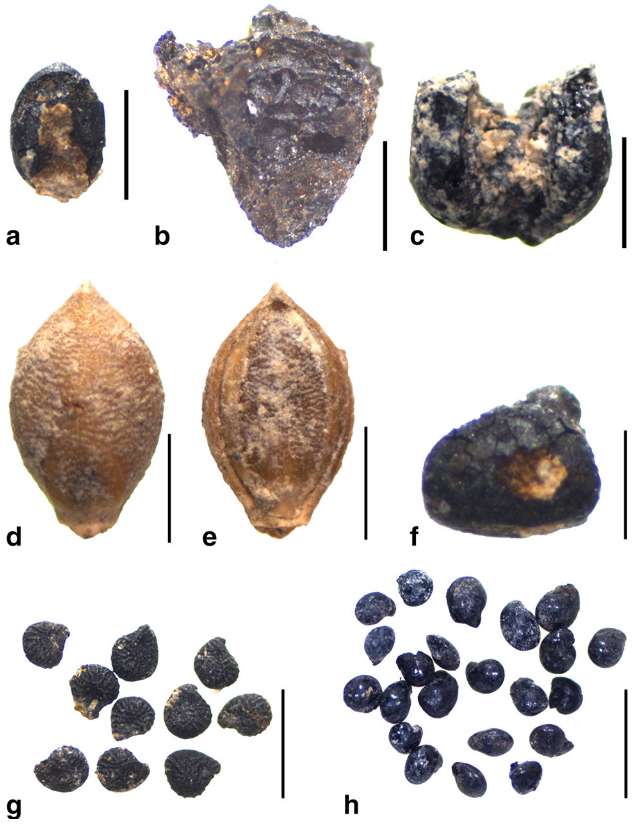

Fig. 2 Macrobotanical remains recovered from Shikarpur. **a** charred caryopsis of a SEB type small millet, **b,** charred spikelet base of *Oryza* sp., **c** half charred caryopsis of *Coix lacryma-jobi* L. (Job's tears), **d** dorsal and **e** ventral view of a mineralised inflorescence of *Brachiaria ramosa* (L.) Stapf. (browntop millet), **f** charred seed of *Vigna* sp., **g** charred grains of *Trianthema* sp., **h** charred grains of *Chenopodium* sp. *Scale bar* 1 mm in **a**–**f** and 2 mm in **g**–**h**

Grinding stones

Plant microremains were abundant in the grinding implements from Shikarpur. Phytolith concentrations were very high compared to other published analyses of grinding stones (e.g. Portillo et al. 2009). The pestle showed particularly high values, whereas Hand 3 is an exception with an extremely low presence of phytoliths (Table 2). The phytolith assemblage from Hand 3, unlike other grinding tools, was dominated by bulliforms and trichomes (included within the undetermined taxa). These morphotypes are, overall, thicker than elongated and short cells, and thus more resistant to taphonomic processes that may have affected the phytolith assemblage from Hand 3 (Madella and Lancelotti 2012). Moreover, this is the sole sample where phytolith concentration is lower than its control. For these reasons, this assemblage might not represent the original phytolith input and has therefore been excluded from the percentages presented below (Fig. 3b).

The analysis of single-cell phytoliths (Table 5) shows similar results to samples from fire-related contexts. Grass morphotypes predominate (91.81 %) and, among grasses, panicoids (39.23 %) are more represented than chloridoids (16.85 %) and pooids (19.60 %). The anatomical analysis also shows the predominance of leaf/culm phytoliths (66.56 %) over inflorescence morphotypes (26.43 %). The presence of sedge and palm phytoliths is worthy of note (although the latter were only encountered in Hand 3). Silica skeletons were scarce and only 25 of these were encountered, among which one was identified as being from pooid grasses.

A total of 650 starch grains were recovered from grinding stones (Table 5; Fig. 3b), most of which belong to the Panicoideae (51.69 %) (Fig. 7a–b) and the Faboideae (30.92 %) (Fig. 7c). Triticeae (2.46 %) (Fig. 7d) and cf. Triticeae (4.15 %) grains were also recovered, although the former were much less common. Three morphotypes that were not encountered in fire-related contexts were recovered from grinding stones: (a) 30 spherical grains with a linear hilum and lines radiating from the centre, attributed to cf. Panicoideae (Fig. 7e); (b) 18 ovoid grains with a smooth surface, a regular extinction cross and an eccentric small vacuole hilum (Fig. 7f–g), most probably from a tuberous plant; and (c) one bell-shaped grain with an eccentric, linear hilum (Fig. 7h–i) that occurs in roots and palms. Finally, 21 starch grains could not be identified due to severe damage.

Discussion

Integrating macro- and microbotanical remains

The scarcity of charred macroremains at Shikarpur, linked to the dry-wet cycles caused by the monsoon climate of this region and the high salinity of the soils, highlights the difficulty of assessing the plant use strategy solely based on this evidence. The few data gathered from macroremains show that small millets appear together with common weeds of millet, such as *Trianthema* sp. and *Chenopodium* sp., suggesting that small millets were being cultivated and not simply gathered. Most charred small millets are identified as SEB type, a group within the tribe Paniceae (Panicoideae, Poaceae). Several species within this group are native to South Asia, whereas *Setaria italica* (L.) P. Beauv. (foxtail millet) was domesticated in China (Nasu et al. 2007). The timing of the arrival of *S. italica* in northwest South Asia is controversial. Some researchers claim that it was already present in Early Harappan times, before 2600 BC (Pokharia et al. 2014 and references therein), while Fuller (2006) suggested that the finds reported as *S. italica* are instead *Brachiaria ramosa*, which is morphologically very similar to *Setaria* spp. Fuller advocates that *S. italica* and *Panicum miliaceum* L. (common millet) were not

Table 4 Results of phytolith and starch grain analyses from fire-related contexts

	Ash 1	Ash 2	Ash 3	Pit 1	Pit 2	BA 1	BA 2	Hearth 1	Hearth 2a	Hearth 2b	Oven
Phytoliths											
Single cells											
Monocotyledons											
Arecaceae	.	.	.	.	1	.	.	.	.	.	.
Cyperaceae	.	.	1	.	.	.	.	2	.	.	.
Poaceae											
Bulliforms (leaf)	1	8	53	9	11	23	22	13	27	30	13
Elongated cells											
Inflorescence	13	9	5	2	4	6	3	14	5	4	7
Leaf/culm	21	33	28	10	31	20	24	33	41	19	20
Undetermined	8	2	7	3	12	6	4	15	6	12	13
Short cells											
Chloridoideae	25	26	24	43	35	44	34	28	30	42	40
Panicoideae	128	111	68	135	97	102	89	86	87	94	112
Pooideae	29	33	25	24	23	32	30	33	27	17	27
Undetermined	69	46	39	52	68	47	77	60	49	57	62
Dicotyledons	.	7	11	4	4	4	4	2	6	3	2
Undetermined taxa	13	27	38	15	14	16	19	16	25	25	7
Total single cells	307	302	299	297	300	300	306	302	303	303	303
Silica skeletons											
Inflorescence											
Chloridoideae	.	.	.	1	.	.	.	.	.	.	.
Panicoideae	1	2	.	2	1	1	.	.	.	.	3
Undetermined	5	5	.	2	4	2	5	.	2	.	8
Leaf/culm											
Chloridoideae	.	1	.	.	1	.	.	.	.	.	.
Panicoideae	.	1	.	.	1	.	.	.	.	.	.
Undetermined	6	12	1	3	7	13	6	.	5	.	8
Undetermined	1	.	.	.	.	1	.	.	.	.	.
Total silica skeletons	13	21	1	8	14	17	11	.	7	.	19
Starch grains											
Fabaceae											
Faboideae	.	.	1	1	1	1	.	.	.	2	1
Poaceae											
Panicoideae											
Type 1 (<10 μm)	.	.	.	.	.	.	.	4	1	.	.
Type 2 (10-20 μm)	.	1	1	2	.	.	.	2	3	3	1
Type 3 (>20 μm)	.	2	.	2	.	1	.	.	1	.	.
Pooideae											
Triticeae	3	2	.	2	.	1	4	.	1	.	.
cf Triticeae	.	.	.	1	1	.	.	.	.	.	.
Total starch grains	3	5	2	8	2	3	4	6	6	5	2

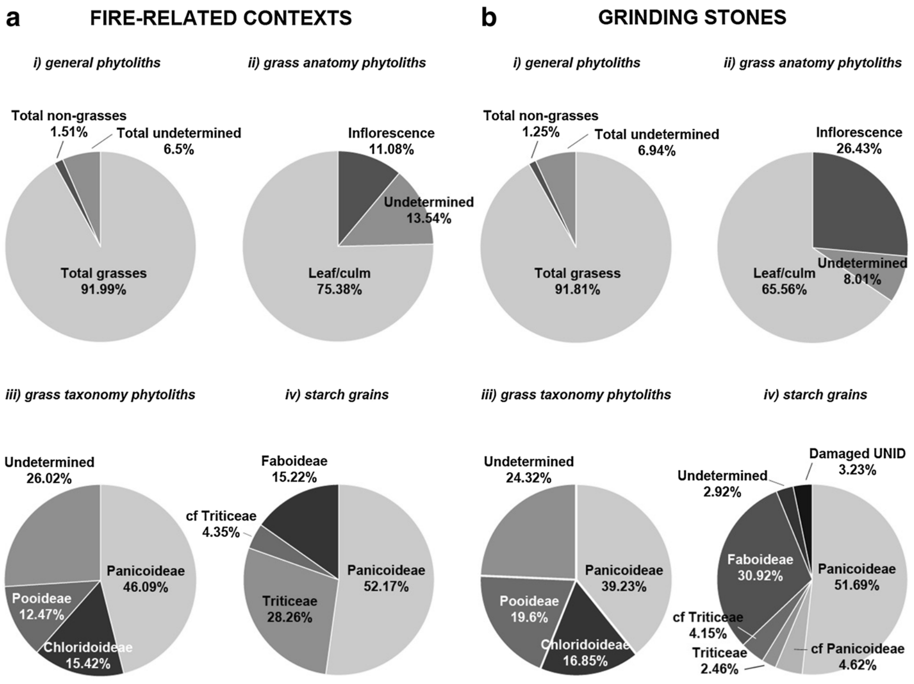

Fig. 3 Percentages of single-cell phytoliths and starch grains recovered from **a** fire-related contexts, **b** grinding stones. *i* single-cell phytoliths, *ii* anatomically diagnostic grass phytoliths (elongated cells and bulliforms), *iii* taxonomically diagnostic grass phytoliths (short cells), *iv* starch grains

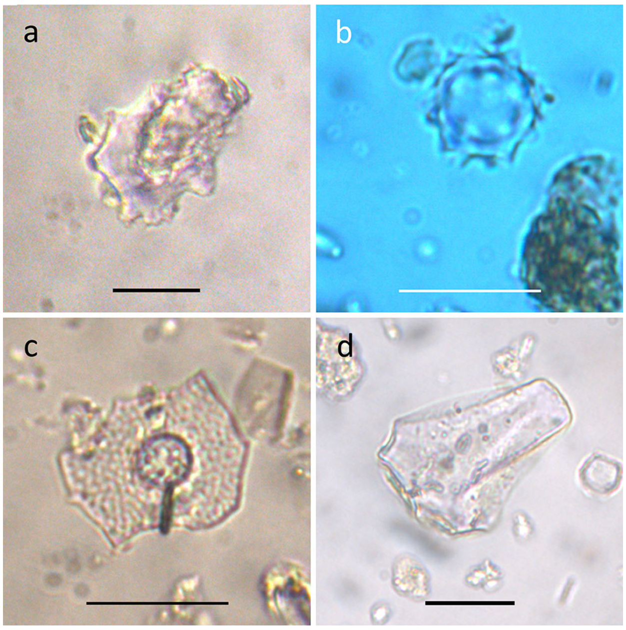

Fig. 4 Single-cell phytoliths recovered from Shikarpur. **a** irregular phytolith from a dicotyledonous plant, **b,** globular echinate phytolith from a palm (Arecaceae), **c** scrobiculated cone phytolith from a sedge (Cyperaceae), **d** bulliform phytolith from a grass (Poaceae) leaf. *Scale bars* are 20 µm

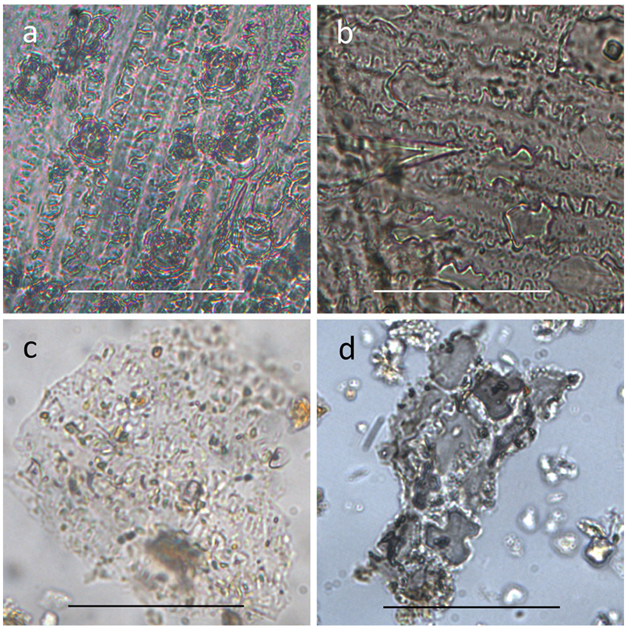

Fig. 5 Modern (**a**–**b**) and archaeological (**c**–**d**) multi-cell phytoliths (silica skeletons) recovered from Shikarpur: **a** lower lemma from *Brachiaria ramosa* (L.) Stapf. (browntop millet), **b** lower glume from *Echinochloa colona* (L.) Link (shama millet), **c**–**d,** panicoid silica skeletons from fire-related contexts. *Scale bars* are 50 µm

present in South Asia until Post Urban Harappan times, after 1900 BC. Charred remains from Shikarpur are not conclusive, but the presence of 10 mineralised *B. ramosa* grains suggests the undeniable presence of this species, although its importance is difficult to estimate.

The evidence from other proxies, phytoliths and starch grains, also suggests that small millets were staples for the inhabitants of Shikarpur. No silica skeletons from the upper lemma and palea of small millets were encountered, which are diagnostic to species level (Lu et al. 2009; Zhang et al. 2011). However, the presence of silica skeletons from the

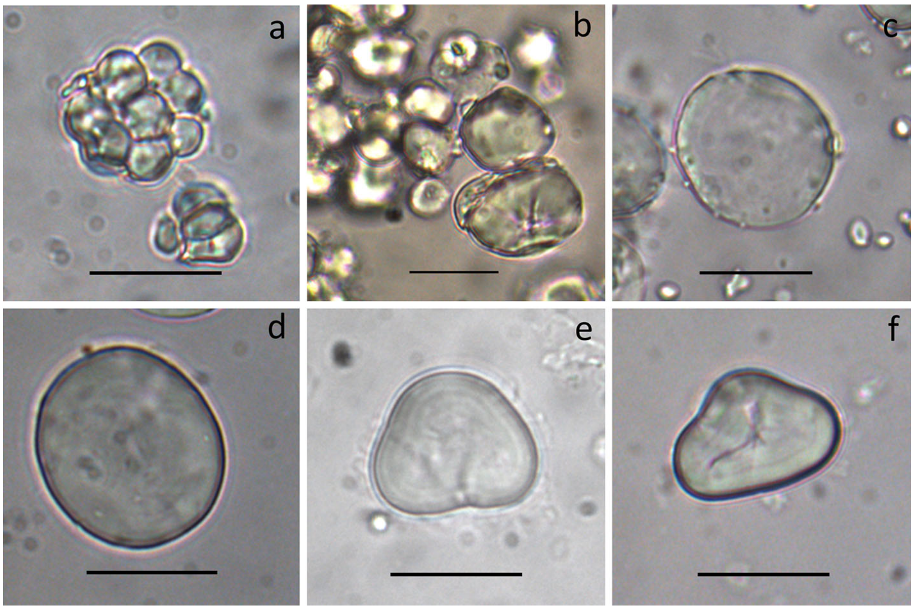

Fig. 6 Modern starch grains from the reference collection. **a** *Brachiaria ramosa* (L.) Stapf. (browntop millet), **b** *Coix lacryma-jobi* L. (Job's tears), **c** *Hordeum vulgare* L. (barley), **d** *Triticum aestivum* L. ssp. *sphaerococcum* (Perc.) MK. (dwarf wheat), **e** *Vigna radiata* (L.) R.Wilczek (mung bean), **f** *Vigna mungo* (L.) Hepper (black gram). *Scale bars* are 20 µm

external parts (glumes, lower lemma and lower palea) suggests that small millet processing was taking place at the settlement. The significant presence of Type 1 Panicoideae starch grains (<10 µm) and the scarcity of inflorescence silica skeletons in grinding implements implies that these tools were used to mill clean small millet grains for flour and not for dehusking. This highlights the use of millets in Shikarpur as flour, possibly for bread making, but not as whole grain food. These starch grains are also produced in *Oryza* (Yang and Perry 2013), but the only rice evidence from the macroremains is a single charred spikelet base found in Pit 2 and there is no evidence of rice phytoliths. Macroremains and missing phytoliths therefore reinforce the hypothesis that Type 1 Panicoideae starch grains are from small millets.

The presence of Type 3 Panicoideae starch grains (>20 µm) seems to suggest that big millets were also milled at Shikarpur. The presence of African millets (*Sorghum bicolor*, *Pennisetum glaucum* and *Eleusine coracana*) in South Asia during the 3rd millennium BC seems to be dubious (Fuller 2003) and it is possible that Type 3 morphologies are from *Coix lacryma-jobi*, the grains of which were found in Pit 1, Shikarpur, and other Chalcolithic sites in northern Gujarat (authors' unpublished data). This plant is still a minor food and fodder crop in some parts of India (Arora 1977).

Triticeae starch grains were also present at Shikarpur. The damage caused by grinding and the small number of grains recovered, 29 grains in total, prevents a more specific taxonomical identification based on surface features as suggested by Yang and Perry (2013). Most of the recovered grains (75.86 %) were larger than >20 µm, suggesting that they were from *Triticum*, *Hordeum*, *Secale*, *Agropyron* or *Aegilops* (Yang and Perry 2013). Moreover, plants from the Triticeae are not native to Gujarat (Fuller 2006) and, according to macrobotanical evidence from excavations of other archaeological sites, the only crops from this tribe which were consumed in this region during Harappan times were *Triticum* and *Hordeum* (Fuller and Madella 2001). Therefore, the Triticeae starch grains identified in both fire-related contexts and grinding stones can be attributed to *Triticum*/*Hordeum*. The macrobotanical evidence for the processing and consumption of these cereals is limited to some charred chaff but, once more, the multi-proxy approach highlights their presence and use in the settlement, even as minor components of the diet.

The combined botanical evidence demonstrates that pulses also played an important role in the diet of the inhabitants at Shikarpur, who seem to have consumed wild *Vigna* taxa. The presence of Fabaceae leaf fragments in fire-related contexts could suggest that the wild *Vigna* grains had entered the archaeobotanical record as fuel, either directly or via animal dung (Lancelotti and Madella 2012). However, the significant presence of Faboideae starch grains on grinding stones makes clear that at least one wild *Vigna* taxon was part of the people's diet. Similarly, sedge nutlet phytoliths from grinding stones, despite being scarce, suggest that sedges may have been processed in small quantities for human consumption. Finally, tuberous plants and roots also appear in the assemblage from Shikarpur and they were probably consumed both whole (charred parenchyma) and ground (starch grains from grinding tools and globular echinate phytoliths).

Table 5 Results of phytolith and starch grain analyses from grinding stones

	Quern 1	Quern 2	Quern 3	Quern 4	Quern 5	Quern 6	Quern 7a	Quern 7b	Quern 8	Quern 9a	Quern 9b	Hand 1	Hand 2	Hand 3	Hand 4	Hand 5	Hand 6	Hand 7	Mortar	Pestle
Phytoliths																				
Single cells																				
Monocotyledons																				
Arecaceae	.	.	.	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.	.	.
Cyperaceae	1	.	3	.	1	.	.	.	.	.	.	.	.	.	.	3	.	.	.	.
Poaceae																				
Bulliforms (leaf)	18	22	20	14	7	22	20	22	18	21	31	25	22	141	12	26	24	17	17	15
Long cells																				
Inflorescence	5	6	21	22	16	10	15	14	7	7	11	14	13	4	15	20	13	18	16	11
Leaf/culm	10	10	24	17	6	6	6	8	3	15	10	16	21	32	26	18	13	12	27	9
Undetermined	2	9	1	6	14	3	3	.	.	1	2	7	8	9	7	1	1	9	2	1
Short cells																				
Chloridoideae	31	34	53	44	33	61	48	32	40	34	41	31	32	8	35	32	42	34	36	35
Panicoideae	111	101	102	105	79	67	84	78	78	84	57	100	102	16	101	77	70	92	85	122
Pooideae	39	25	36	44	53	50	34	57	68	49	39	39	36	6	34	58	59	51	37	39
Undetermined	54	72	46	34	72	58	79	78	54	64	77	51	36	8	37	40	48	47	45	59
Dicotyledons	3	7	2	4	.	2	.	5	2	2	.	5	7	8	5	2	4	2	11	1
Undetermined taxa	25	18	15	8	22	20	19	13	30	27	31	14	22	102	26	25	28	19	23	14
Total single cells	299	304	323	298	303	299	308	307	300	304	299	302	299	337	298	302	302	301	299	306
Silica skeletons																				
Inflorescence																				
Pooideae	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.	.	.	.	.	.
Undetermined	.	.	.	.	1	.	1	.	.	.	.	1	.	.	1	.	.	.	.	8
Leaf/culm																				
Undetermined	.	.	2	.	2	.	.	.	1	.	.	2	.	4	1	.	.	.	.	2
Undetermined	.	.	1	.	.	.	1	.	.	.	.	.	.	.	.	.	.	.	.	.
Total silica skeletons	.	.	3	.	3	.	2	.	1	.	1	3	.	4	2	.	.	.	.	10
Starch grains																				
Fabaceae																				
Faboideae	3	.	4	20	5	11	12	4	17	18	13	8	19	5	3	14	10	15	5	16
Poaceae																				
Panicoideae																				
Type 1 (<10 μm)	.	.	89	.	41	1	.	.	15	.	10	.	.	.	.	4	12	1	.	5
Type 2 (10-20 μm)	1	1	.	3	18	.	8	3	4	2	1	15	19	1	9	18	6	1	2	18
Type 3 (>20 μm)	.	1	.	.	2	.	1	.	.	.	.	5	4	.	2	7	.	1	.	5
cf. Panicoideae	1	1	1	1	.	5	2	1	1	5	.	.	2	.	4	5	.	1	.	.
Pooideae																				
Triticeae	1	.	.	.	1	.	1	.	.	.	3	2	.	1	2	.	.	.	4	1
cf. Triticeae	.	.	1	.	1	.	9	2	.	.	2	1	3	1	1	1	.	3	1	1
Root/palm undet.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	.
Tuber undet.	1	.	2	.	.	.	.	.	1	.	.	1	2	.	2	7	2	.	.	.
Damaged UNID	.	2	1	.	1	2	1	2	7	.	.	.	1	1	.	1	1	1	.	.
Total starch grains	7	5	98	24	69	19	33	12	45	25	29	32	50	9	23	57	31	24	12	46

Subsistence strategies at Shikarpur

The multi-proxy approach shows that the subsistence strategy of the inhabitants of Shikarpur was based on local summer crops, mostly small millets (*B. ramosa* and some other taxa) but also a wild *Vigna* legume. Taking into account the environmental settings of this region, with low water availability, high inter-annual variability including droughts, short cropping period and high salinity, the combination of small millets and wild pulses would probably have constituted the most profitable land use strategy. The possibility of the cultivation of wild *Vigna* taxa, which

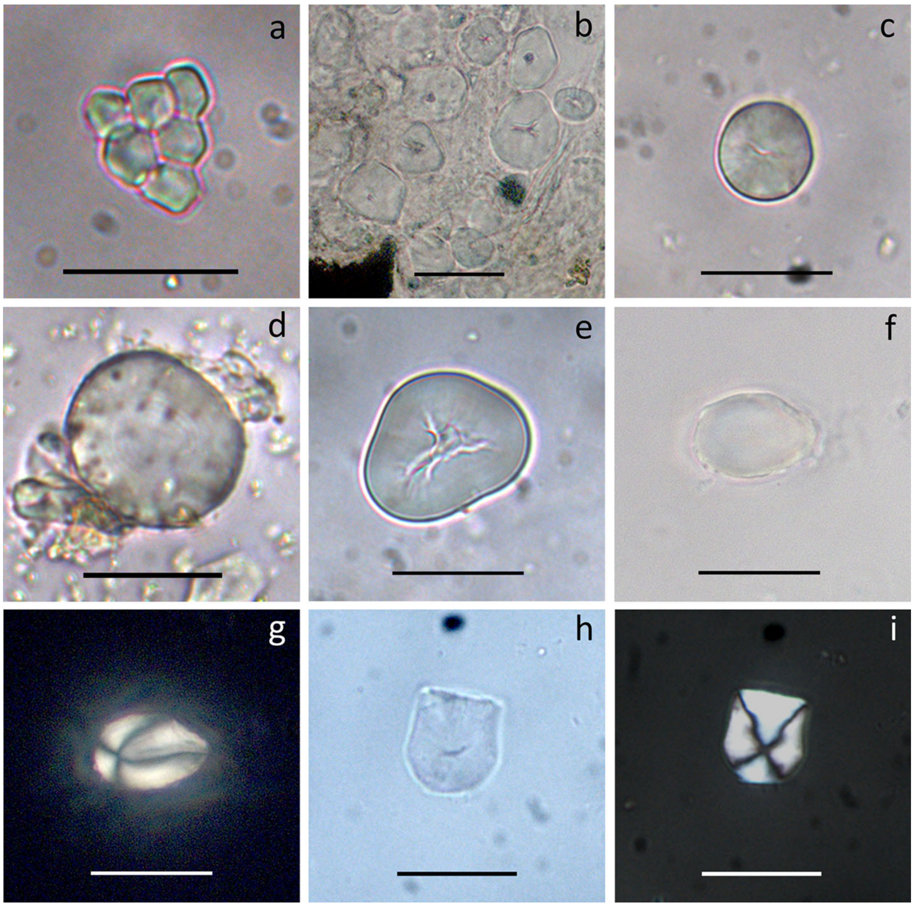

Fig. 7 Starch grains recovered from Shikarpur. **a** Panicoideae Type 1 (<10 µm) grains, **b** Panicoideae Type 2 (10–20 µm) and Type 3 (>20 µm) grains, **c** cf. Panicoideae grain, **d** Triticeae grain, **e** Faboideae grain, **f**–**g** tuberous grain, **h**–**i** root/palm grain. *Scale bars* are 20 µm. Images **g** and **i** are under cross-polarised light

could also have improved the soil by nitrogen enrichment, cannot be discarded completely. Other resources such as rice and sedges and also some kinds of roots and tubers also seem to have been consumed, possibly as condiments or spices.

Triticum and *Hordeum*, which were staple crops in the core Harappan areas, were scarcely present at Shikarpur. Macrobotanical evidence is limited to one *Hordeum* rachis. Pooideae phytoliths were only marginally present both in all analysed contexts and tools. The best evidence for *Triticum*/*Hordeum* consumption comes from Triticeae starch grains which were recovered from grinding stones. This minor presence of big grain C3 cereals at Shikarpur might represent a local, small-scale cultivation, which seems unlikely in the absence of chaff phytoliths or, most probably, the trading between Harappan settlements set in different ecological regions of which Shikarpur was part (Bahn and Ajithprasad 2008; Gadekar et al. 2014). *Triticum* and *Hordeum* were not the main staples in northern Gujarat, and their use may be related to cultural preferences of the inhabitants of Shikapur as part of the area of Harappan influence.

Conclusions

We believe that a combined approach, in which several botanical proxies and a broad-spectrum sampling strategy are used together, is the best possible way to explore diet and plant use strategies in past societies. This paper has shown how effective this method can be and how the information obtained can be enhanced. The combined information from the different deposits and grinding tools at Shikarpur highlights not only the presence at the site of various taxa, both cultivated and wild, but also the pathways of their use. The macrobotanical evidence helped, regardless of its paucity, in identifying some of the staple grains, such as the small millets, and some secondary grains such as the *Vigna* sp. wild pulses, which could have been interpreted as part of the weed or fuel (dung) assemblage. However, the starch from the grinding stones undeniably shows that these seeds were ground to flour and therefore that they were part of the diet. The microbotanical remains broadened the information on the plant spectrum used for food such as sedges and tubers, as the remains were connected to processing with grinding stones. Finally, it is remarkable to see how the different proxies can reinforce and complement each other; as is the case of the wild *Vigna* identified in the macroremains for which the microremains strongly highlighted their pre-domestic character.

Acknowledgments This research benefited from discussions with P. Ajithprasad, H. Barton and the participants of the 16th Conference of the IWGP in Thessaloniki (Greece). Thanks are due to the members of the Department of Archaeology and Ancient History, MSU Baroda, for helping during the 2012 fieldwork at Shikarpur, and the Archaeological Survey of India for granting permission for the excavation. Some of the modern reference seeds are from the US Department of Agriculture (USDA) gene bank. JJGG acknowledges funding from a JAE-Predoc doctoral research grant (Spanish National Research Council and European Social Fund) and CL from the SimulPast project, funded by the Spanish Ministry for Science and Innovation (CSD2010-00034).

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García-Granero JJ, Arias-Martorell J, Lancelotti C, Madella M (submitted) Geometric morphometric analysis of *Setaria italica* (L.) P.Beauv. (foxtail millet) and *Brachiaria ramosa* (L.) Stapf. (browntop millet) and its implications for understanding small millets biogeography. Veget Hist Archaeobot

Geometric morphometric analysis of *Setaria italica* (L.) P.Beauv. (foxtail millet) and *Brachiaria ramosa* (L.) Stapf. (browntop millet) and its implications for understanding small millets biogeography

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Paper submitted to Vegetation History and Archabotany on 09 December 2014

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Abstract

Setaria italica (L.) P.Beauv. (foxtail millet) was domesticated in northern China. The time and route of its introduction in South Asia is currently unclear due to the possible confusion with autochthonous *Brachiaria ramosa* (L.) Stapf. (browntop millet). Geometric morphometrics (GM) offer an alternative to traditional archaeobotanical methods to distinguish between these two small millet species. This study aims at finding a method to securely distinguish among charred caryopses of *S. italica* and *B. ramosa*, testing its validity on archaeobotanical assemblages and proposing a new approach for studying the dispersion of *S. italica* throughout Eurasia. Over 30 modern *S. italica* and *B. ramosa* caryopses and 15 archaeological specimens from a fifth millennium BP archaeological occupation in northwestern India were analysed. Archaeological and modern caryopses (before and after charring) were photographed with a Leica EZ4D stereoscope, and TPSdig software was used to scale the photographs and manually apply a nine-landmark configuration on the contour of the embryo. Multivariate statistics were carried out to analyse the shape differences between modern *S. italica* and *B. ramosa* and to classify the archaeological specimens. The results show that the shape of the embryo of both species can be clearly distinguished using a GM approach, both before and after charring. However, charring tends to smooth the shape differences between the two groups, which may affect the interpretation of archaeobotanical assemblages. The comparison between modern and archaeological caryopses suggests that *S. italica* was not present in northwestern India during the fifth millennium BP.

Key words: geometric morphometrics; archaeobotany; plant dispersion; shape analysis; small millets

Introduction

Understanding the processes of plant domestication and dispersion is necessary to fully comprehend human-plant coevolution (Rindos and Dunell 1984; Jackson 1996; Purugganan and Fuller 2009, 2011). In particular, the domestication of grasses (Poaceae) has had a major impact in human history, ultimately giving rise to current human cultures (Diamond 2002). *Setaria italica* (L.) P.Beauv. (foxtail millet) is a grass from the sub-tribe Cenchrinae (Paniceae, Panicoideae, Poaceae). Nowadays regarded as a minor cereal, it was widely cultivated across Eurasia during prehistoric times (Hunt et al. 2008). *S. italica* presumably originated from *Setaria viridis* (L.) P.Beauv. (green foxtail) and was domesticated in the upper Yellow River basin (northern China) during the eighth millennium BP, from where it dispersed east and westwards (Nasu et al.

2007). One or more additional domestications may have occurred in Eastern Europe or Central Asia (Fuller 2003).

The time and route of introduction of *S. italica* in South Asia is a controversial issue (Hunt and Jones 2008). Findings of this crop have been reported from archaeological sites in India and Pakistan during the fifth millennium BP (e.g. Weber 1999). However, Fuller (2002, 2003, 2006) argued that *S. italica* most likely reached South Asia during the fourth millennium BP, and that earlier findings of this crop actually belong to *Brachiaria ramosa* (L.) Stapf. (bronwtop millet) or other *Setaria* spp.

B. ramosa [syn. *Urochloa ramosa* (L.) T.Q.Nguyen] is a grass from the sub-tribe Melinidinae (Paniceae, Panicoideae, Poaceae). It was domesticated in South Asia during the fifth millennium BP, with probably two independent centres of domestication in southern and northwestern India (Fuller et al. 2004; García-Granero et al. in press). Although it is usually regarded as a weed, *B. ramosa* is still a minor crop cultivated in some areas of southern India for both human and animal consumption (Kimata et al. 2000).

Traditional archaeobotanical methods have failed to securely distinguish among *S. italica* and *B. ramosa*. Identification of charred *S. italica* usually relies on length to breath ratio of the caryopses and the surface sculpture of the lemma (Nasu et al. 2007). However, there is a wide range of variation in the size and shape of many wild and cultivated *Setaria* and related species, and carbonisation often deforms the grain morphology. The rugose husk patterns of *S. italica* are also likely to be confused with those of *B. ramosa* (Fuller 2006); furthermore, small millet husk is seldom recovered from archaeological contexts.

Geometric morphometrics (GM) offer an alternative approach to shape analyses based on Cartesian coordinates of anatomical points –called landmarks (Slice 2007). GM emphasise the complete retention of geometric information throughout the research process, as opposed to the mere collection of distances or angles. 2D landmark-based GM is a method of analysis that uses two-dimensional (*x, y*) coordinates to define a series of (preferably) homologous points on an anatomical structure as variables to conduct numerical analyses of shape (Bookstein et al. 1999; Zelditch et al. 2012). These methods have been widely used in (palaeo)anthropological, zoological and botanical research (e.g. Slice 2007; Lawing and Polly 2010; Cope et al. 2012), but their application in archaeology is relatively recent. Examples include artefact studies such as ceramics (Wilczek et al. 2014) and lithics (Archer and Braun 2010; Buchanan and Collard 2010a, b; Cardillo 2010; Costa 2010; Lycett et al. 2010; Iovita and McPherron 2011; Charlin and González-José 2012; Thulman 2012; Buchanan et al. 2013; Lycett and von Cramon-Taubadel 2013). However, GM are most suited for the analysis of shape in biological structures (Slice 2007). As such, GM techniques have been applied in zooarchaeological research to study the evolution and dispersion of pigs (Cucchi et al. 2009, 2011a; Evin et al. 2013; Krause-Kyora et al. 2013; Ottoni et al. 2013; Owen et al. 2014), horses (Seetah et al. 2014), house mice (Cucchi et al. 2011b; Valenzuela-Lamas et al. 2011), sheep (Yalçin et al. 2010), pipistrelle bats (Evin et al. 2011) and cave bears (Seetah et al. 2012). Archaeobotanically, this approach has been employed to study the domestication and dispersion of olives (Terral et al. 2004; Newton et al. 2006, 2014), Prunus spp. (Nielsen and Olrik 2001; Depypere et al. 2007, 2009; Burger et al. 2011), barley (Ros et al. 2014), grapevine (Terral et al. 2010; Pagnoux et al. 2015) and date palm (Terral et al. 2012).

In this study we apply GM to analyse the shape of modern caryopses of *S. italica* and *B. ramosa* before and after charring. The results of the GM analyses of charred modern caryopses are further compared with small millet caryopses recovered from archaeological deposits in Gujarat (northwestern India). The aims of this study are:

a) to develop a method to securely distinguish among charred caryopses of *S. italica* and *B. ramosa*;
b) to test the validity of the method on archaeobotanical assemblages;
c) to propose a new approach for studying the dispersion of *S. italica* through Eurasia.

Materials and Methods

Over 30 modern *S. italica* and *B. ramosa* caryopses were randomly selected for the analyses (Table 1). Archaeobotanical specimens belong to archaeological deposits dated to the end of the fifth millennium BP from Shikarpur, an urban settlement located in Kachchh, Gujarat (Bhan and Ajithprasad 2008). The archaeobotanical assemblage contained a total of 31 charred small millet caryopses, among which 22 were identified as pertaining to the SEB type (*Setaria*, *Echinochloa* and *Brachiaria* genera) (García-Granero et al. 2015). Severe damage on most caryopses, due to charring and post-depositional processes, prevented a more accurate taxonomical identification. Despite the damage to the overall grain morphology, in most cases the shape of the embryo was still clearly distinguishable (Fig. 1e). After close examination, only 15 grains from Shikarpur were suitable for the implementation of GM. The remaining seven grains lacked at least one of the homologous anatomical features required for the landmark configuration implemented in this study (see below). The archaeobotanical assemblage also included mineralised inflorescences from *B. ramosa*, suggesting that al least some charred grains belong to this species.

Table 1. Modern and archaeological specimens analysed in this study.

Species	**number of grains**		**Origin**
	uncharred	**charred**	
Brachiaria ramosa	34	30	India
Setaria italica	35	31	Karnataka (India)
Archaeological grains	-	15	Gujarat (India)

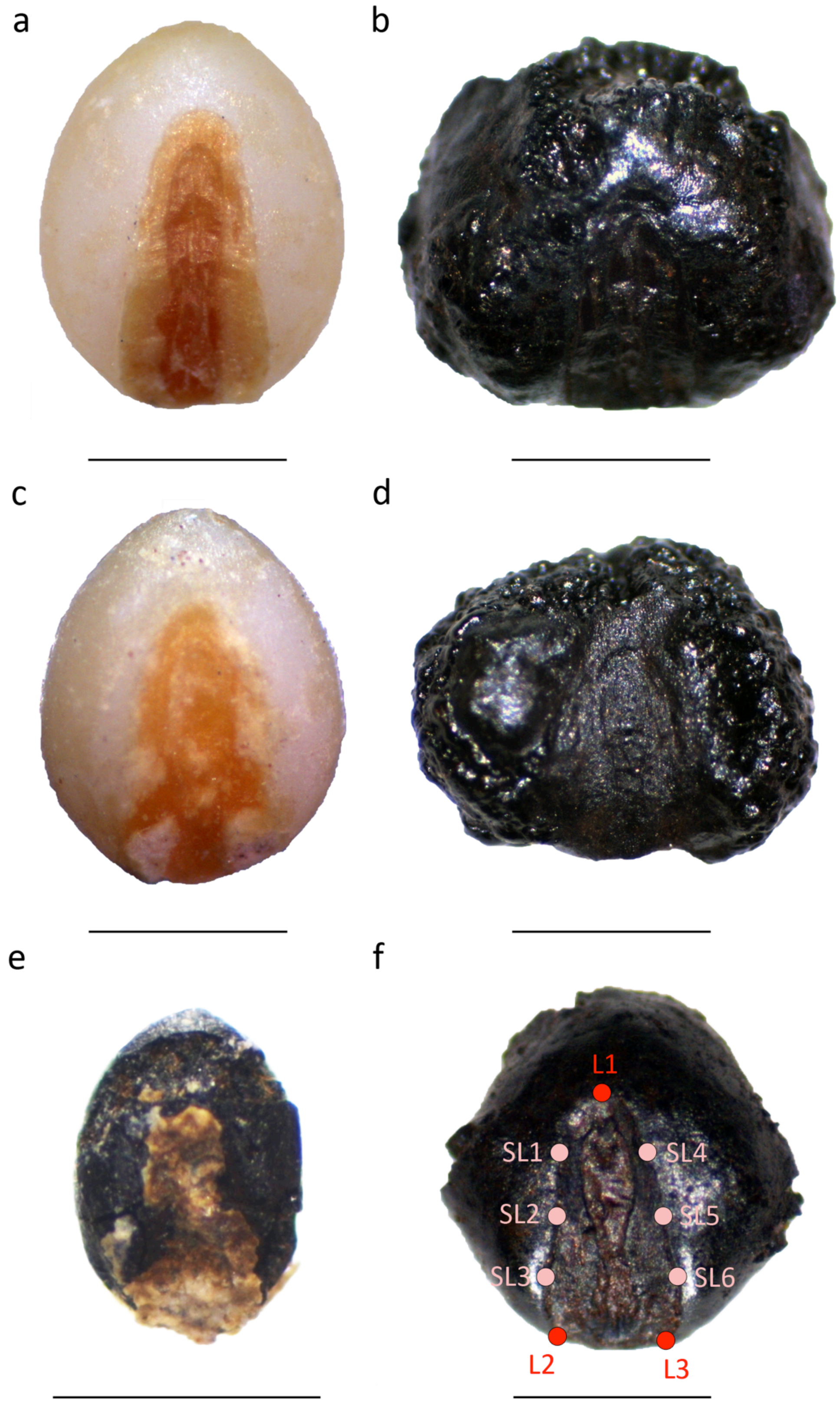

Figure 1. Modern *Setaria italica* caryopsis a) before and b) after charring at 250°C in reducing conditions for 3h, modern *Brachiaria ramosa* caryopsis c) before and d) after charring at 250°C in oxidising conditions for 3h, e) archaeological small millet from Shikarpur, and f) landmark configuration used in this study implemented on a modern *Setaria italica* caryopsis after charring at 250°C in totally anoxic conditions for 3h. Scale bars 1 mm.

Carbonisation

Previous charring experiments, carried out with *S. italica* and *Panicum miliaceum* L. (broomcorn millet), showed that small millets caryopses are usually deformed when carbonised, and that charring conditions (oxidising/reducing, temperature, time) greatly affect their likelihood of preservation in the archaeological record (Märkle and Rösch 2008; Yang et al. 2011; Motuzaite-Matuzeviciute et al. 2012). After a series of charring experiments (Table 2), we determined the optimum carbonising conditions for *S. italica* and *B. ramosa* for this study; grains were individually wrapped in aluminium foil (ensuring totally anoxic conditions) and charred into a furnace for 3h at 250°C.

Table 2. Charring experiments with modern *Setaria italica* and *Brachiaria ramosa* caryopses.

Temp	Time	Condition	*Species*	Result
250 °C	3h	Oxidising	*S. italica*	Open crease
			B. ramosa	Deformed
250 °C	3h	Reducing	*S. italica*	Deformed
			B. ramosa	Deformed
200 °C	3h	Reducing	*S. italica*	Not charred
			B. ramosa	Not charred
200 °C	5h	Reducing	*S. italica*	Partly charred
			B. ramosa	Partly charred
200 °C	8h	Reducing	*S. italica*	Partly charred
			B. ramosa	Partly charred
250 °C	3h	Totally anoxic	*S. italica*	Charred
			B. ramosa	Charred

Data acquisition

Archaeological and modern caryopses (before and after charring) were photographed with a Leica EZ4D stereoscope. TPSdig software (Rohlf 2013) was used to scale the photographs and manually apply the landmark configuration designed for this study. In order to overcome the morphological bias caused by carbonisation on the overall grain shape, the landmark configuration focused on the shape of the embryo, less affected by charring (Fig. 1a-d). A total of nine homologous points were recorded (Fig. 1f, Table 3); L1 to L3 are anatomical, type II landmarks that further served as anchors for sliding the semilandmarks (SL1 to SL6). The use of semilandmarks enables the quantification of homologous curves and their analysis together with traditional landmarks (Gunz and Mitteroecker 2013). Semilandmark sliding was conducted using the approach of minimising the Procrustes distance, where each landmark separately slides on tangent lines to the respective curve (outline of the embryo). Sliding removes the effect of arbitrary placing by minimising the position of the semilandmarks respect to the average shape of the sample (Bookstein 1997; Gunz et al. 2005; Adams and Otárola-Castillo 2013; Gunz and Mitteroecker 2013). Semilandmark sliding was computed in the Geomorph package for geometric morphometric analyses (Adams and Otárola-Castillo 2013) developed for R (R Development Core Team 2008).

Table 3. Description of the landmark configuration used in this study.

Name	Type	Description
L1	II	Maximum curvature point of the superior aspect of the embryo outline.
L2	II	Distal end of the left half of the embryo outline.
L3	II	Distal end of the right half of the embryo outline.
SL1	III	Middle point between L1 and SL2.
SL2	III	Middle point between L1 and L2.
SL3	III	Middle point between L2 and SL2.
SL4	III	Middle point between L1 and SL5.
SL5	III	Middle point between L1 and L3.
SL6	III	Middle point between L3 and SL5.

Data analysis

The statistical analyses were carried out in MorphoJ (Klingenberg 2011). A General Procrustes Analysis (GPA) was conducted to perform the superimposition in which the landmark configuration of each individual was rotated, translated to an origin point and scaled to unit of centroid size (CS) using the criterion of minimising the sum of square differences among configurations (Rohlf 1999; Zelditch et al. 2012). The coordinates were afterwards projected onto the tangent space to allow flat-space (Euclidean) statistical implementation. A permutation test of 1000 replicates was performed using both Procrustes and Mahalanobis distances to test for significant differences between groups for charred and uncharred modern caryopses (Klingenberg 2011).

Principal Components Analysis (PCA) was used to ordinate the Procrustes aligned coordinates, reducing the multidimensional data to a set of eigenvectors according to the accumulation of maximum variability criteria in each vector. A PCA was conducted on the modern uncharred caryopses, and the distribution of the sample was explored by plotting the first against the second PC. A second PCA was conducted after charring the caryopses. Finally, a PCA of the charred modern and archaeological caryopses was conducted in order to assess the morphological affinities of the latter group.

We conducted a Discriminant Analysis on the Procrustes coordinates using SPSS v.20 (Chigaco, IL). The modern charred caryopses were given an *a priori* group ascription while leaving the archaeological ones ungrouped. Thus, the archaeological specimens were classified by the analysis based on classification probabilities –in turn, derived on the basis of Mahalanobis square distances, D^2. Only those discriminant functions with a significant Wilk's lambda were employed. The performance of the analysis for discriminating among extant taxa was assessed on the basis of cross-validation percentages.

Results

Uncharred caryopses

The PCA yielded 14 Principal Components explaining 100% of the variance (Table 4). PC1 (explaining 63.77% of the variance) reflects the differentiation between the two groups, with *B. ramosa* falling towards the positive end of the axis, and *S. italica* towards the negative (Fig. 2a). There is overlapping between the two groups around the zero value of the axis. As shown by the vectors of shape changes towards the positive end of PC1, *B. ramosa* is characterised by having a wider embryo in its lower half than its upper half, resembling an arch, also being superior-inferiorly short; whereas *S. italica* is characterised by having an overall longer and narrower embryo, with a characteristic constriction in the middle (semilandmarks SL2 and SL5).

Table 4. Eigenvalues, percentage of variance and cumulative variance of the three Principal Components Analyses (PCAs) carried out in this study.

PC	**Uncharred**			**Charred**			**Charred + archaeological**		
	Eigenvalues	**% var.**	**Cum. %**	**Eigenvalues**	**% var.**	**Cum. %**	**Eigenvalues**	**% var.**	**Cum. %**
1	0.00370470	63.766	63.766	0.00261405	47.038	47.038	0.00498793	60.662	60.662
2	0.00105075	18.086	81.852	0.00149298	26.865	73.903	0.00157559	19.162	79.824
3	0.00033114	5.700	87.552	0.00044198	7.953	81.856	0.00049454	6.014	85.839
4	0.00024287	4.180	91.732	0.00035642	6.414	88.269	0.00036641	4.456	90.295
5	0.00017502	3.013	94.745	0.00019803	3.563	91.832	0.00024044	2.924	93.219
6	0.00012142	2.090	96.835	0.00015238	2.742	94.574	0.00021889	2.662	95.881
7	0.00006587	1.134	97.968	0.00013457	2.421	96.996	0.00015176	1.846	97.727
8	0.00006116	1.053	99.021	0.00008657	1.558	98.553	0.00009854	1.198	98.925
9	0.00003521	0.606	99.627	0.00004953	0.891	99.445	0.00004803	0.584	99.509
10	0.00001187	0.204	99.831	0.00001816	0.327	99.771	0.00002641	0.321	99.831
11	0.00000661	0.114	99.945	0.00000724	0.130	99.902	0.00000732	0.089	99.920
12	0.00000159	0.027	99.973	0.00000285	0.051	99.953	0.00000313	0.038	99.958
13	0.00000120	0.021	99.993	0.00000178	0.032	99.985	0.00000229	0.028	99.986
14	0.00000040	0.007	100.000	0.00000084	0.015	100.000	0.00000117	0.014	100.000

The second Principal Component (PC2) explains 18.09% of the variance and does not portray group differentiation, with both *B. ramosa* and *S. italica* broadly overlapping. Shape changes are mainly driven by the differential position of the endpoint landmarks of the configuration (L2 and L3), being positioned closer together towards the negative end of the axis and exhibiting the contrary feature towards the positive end of the axis (Fig. 2a). PC3 to PC14 explained <10% of the variance, not reflecting differences between the two groups (Table 4).

The results from the permute test show significant pairwise differences ($p \leq 0.05$) between uncharred caryopses of *S. italica* and *B. ramosa* for both the Mahalanobis and the Procrustes distances (Table 5).

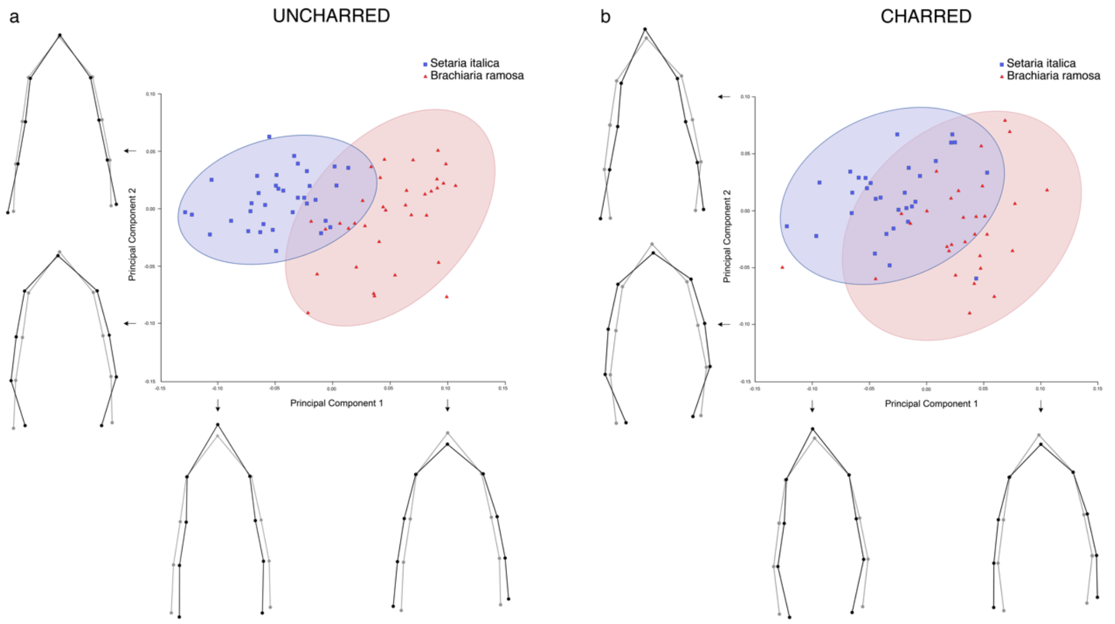

Figure 2. PC1 and PC2 scatterplots of the Principal Components Analyses (PCAs) of modern *Setaria italica* and *Brachiaria ramosa* caryopses before (a) and after (b) charring. Grey outlines represent the main shape (0.00/0.00) of the scatterplot and black outlines represent the shape changes at the extremes of each Principal Component.

Table 5. Results of the permutation test of 1000 replicates with Procrustes and Mahalanobis distances between groups for modern *Setaria italica* and *Brachiaria ramosa* caryopses before and after charring.

	Uncharred	**Charred**
Procrustes distance	0.09914316	0.06670446
Significance	<0.001	<0.001
Mahalanobis distance	4.0854	2.6807
Significance	<0.001	<0.001

Charred caryopses

The PCA yielded 14 Principal Components explaining 100% of the variance (Table 4). PC1 (explaining 74.04% of the variance) also reflects the differentiation between the two groups –*B. ramosa* towards the positive end and *S. italica* towards the positive–, although there is a more visible overlap (Fig. 2b). PC2 explained the 26.86% of the variance, not reflecting group differentiation, and PC3 to PC14 explained <10% of variance (Table 4). The vectors of shape change (for both PC1 and PC2) are virtually the same than those of the previous PC analysis, with the particularity that towards the negative end of the PC1 axis L2 and L3 are brought closer together by charring – narrowing the embryo on its lower end (Fig. 2b).

The results from the permute test shows significant pairwise differences ($p \leq 0.05$) between charred caryopses of *S. italica* and *B. ramosa* for both the Mahalanobis and the Procrustes distances (Table 5).

Charred and archaeological caryopses

The PCA yielded 14 Principal Components explaining 100% of the variance. PC1 (explaining 60.66% of the variance) reflects the group differentiation between *S. italica* (negative end) and *B. ramosa* (positive end) (Fig. 3). The archaeological caryopses have a broad distribution, mostly overlapping with *B. ramosa* or occupying a more negative position on the axis (outside the distribution of *B. ramosa*); however, three seeds are located in the overlapping zone between *B. ramosa* and *S. italica*, around the zero value of the axis. PC2 explained 19.16% of the variance, not portraying group differentiation, and the remaining PCs explained less than 10% of variance (Table 4).

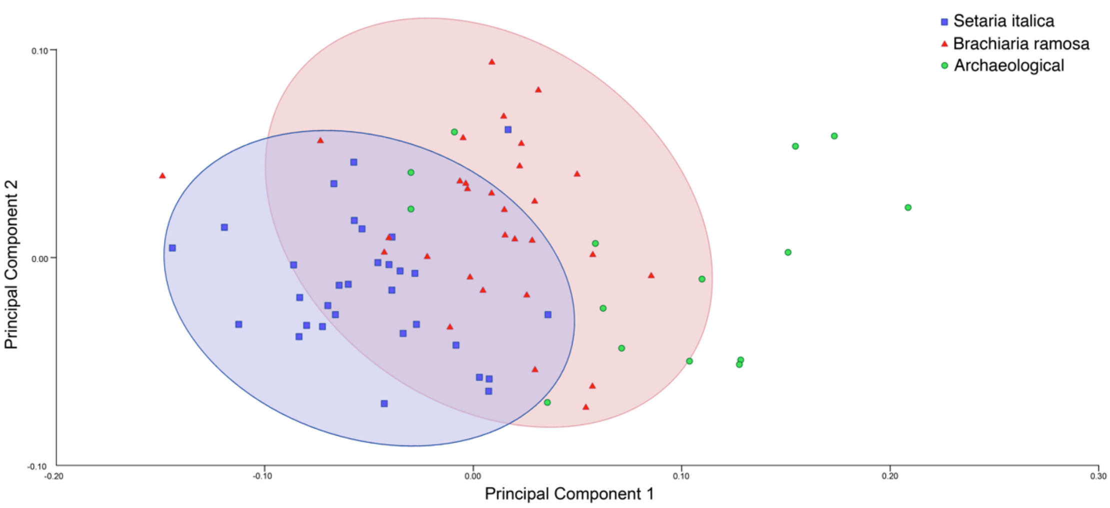

Figure 3. PC1 and PC2 scatterplot of the Principal Components Analysis (PCA) of charred modern *Setaria italica* and *Brachiaria ramosa* caryopses and archaeological specimens.

The Discriminant Analysis (Table 6) yielded one discriminant function, significant at $p \leq 0.05$, which provides a fairly good discrimination among the modern charred caryopses: 90.2% of the original cases are correctly classified, and 78.7% when cross-validation is employed. Based on Mahalanobis distances from modern group centroids, the analysis classified 14 of the archaeological specimens as *B. ramosa* and one individual as *S. italica*.

Table 6. Results of the Discriminant Analysis on the Procrustes coordinates of charred modern *Setaria italica* and *Brachiaria ramosa* caryopses and archaeological specimens.

Specimen	1st group	D^2	2nd group	D^2
Archaeological #1	*S. italica*	0.278	*B. ramosa*	10.292
Archaeological #2	*B. ramosa*	1.153	*S. italica*	14.099
Archaeological #3	*B. ramosa*	1.89	*S. italica*	16.45
Archaeological #4	*B. ramosa*	1.733	*S. italica*	1.863
Archaeological #5	*B. ramosa*	0.379	*S. italica*	4.266
Archaeological #6	*B. ramosa*	7.523	*S. italica*	29.418
Archaeological #7	*B. ramosa*	0.293	*S. italica*	4.58
Archaeological #8	*B. ramosa*	0.186	*S. italica*	5.064

Specimen	1st group	D^2	2nd group	D^2
Archaeological #9	*B. ramosa*	15.997	*S. italica*	44.632
Archaeological #10	*B. ramosa*	14.689	*S. italica*	42.428
Archaeological #11	*B. ramosa*	0.077	*S. italica*	8.756
Archaeological #12	*B. ramosa*	0.352	*S. italica*	10.72
Archaeological #13	*B. ramosa*	0.247	*S. italica*	4.77
Archaeological #14	*B. ramosa*	25.408	*S. italica*	59.624
Archaeological #15	*B. ramosa*	1.189	*S. italica*	2.53

Discussion

The results show that the shape of the embryo of *S. italica* and *B. ramosa* can be clearly distinguished using a geometric morphometric approach, both before and after charring. However, charring tends to smooth the shape differences between the two groups. This is particularly relevant when dealing with archaeobotanical assemblages, and further reinforces the need for a geometric morphometric approach when analysing subtle shape changes.

The only archaeobotanical specimen classified as *S. italica* by the Discriminant Analysis falls within the variation of charred *B. ramosa* in the PCA (Fig. 3), suggesting that all the archaeological seeds belong to *B. ramosa* and that *S. italica* was not present at Shikarpur during the fourth millennium BC. These results are in agreement with archaeobotanical data from Shikarpur (mineralised *B. ramosa* inflorescences; García-Granero et al. 2015) and neighbouring Bagasra (Luddy 2008), and support Fuller's (2002, 2003, 2006) hypothesis about the dispersion of *S. italica* in South Asia during the fourth millennium BP.

Several archaeological specimens were classified outside the variability of both *S. italica* and *B. ramosa* (Fig. 3), suggesting that the archaeobotanical assemblage from Shikarpur may be composed of other SEB type small millets, such as *Setaria pumila* (Poir.) Roem. and Schult. (yellow foxtail) and *Setaria verticillata* (L.) P.Beauv. (bristly foxtail). These autochthonous small millets have been identified in earlier occupations in northern Gujarat, indicating that these species, together with *B. ramosa* and *Panicum sumatrense* Roth (little millet), were domesticated in this region (García-Granero et al. in press).

Distinguishing among archaeological small millet charred caryopses is mandatory to understand the biographical history of these critical crops in arid and semi-arid regions worldwide. Traditional archaeobotanical methods have failed to securely identify some small millet species due to their fragility and their overlapping morphological features. When compared to traditional methods, the geometric morphometric approach presented in this paper has several advantages:

a) it enables an objective, quantitative approach for the analysis of shape change;
b) it can be applied when the overall morphology of the caryopsis has been deformed during the charring process; and
c) it can be applied on old imagery, even when the original seeds are no longer available for analysis.

Future work will include the geometric morphometric analysis of other *Setaria* spp. native to South Asia and the putative wild ancestor of *S. italica*, *S. viridis*. Moreover, the analysis of more archaeological specimens from northwestern South Asia and other regions of Eurasia will allow for the understanding of the biographical history of *S. italica*, including the existence of alternative domestication centres and its time and route of dispersion.

Acknowledgments

We thank the members of the Department of Archaeology and Ancient History of the M. S. University of Baroda (India) for their help during fieldwork at Shikarpur and to the Archaeological Survey of India for granting excavation permission. This work was supported by the Spanish Ministry of Economy and Competitiveness (Programa I+D, HAR2010-16052), the Spanish National Research Council and the European Social Fund (JAE-Predoc PhD grant to J.J.G.G). and the University of Barcelona (APIF PhD grant to J.A.M.).

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Dear Dr. García-Granero,

Thank you for your revised manuscript, "Millets and herders: the origins of plant cultivation in semi-arid North Gujarat (India)". This version is clearer and more tightly organized. I appreciate your efforts to address the specific concerns of the reviewers, particularly the matters of the level of detail and the intentionality. It benefits greatly from the reorganization and the clarifications and notes. I am delighted to accept it for publication in Current Anthropology.

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Millets and herders: the origins of plant cultivation in semi-arid North Gujarat (India)

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Paper submitted to Current Anthropology on 11 November 2014, accepted for publication on 16 April 2015

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Abstract

Botanical evidence suggests that North Gujarat (India) was a primary centre of plant domestication during the mid-Holocene. However, lack of systematic archaeobotanical research and significant taphonomic processes have so far hampered the possibility of substantiating this hypothesis. This paper explores the role of plants in the subsistence strategies of early-middle Holocene populations in this semi-arid region and the processes leading to plant cultivation. To do so, we carry out a multi-proxy archaeobotanical study –integrating macro and microbotanical remains– at two hunter-gatherer and agro-pastoral occupations. The results show that the progressive weakening of the Indian Summer Monsoon ca. 7000 years ago compelled human populations to adopt semi-nomadic pastoralism and plant cultivation, which resulted in the domestication of several small millet species, pulses and sesame.

Keywords: archaeobotany; multi-proxy; cultivation; plant domestication; millets; pulses; sesame; pastoralism; South Asia

Introduction

Understanding how human societies adapted to environmental and climatic variability in the past is fundamental to face present and future climatic events, particularly in highly vulnerable arid and semi-arid regions (Brooks et al. 2009; Costanza et al. 2007). Archaeological research in marginal areas has revealed how humans reacted to changing ecological conditions by integrating short-term coping mechanisms and long-term adaptive strategies such as innovation, enhanced social networks, increased mobility and, ultimately, migration (e.g. An et al. 2005; Dillehay and Kolata 2004; Kuper and Kröpelin 2006; Rosen and Rivera-Collazo 2012; Spielmann et al. 2011).

North Gujarat (northwestern India) is a semi-arid ecotone (400-600 mm of annual precipitation) between the Thar Desert and the semi-humid South Gujarat (Fig. 1). The region is characterised by a strong seasonality –Indian Summer Monsoon regime, in which most of the rainfall occurs between June and September–, as well as a high variability in inter-annual precipitation (Balbo et al. 2014a), and it is prone to both severe droughts and floods every few years (Parthasarathy et al. 1987).

North Gujarat can be divided in four physiographical units: the uplands (Aravalli Hills), the silt belt, the dune-interdune area and the Little Rann of Kachchh (Balbo et al. 2013; Conesa et al. 2014a). Archaeological evidence is mostly found in the dune-interdune area, which is characterised by stabilised dunes from the retreat of the Thar Desert ca. 7000 years ago (Balbo et al. 2013 and references therein). Interdunal depressions accumulate monsoon rainwater and retain high moisture levels for a good part of the year, offering water to pastoral and agricultural activities. The major agricultural season in North Gujarat is the summer *kharif*, which involves sowing with the first monsoonal rains (June-July) and harvesting in October-November (Reddy 1997). Winter *rabi* cultivation (crops grown between November and April) occurs only with the aid of modern irrigation, although dry farming is possible in some interdunal depressions (Bhan 1994).

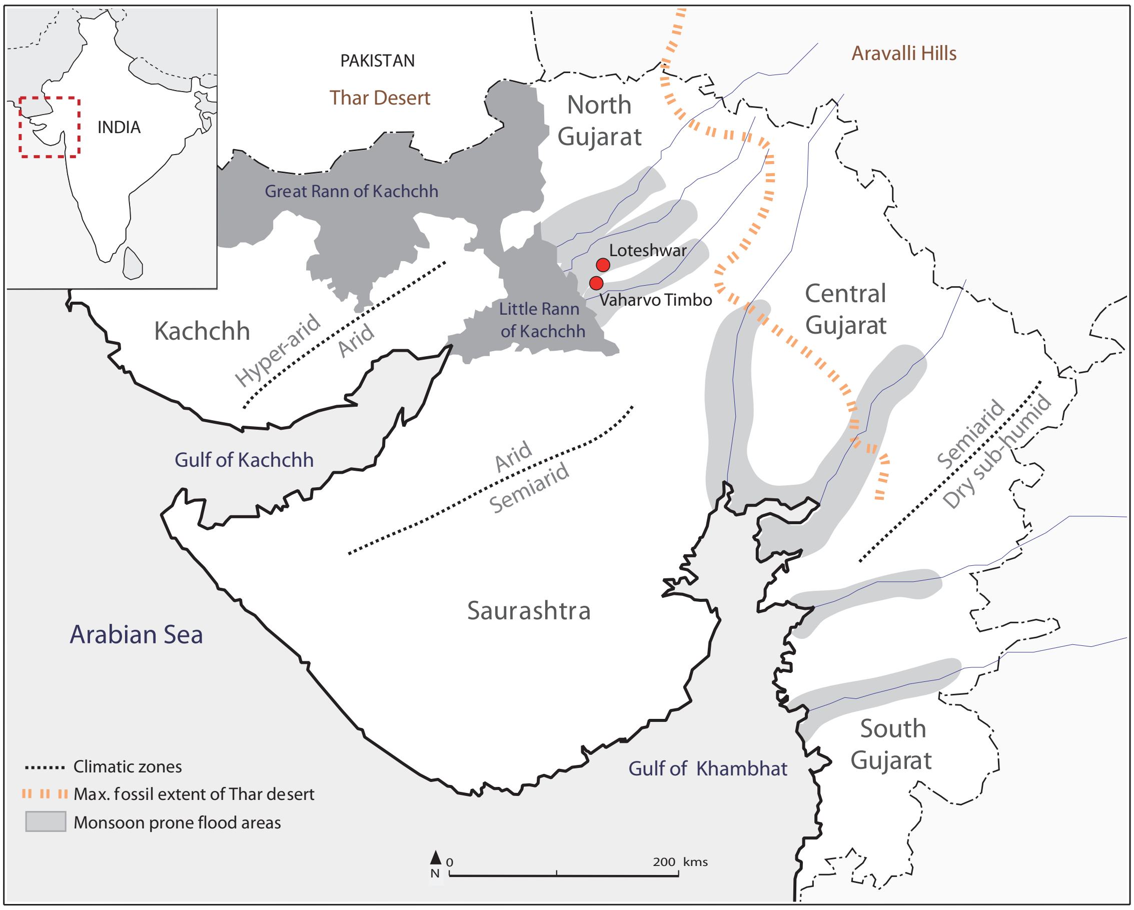

Figure 1. Map of North Gujarat, showing climatic zones, the maximum fossil extent of the Thar Deset, monsoon prone flood areas and the location of Loteshwar and Vaharvo Timbo. Image by Francesc C. Conesa.

During the early and middle Holocene, hunter-gatherer and agro-pastoral communities occupied North Gujarat. Hunter-gatherer occupations are characterised by the presence of a microlithic industry and the absence of ceramics, and are often called 'Mesolithic' (e.g. Sankalia 1987) or 'Microlithic' (Patel 2009) in the literature. Over two decades ago scholars identified the existence of autochthonous food-producing communities in North Gujarat and Kachchh dating to the mid fourth millennium BC (Ajithprasad 2002; Ajithprasad and Sonawane 2011; Patel 2009; Possehl 1992; Sonawane and Ajithprasad 1994). This cultural tradition, mainly defined by a distinctive pottery assemblage, was named 'Anarta' after the traditional name of North Gujarat. The importance of pastoral activities for Anarta communities seems clear (Ajithprasad and Sonawane 2011 and references therein); however, the role of plant resources in their subsistence strategies remains poorly understood (Sonawane 2000: 143). During the mid third millennium BC a series of walled urban settlements with characteristic Harappan material culture from the Indus Civilisation (northwest South Asia) appear along trade and travel corridors throughout Gujarat (Chase et al. 2014). Archaeobotanical research at Harappan (ca. 2500-1700 BC) settlements in Saurashtra (e.g. Reddy 1997; Weber 1999) shows an agricultural system based on native small millets and tropical pulses, as opposed to the Near Eastern crop package characteristic of the core Indus Valley (Fuller and Madella 2002).

The aim of this paper is to explore the role of plants in the subsistence strategies of pre-Harappan populations in North Gujarat, with a focus on testing Fuller's (2006) hypothesis on the origins of cultivation in this semi-arid region. To do so, we discuss the results of a multi-proxy study –integrating macro and microbotanical remains– from two early-middle Holocene occupations: Loteshwar, the most thoroughly investigated Mesolithic and Anarta site, and the near-by hunter-gatherer occupation of Vaharvo Timbo.

Case study

Loteshwar (23° 36'1.8″ N; 71° 50'11.8″ E), locally known as Khari no Timbo, is located about 500 m east of the Khari River (Fig. 1). The excavation conducted by the Department of Archaeology and Ancient History of the M.S. University of Baroda (MSUB, India) in the early 1990s uncovered two occupational levels: a Mesolithic hunter-gatherer occupation with superimposed Anarta Chalcolithic deposits (IAR 1995a). A series of AMS ^{14}C determinations (Ajithprasad 2002, 2004; Patel 2009; Sonawane and Ajithprasad 1994) place Loteshwar as one of the earliest Holocene hunter-gatherer occupations in northwestern India (7168 to 4703 cal BC). The Anarta occupation of the dune (3681 to 2243 cal BC) predates the establishment of Urban Harappan communities in Gujarat (Ajithprasad and Sonawane 2011). Furthermore, the study of faunal remains (Patel 2009) suggested that North Gujarat had the potential for local domestication of *Bos taurus* ssp. *indicus* (zebu).

The North Gujarat Archaeological Project (NoGAP), a collaboration between the MSUB and the IMF-CSIC (Spain) (Madella et al. 2010), excavated a 4x4 m trench at Loteshwar in 2009. The stratigraphic sequence uncovered features comparable to those identified in the previous excavations: an aceramic hunter-gatherer (Mesolithic) occupation of about 80 cm and an Anarta deposit of about 60 cm (Madella et al. 2011), separated by a mixed level of ca. 40 cm with a few, small potsherds. The hunter-gatherer and the mixed levels were cut by three Anarta pits down to 50/170 cm, with a lining of plant material preserved as pure phytoliths (Balbo et al. 2014b).

Vaharvo Timbo (23° 33'17.05" N; 71° 48'12.01" E) lies 6 km southwest of Loteshwar (Fig. 1). The site, reported in the early 1980s as Wasaro no Timbo (Bhan 1994, Appendix), was excavated by the NoGAP team in 2011. Two 4x4 m trenches were opened (Madella et al. 2012): Trench I had a uniform aceramic hunter-gatherer occupation of ca. 100 cm with three pits of different size and shape down to about 135 cm; Trench II had also an aceramic deposit cut by a human burial. The grave goods of the burial included two full Early Harappan Sindh pots (ca. 2800-2600 BC, Ajithprasad 2011).

The archaeological deposits uncovered by the NoGAP excavations at Loteshwar and Vaharvo Timbo were AMS dated (Table 1). At Loteshwar, the dates show a shorter Anarta occupation of the dune (ca. 2700-2300 cal BC) in respect to the deposits from the previous excavations (ca. 3700–2250 cal BC). The Mesolithic and mixed levels were also dated ca. 2700-2300 cal BC, suggesting that there was a post-depositional infiltration (or mixing as suggested in the mixed level) of wood charcoal from the uppermost Anarta deposits. The dates from Trench I at Vaharvo Timbo (ca. 5600-5000 cal BC) show a relatively long hunter-gatherer occupation of the dune, contemporaneous with the end of the hunter-gatherer occupation at Loteshwar (Ajithprasad 2004; Patel 2009; Sonawane and Ajithprasad 1994).

Materials and Methods

A systematic sampling strategy for the recovery of macro (seeds and charred wood) and microbotanical (phytoliths and starch grains) remains was carried out for the entire stratigraphic sequences of the sites (Tables 1 and 2). Bulk samples were collected from each excavation spit (ca. 10 cm) on a 2x2 m grid and macroremains recovered by bucket flotation with a 0.25 mm mesh. Sediment samples (ca. 50 g) were separated prior to flotation for microbotanical and soil pH analyses. All macroremains in the fraction >0.5 mm were sorted using a Leica EZ4 D stereoscope. Microremains from sediments and grinding tools were extracted following the protocols described in García-Granero et al. (2015, submitted) and observed at 200x and 630x magnifications with a Leica DM 2500 microscope equipped with a Leica DF 470 camera for microphotography.

When possible, 300 identifiable single-cell phytoliths were counted and in samples with very low phytolith presence the whole slide was scanned. Multi-cell phytoliths (silica skeletons) were counted independently and photographed. Phytolith concentration was calculated per g of AIF (Acid Insoluble Fraction) according to Albert and Weiner (2001), whereas starch concentration was calculated per g of processed sediment. Phytoliths were described using the International Code for Phytoliths Nomenclature (ICPN – Madella et al. 2005) and starch grains according to the International Code for Starch Nomenclature (ICSN 2011). Taxonomical identification of all plant remains relied on the plant reference collection of the BioGeoPal Laboratory (CaSEs, Barcelona) and seed atlases (Cappers and Bekker 2013; Cappers et al. 2009; Neef et al. 2012).

Soil pH was measured using a Combo pH & EC HI98129 by HANNA® instruments to understand how soil acidity/alkalinity might have affected the preservation of plant remains.

Table 1. Sediment samples analysed in this study and radiocarbon estimations. Radiocarbon estimations from Loteshwar were provided by the Centro Nacional de Aceleradores, Sevilla, Spain. Radicarbon estimations from Vaharvo Timbo were provided by Beta Analytics.

Site	ID	Period	Description	Dated material	^{14}C-age (yr BP)	2-σ cal. age (yr BC)	Lab code
LTS	Dep 1	Anarta	General deposit	Wood charcoal	3975 ± 35	2577-2438	2219.1.1
LTS	Dep 2	Mixed	General deposit	Wood charcoal	3915 ± 35	2487-2290	2221.1.1
LTS	Dep 3	Mesolithic	General deposit	Wood charcoal	4075 ± 35	2701-2557	2223.1.1
LTS	Pit 1	Anarta	SE pit	-	-	-	-
LTS	Pit 2	Anarta	NE pit	-	-	-	-
LTS	Pit 3	Anarta	NW pit	Wood charcoal	3925 ± 35	2491-2295	2225.1.1
LTS	Ash 1	Anarta	NE ashy patch	Wood charcoal	4055 ± 35	2678-2475	2220.1.1
LTS	Ash 2	Anarta	NW ashy patch	-	-	-	-
VHV	Dep 1	Mesolithic	General deposit	-	-	-	-
VHV	Dep 2	Mesolithic	General deposit	Charred bone	6160 ± 40	5220-5000	Beta-366711
VHV	Dep 3	Mesolithic	General deposit	-	-	-	-
VHV	Dep 4	Mesolithic	General deposit	-	-	-	-
VHV	Pit S	Mesolithic	S pit	Charred bone	6290 ± 40	5320-5210	Beta-366709
VHV	Pit N1	Mesolithic	N pit, upper part	-	-	-	-
VHV	Pit N2	Mesolithic	N pit, lower part	Charred bone	6650 ± 40	5640-5510	Beta-366710

Table 2. Grinding stones analysed in this study. Descriptive terms after Wright (1992).

Site	ID	Description	Context
LTS	GS 1a	Frag. bifacial discoidal/lens handstone, face a	Dep 1
LTS	GS 1b	Frag. bifacial discoidal/lens handstone, face b	Dep 1
LTS	GS 2a	Half bifacial ovate/oval handstone, face a	Dep 1
LTS	GS 2b	Half bifacial ovate/oval handstone, face b	Dep 1
LTS	GS 3a	Frag. bifacial handstone, face a	Dep 1
LTS	GS 3b	Frag. bifacial handstone, face b	Dep 1
LTS	GS 4	Frag. basin grinding slab	Pit 1
LTS	GS 5	Frag. saddle-shaped grinding slab	Dep 3
LTS	GS 6a	Broken handstone, used as grinding slab	Pit 3
LTS	GS 6b	Unifacial ovate handstone	Pit 3
LTS	GS 7a	Half basin grinding slab, face a (not used?)	Dep 2
LTS	GS 7b	Half basin grinding slab, face b	Dep 2
LTS	GS 8	Half basin grinding slab	Dep 2
LTS	GS 9	Half bifacial ovate/oval handstone	Dep 2
LTS	GS 10	Half unifacial rectilinear handstone	Dep 2
LTS	GS 11	Half unifacial ovate handstone	Dep 3
LTS	GS 12a	Frag. bifacial rectilinear/flat handstone, face a	Dep 3
LTS	GS 12b	Frag. bifacial rectilinear/flat handstone, face b	Dep 3
LTS	GS 13	Frag. basin grinding slab	Dep 3
VHV	GS 1	Frag. basin grinding slab	Dep 1
VHV	GS 2	Frag. unifacial rectilinear handstone	Dep 1
VHV	GS 3	Frag. basin grinding slab	Dep 1
VHV	GS 4	Frag. basin grinding slab	Dep 1

Site	ID	Description	Context
VHV	GS 5	Half unifacial ovate handstone	Dep 1
VHV	GS 6	Frag. basin grinding slab	Dep 2
VHV	GS 7	Frag. basin grinding slab	Dep 2
VHV	GS 8	Frag. basin grinding slab	Dep 1
VHV	GS 9	Frag. unifacial rectilinear handstone	Dep 2
VHV	GS 10	Frag. unifacial rectilinear handstone	Dep 2
VHV	GS 11	Frag. basin grinding slab	Dep 2
VHV	GS 12	Frag. basin grinding slab	Dep 2
VHV	GS 13	Frag. unifacial rectilinear handstone	Dep 2
VHV	GS 14	Frag. unifacial rectilinear handstone	Dep 3
VHV	GS 15	Unifacial discoidal handstone	Dep 3
VHV	GS 16a	Frag. unifacial rectilinear handstone, frag. a	Dep 3
VHV	GS 16b	Frag. unifacial rectilinear handstone, frag. b	Dep 3
VHV	GS 17	Frag. basin grinding slab	Dep 3
VHV	GS 18	Frag. basin grinding slab	Dep 4
VHV	GS 19	Frag. unifacial rectilinear handstone	Dep 4

Results

Loteshwar

The majority of the recovered macrobotanical remains are from the Anarta contexts (Table 3, Fig. 2). The assemblage is dominated by charred caryopses of small millets, mostly *Setaria verticillata* (bristly foxtail) and *S. pumila* (yellow foxtail), including one yellow foxtail hulled caryopsis. Other taxa include cf. *Panicum sumatrense* (little millet), *Brachiaria ramosa* (browntop millet), *Digitaria* sp. and *Echinochloa* cf. *colona* (jungle rice). Due to their poor preservation, several grains were identified only at SEB group level (*Setaria*, *Echinochloa* and *Brachiaria*) or simply as undetermined small millets. Small millet inflorescences were also preserved mineralised, including *B. ramosa*, *P. sumatrense* and SEB type. A whole pseudocarp and fragments of mineralised *Coix lacryma-jobi* (Job's tears) were also found. Other grass remains included *Dactyloctenium aegyptium* (crowfoot grass) grains, several fragmented grains of C_3 cereals (including free-threshing wheat, identified as *Triticum* cf. *aestivum*, bread wheat), a *Triticum* sp. glume base and the involucre base of an unidentified grass. The macrobotanical assemblage also consisted of *Sesamum indicum* (sesame), *Papaver* sp. (poppy seed), a small *Macrotyloma uniflorum* seed (horsegram) and two taxa from the Solanaceae family: *Lycium* sp. and cf. *Solanum* sp. Finally, several unidentified species of sedges (Cyperaceae), parenchymatic tissue and weed taxa such as *Trianthema* spp. and *Chenopodium* sp. were also encountered.

Table 3. Results of the macrobotanical analyses from Loteshwar and Vaharvo Timbo.

	Loteshwar					**Vaharvo T.**				
Context	**Dep 1**	**Dep 2**	**Dep 3**	**Pit 1**	**Pit 3**	**Ash 2**	**Dep 1**	**Dep 2**	**Dep 3**	**Dep 4**
Sediment volume (l)	240	75	50	135	160	80	80	60	140	100
Aizoaceae										
Trianthema portulacastrum	6	.	.	2	.	2	.	.	.	.
Trianthema triquetra	2	.	.	.	.	.	.	.	.	.
Amaranthaceae										
Chenopodium sp.	11	1	.	1	16	18	.	.	.	.
Cyperaceae	9	1	2	10	5	2	.	.	.	.
Fabaceae										
Macrotyloma uniflorum	.	.	.	.	.	1	.	.	.	.
Papaveraceae										
Papaver sp.	1	.	.	1	1	1	.	.	.	.
Pedaliaceae										
Sesamum indicum	.	.	.	32	.	.	.	.	.	.
Sesamum cf. *malabaricum*	.	.	.	.	.	.	2	.	.	.
Poaceae										
Chloridoideae										
Dactyloctenium aegyptium caryopsis	3	1	.	.	1	2	.	.	.	.
cf. *D. aegyptium* inflorescence	.	.	.	.	.	.	1	.	.	.
Panicoideae										
Brachiaria ramosa caryopsis	1	.	.	.	.	.	.	.	.	.
B. ramosa mineralised inflorescence	6	.	1	.	2	.	.	.	.	.
B. ramosa mineralised lemma	2	.	.	.	.	.	.	.	.	.
Coix lacryma-jobi pseudocarp	+	+	+	>1	+	+	.	.	.	.
Digitaria sp. caryopsis	1	.	.	.	.	.	1	.	.	.
Echinochloa cf. *colona* caryopsis	1	.	.	.	.	.	.	.	.	.
cf. *Panicum sumatrense* caryopsis	2	1	.	1	.	4	.	.	.	.
P. sumatrense mineralised lemma	.	.	.	.	.	1	.	.	.	.
Setaria pumila caryopsis	8	.	.	.	1	3	.	.	.	.
S. pumila caryopsis (hulled)	.	.	.	.	.	1	.	.	.	.
Setaria verticillata caryopsis	9	2	.	8	2	10	.	.	.	.
SEB type caryopsis	7	.	.	.	.	7	.	.	.	.
SEB type mineralised inflorescence	3	1	.	1	1	1	.	.	.	.
small millet undet. caryopsis	1	1	.	1	2	2	.	.	.	.
Pooideae										
Triticum cf. *aestivum* caryopsis	.	.	.	1	.	.	.	.	.	.
Triticum sp. glume base	.	.	.	1	.	.	.	.	.	.
Cerealia undet. caryopsis	.	.	.	.	1	1	.	.	.	.
Poaceae undet. inflorescence	.	.	.	.	.	.	3	.	.	.
Poaceae undet. involucre base	.	1	.	.	.	.	.	.	.	.
Poaceae undet. glume	.	.	.	.	.	.	3	.	.	.
Poaceae undet. node	.	.	.	.	.	.	4	.	.	.
Poaceae undet. spikelet base	.	.	.	.	.	.	27	.	.	.
Solanaceae										
Lycium sp.	.	.	.	.	1	.	.	.	.	.
cf. *Solanum* sp.	4	1	.	4	1	1	.	.	.	.

	Loteshwar					Vaharvo T.				
Context	**Dep 1**	**Dep 2**	**Dep 3**	**Pit 1**	**Pit 3**	**Ash 2**	**Dep 1**	**Dep 2**	**Dep 3**	**Dep 4**
Parenchyma fragments	+	.	.	+	.	+	.	.	.	.

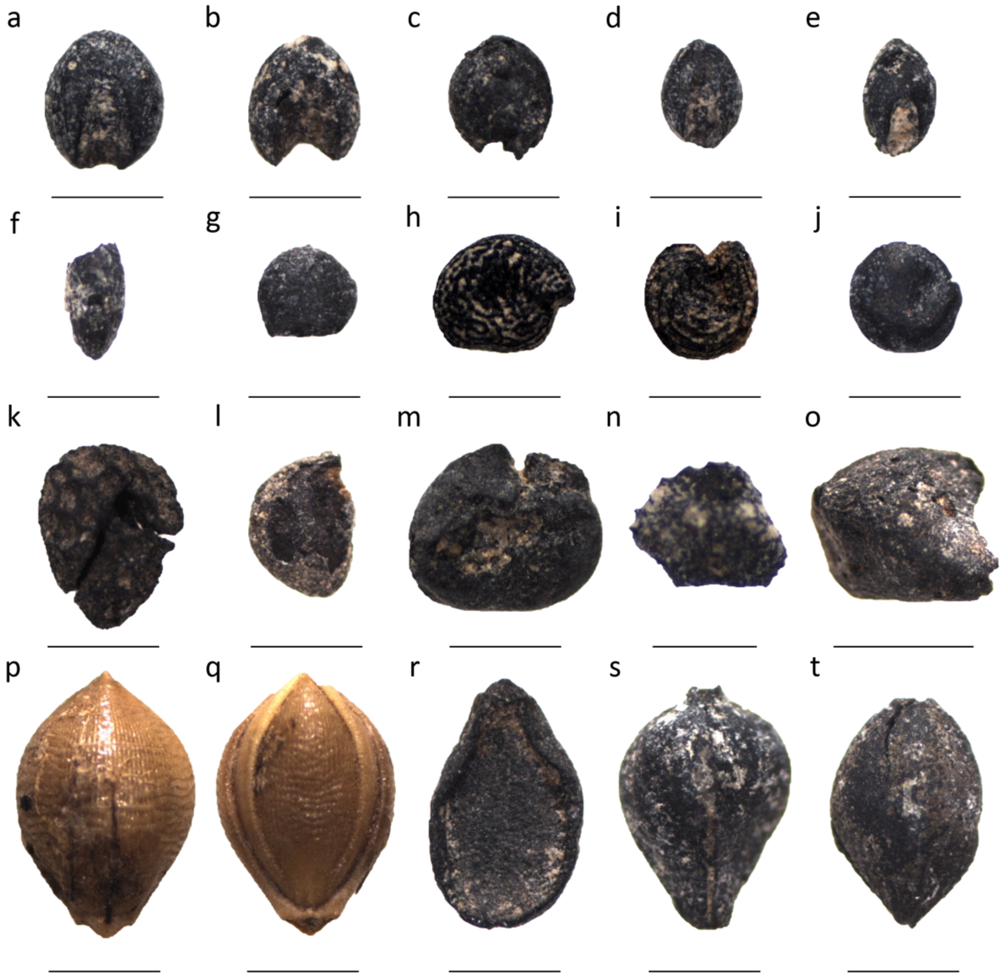

Figure 2. Macrobotanical remains recovered from Loteswar. a) charred *Brachiaria ramosa* caryopsis, b) charred *Setaria pumila* caryopsis, c) charred *Echinochloa* cf. *colona* caryopsis, d) charred *S. verticillata* caryopsis, e) charred cf. *Panicum sumatrense* caryopsis, f) charred *Digitaria* sp. caryopsis, g) charred cf. *Solanum* sp. seed, h) charred *Trianthema portulacastrum* seed, i) charred *T. triquetra* seed, j) charred *Chenopodium* sp. seed, k) charred *Papaver* sp. seed, l) charred *Lycium* sp. seed, m) charred *Macrotyloma uniflorum* seed, n) charred *Dactyloctenium aegyptium* caryopsis, o) half charred *Triticum* cf. *aestivum* caryopsis, p) dorsal and q) ventral view of a mineralised inflorescence of *B. ramosa*, r) charred *Sesamum indicum* seed, s-t) charred Cyperaceae seeds. Scale bars 1 mm in a-m and p-t, 0.5 mm in n, 2 mm in o.

Sediment samples had very high phytolith concentrations (Table 4) and a total of 154 silica skeletons, some of which showed characteristic threshing marks as described by Cummings (2007) (Fig. 3). Among the single cells, grass short cells had an interesting trend: in all Anarta samples panicoid morphotypes predominated, whereas samples from the mixed and Mesolithic levels showed more pooids. In all the samples leaf/culm morphotypes (elongate psilates and sinuates) were the main grass long cells. The single-cell assemblage further included dicotyledon types and tabular scrobiculated cones from sedge achenes. Finally, the assemblage had several undetermined taxa and unidentified phytoliths. The undetermined group includes phytoliths characteristic of several taxa (which cannot be securely assigned to a specific one) and phytoliths whose taxonomical or anatomical origin could not be determined. Unidentified phytoliths are weathered phytoliths without sufficient diagnostic traits for their identification.

Table 4. Results of phytolith, starch grain and soil pH analyses from sediment samples from Loteshwar and Vaharvo Timbo. Phytolith concentration is expressed in millions per g of AIF (Acid Insoluble Fraction). Starch concentration is expressed in grains per g of original sediment. - = sample not analysed.

	Loteshwar								**Vaharvo Timbo**						
	Dep 1	**Dep 2**	**Dep 3**	**Pit 1**	**Pit 2**	**Pit 3**	**Ash 1**	**Ash 2**	**Dep 1**	**Dep 2**	**Dep 3**	**Dep 4**	**Pit S**	**Pit N1**	**Pit N2**
Phytoliths															
Monocotyledons															
Arecaceae	.	.	.	.	.	.	.	.	1	-	-	-	.	-	.
Cyperaceae															
Silica skeletons (leaf)	.	.	.	.	1	.	.	.	.	-	-	-	.	-	.
Single cells (achene)	1	1	.	1	.	2	.	3	.	-	-	-	.	-	.
Poaceae															
Silica skeletons															
Inflorescence															
Panicoideae	.	.	.	1	.	.	.	.	.	-	-	-	.	-	.
Undetermined	2	5	9	6	5	3	5	2	1	-	-	-	.	-	.
Leaf/culm															
Chloridoideae	.	.	.	.	.	.	.	1	.	-	-	-	.	-	.
Panicoideae	.	.	.	2	2	.	1	.	.	-	-	-	.	-	.
Pooideae	.	.	.	.	1	.	.	.	.	-	-	-	.	-	.
Undetermined	12	5	47	9	10	3	9	7	1	-	-	-	.	-	.
Undetermined	.	1	.	1	.	1	.	1	.	-	-	-	.	-	.
Single cells															
Long cells															
Inflorescence	21	5	33	6	9	12	8	10	5	-	-	-	.	-	.
Leaf/culm	34	30	100	19	26	38	28	34	42	-	-	-	.	-	1
Indetermined	2	6	8	9	4	6	2	10	3	-	-	-	.	-	.
Bulliform (leaf)	3	9	2	2	1	5	1	2	7	-	-	-	.	-	2
Short cells															
Chloridoideae	43	51	24	35	40	40	56	69	4	-	-	-	1	-	.
Panicoideae	67	36	14	81	83	58	78	73	7	-	-	-	.	-	2
Pooideae	46	54	31	52	55	53	42	46	3	-	-	-	.	-	.
Undetermined	49	39	25	69	50	57	60	22	6	-	-	-	.	-	1
Dicotyledons	7	15	11	.	3	1	1	2	.	-	-	-	.	-	1
Undetermined taxa															
Silica skeletons	.	.	.	.	1	.	1	.	.	-	-	-	.	-	.

	Loteshwar								Vaharvo Timbo						
	Dep 1	**Dep 2**	**Dep 3**	**Pit 1**	**Pit 2**	**Pit 3**	**Ash 1**	**Ash 2**	**Dep 1**	**Dep 2**	**Dep 3**	**Dep 4**	**Pit S**	**Pit N1**	**Pit N2**
Single cells	33	53	51	23	28	31	22	32	65	-	-	-	3	-	4
Unidentified phytoliths	5	5	16	1	2	.	7	8	17	-	-	-	3	-	4
Total silica skeletons	14	11	56	19	20	7	16	11	2	-	-	-	.	-	.
Total cells in silica seletons	52	34	219	80	71	19	53	48	4	-	-	-	.	-	.
Total single cells	311	304	315	298	301	303	305	311	160	-	-	-	7	-	15
Phytolith concentration	6.3	.6	.7	12.6	15.1	3.9	23.1	6.8	0	-	-	-	0	-	0
Starch grains															
Fabaceae															
Faboideae	.	.	.	1	.	.	.	.	.	.	1	.	.	.	.
Poaceae															
Panicoideae															
Type 2 (10-20 µm)	.	1	1	.	.	1	1	.	1	.	.	2	3	1	1
Type 3 (>20 µm)	.	.	1	.	.	2	1	.	.	.	.	.	1	.	.
Pooideae															
Triticeae	.	.	1	.	2	.	1	.	.	1	1	.	.	1	.
cf Triticeae spherical	.	.	.	.	.	.	.	.	.	.	.	.	.	.	2
cf Triticeae bell-shaped	.	.	.	.	2	.	.	.	.	.	.	.	.	.	.
Solanaceae															
Solanum tuberosum	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.
Tuber undetermined 1	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.
Undetermined	.	.	.	.	.	.	.	.	.	2	.	.	.	.	.
Damaged unidentified	.	1	.	.	1	.	.	.	.	.	.	.	.	.	.
Total starch grains	.	2	3	1	5	3	3	.	1	3	2	3	4	3	3
Starch concentration	.	5	8	2	13	7	7	.	3	7	5	7	11	7	7
Soil pH	8.38	8.88	8.88	8.25	8.42	8.88	8.32	8.34	8.44	8.39	8.41	8.70	8.57	8.29	8.60

Phytolith samples from grinding stones had extremely variable concentrations (Table 5). A total of 114 grass silica skeletons were encountered, including eight from panicoid grasses. Only 10 samples –six from Anarta contexts, two from the mixed level and two from the Mesolithic deposit– had enough phytoliths (>100) to be discussed quantitatively. Leaf/culm morphotypes were again the main grass long cells in all the samples, and the pattern of grass short cell distribution observed in the sediment samples also occurred in the grinding stones.

Starch grains were scarce in sediment samples but abundant in grinding stones (Tables 4 and 5). There is no difference in the composition of starch assemblages between samples from the various levels. A total of eight morphotypes were identified (Fig. 4). The most common typology in all samples was the Panicoideae (Poaceae), divided into three sub-types according to size. Type 1 grains (3-10 µm) are characteristic of small millets, Type 3 (>20 µm) occur mostly in big millets and Type 2 (10-20 µm) are found in both groups (Madella et al. 2013 and references therein). Six spherical grains found on grinding stones and showing a linear hilum with lines radiating from the centre were attributed to cf. Panicoideae. Starch grains belonging to the Triticeae tribe (Pooideae, Poaceae) were also found: discoidal grains with a smooth surface and lamellae (Type A, Yang and Perry 2013), small spherical grains with a smooth surface and a small vacuole (Type B, Yang and Perry 2013), and bell-shaped grains with an eccentric, linear hilum. These last two morphotypes can occur in other taxa and were therefore grouped in cf. Triticeae. Other finds include ovoid grains with a smooth surface, lamellae and a linear hilum diagnostic of the Faboideae (Fabaceae). Six medium-sized (10-20 µm) ovoid grains with a smooth surface, a regular extinction cross and an eccentric small hilum, and one very large (>50 µm) tri-prismatic grain with a smooth surface, lamellae and a highly eccentric linear hilum could not be assigned to any specific taxonomic group but their morphology suggests an origin from underground storage organs (rhizomes/tubers). Finally, 61 starch grains could not be identified due to severe damage.

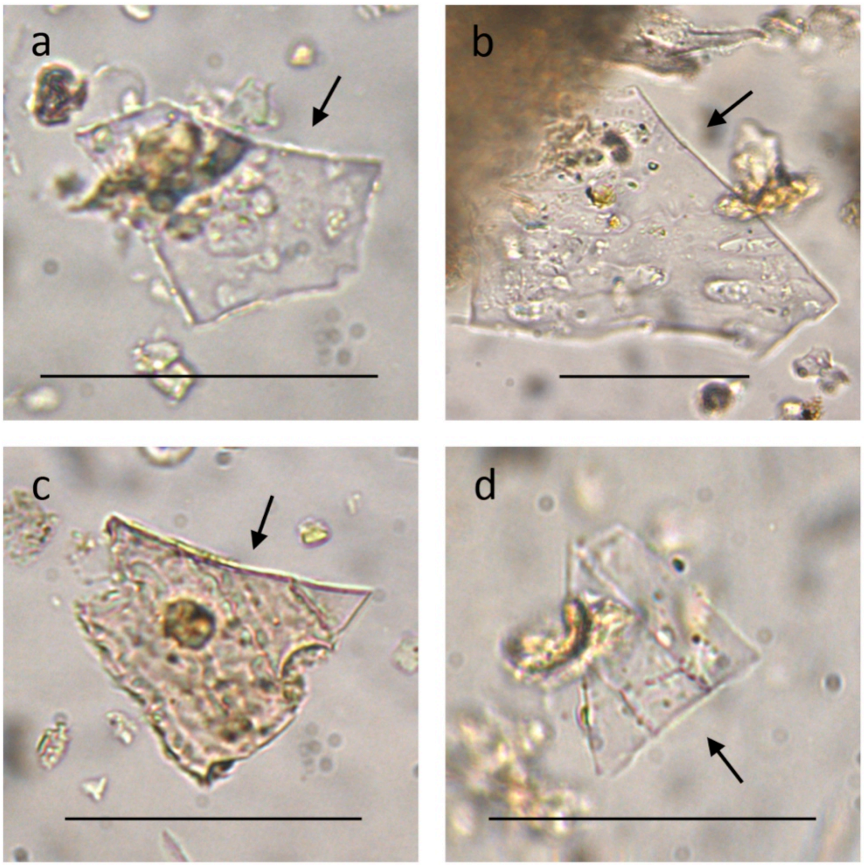

Figure 3. Silica skeletons with potential threshing sledge marks (marked with arrows) recovered from Loteshwar. a) *Panicum*/*Setaria*-type inflorescence, b) *Echinochloa*-type inflorescence and c-d) Poaceae leaf/culm. Scale bars 50 µm.

Table 5. Results of phytolith and starch grain analyses from grinding stones from Loteshwar. Phytolith concentration is
Insoluble Fraction). Starch grain concentration is expressed in thousands per g of original sediment.

	GS 1a	**GS 1b**	**GS 2a**	**GS 2b**	**GS 3a**	**GS 3b**	**GS 4**	**GS 5**	**GS 6a**	**GS 6b**	**GS 7a**	**GS 7b**	**GS 8**
Phytoliths													
Monocotyledons													
Cyperaceae (achene)	1	.	.	.	.	.	1	1	.	.	.	3	.
Poaceae													
Silica skeletons													
Inflorescence													
Panicoideae	2	.	1	.	.	.	1	.	.	.	1	.	.
Undetermined	4	.	2	.	.	.	1	1	.	.	.	.	.
Leaf/culm													
Panicoideae					1		2	.	.	.	.	.	.
Undetermined	2	1	5	.	29	37	6	1	.	1	.	3	.
Undetermined	1	.	2	.	4	2	1	.	.	.	.	1	.
Single cells													
Long cells													
Inflorescence	6	5	2	1	11	5	10	6	.	3	1	13	4
Leaf/culm	43	17	34	.	51	47	34	30	.	9	1	50	22
Undetermined	8	1	8	.	1	0	14	15	.	.	.	13	22
Bulliform (leaf)	7	4	3	.	8	18	2	7	.	1	.	4	15
Short cells													
Chloridoideae	19	41	54	.	42	24	29	27	.	.	.	32	12
Panicoideae	71	32	64	.	49	45	65	33	.	2	.	43	38
Pooideae	54	28	49	.	35	48	61	39	.	.	.	33	50
Undetermined	34	15	35	.	30	36	37	14	.	.	.	30	15
Dycotyledons	3	2	5	.	.	.	7	23	.	.	.	15	35
Undetermined taxa	54	58	46	1	73	79	38	107	1	3	.	65	90

	GS 1a	GS 1b	GS 2a	GS 2b	GS 3a	GS 3b	GS 4	GS 5	GS 6a	GS 6b	GS 7a	GS 7b	GS 8
Unidentified phytoliths	8	12	3	.	12	13	3	8	1	2	.	43	7
Total silica skeletons	9	1	10	.	34	39	11	2	.	1	1	4	.
Total cells in silica skeletons	57	5	24	.	153	243	49	6	.	10	2	12	.
Total single cells	308	215	303	2	312	315	301	310	2	20	2	344	310
Phytolith concentration	3.6	.1	2.4	0	.2	.1	8.1	.5	0	0	0	1.1	.4
Starch grains													
Fabaceae													
Faboideae	7	1	11	5	4	5	3	7	5	2	3	10	5
Poaceae													
Panicoideae													
Type 1 (<10 µm)	8	13	.	.	.	.	1	.	.	2	.	.	.
Type 2 (10-20 µm)	1	1	2	4	2	3	4	4	3	4	2	2	3
Type 3 (>20 µm)	4	1	1	1	1	.	.	.	2	2	.	2	.
cf. Panicoideae	.	.	.	.	.	1	.	.	.	.	.	.	1
Pooideae													
Triticeae	.	.	.	.	.	.	1	.	2	.	.	.	.
cf. Triticeae spherical	.	1	.	1	.	.	6	.	2	1	1	.	.
Tuber undetermined 1	.	1	.	.	.	.	.	1	1	.	1	1	.
Tuber undetermined 2	.	.	.	.	.	.	.	.	1	.	.	.	.
Damaged unidentified	7	18	1	.	1	2	6	2	3	1	.	2	.
Total starch grains	27	36	15	11	8	11	21	14	19	12	7	17	9
Starch concentration	4.4	8.3	3.7	4.9	3.4	5.2	2.7	1.5	5.9	3.9	.4	2.1	1.6

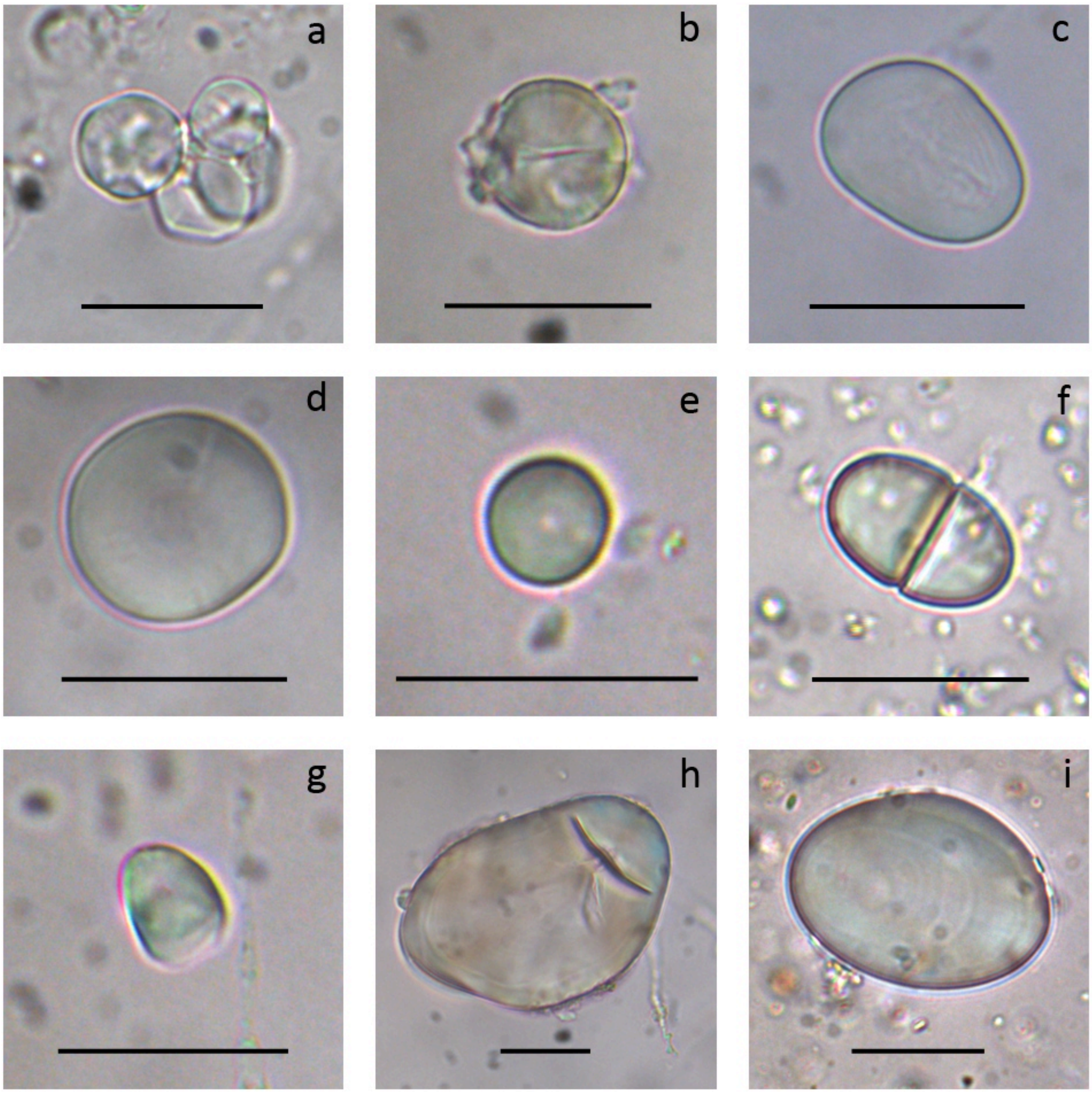

Figure 4. Starch grains recovered from Loteshwar and Vaharvo Timbo. a) Panicoideae Type 1/2 grains, b) cf. Panicoideae grain, c) Faboideae grain, d) Triticeae grain, e) cf. Triticeae (spherical) grain, f) cf. Triticeae (bell-shaped) grain, g) tuber undetermined 1 grain, h) tuber undetermined 2 grain and i) *Solanum tuberosum* grain. Scale bars 20 µm.

Vaharvo Timbo

Macrobotanical remains were only recovered from the upper layer of the archaeological sequence (Table 3, Fig. 5), and included two morphologically wild *Sesamum* sp. grains (tentatively identified as *Sesamum* cf. *malabaricum*), one *Digitaria* sp. grain and one cf. *Dactyloctenium aegyptium* inflorescence. Additionally, several unidentified grass inflorescences, glumes, nodes and spikelet bases were recovered.

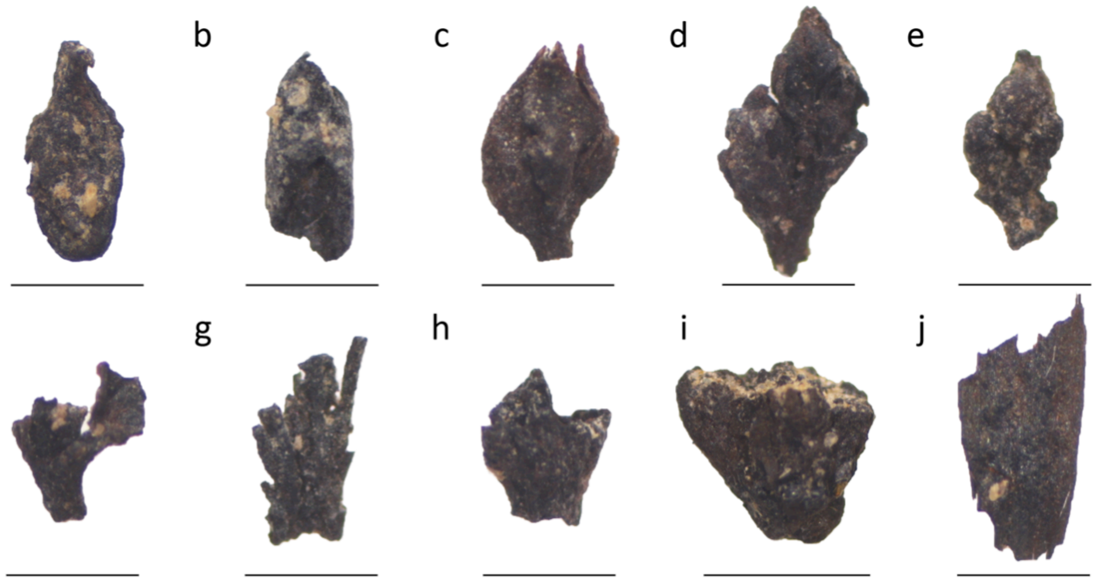

Figure 5. Macrobotanical remains from Vaharvo Timbo. a) charred *Sesamum* cf. *malabaricum* seed, b) charred *Digitaria* sp. caryopsis, c) charred cf. *Dactyloctenium aegyptium* inflorescence, d-e) charred Poaceae inflorescences, f-i) Poaceae spikelet bases, and j) Poaceae glume. Scale bars 1 mm in a-h and j, 2 mm in i.

Phytoliths were very scarce, both in sediment samples and grinding stones (Tables 4 and 6). Among sediment samples, only one had enough phytoliths for quantitative analysis (Dep 1), with the majority of morphotypes from grass leaf/culm and a few from grass inflorescence (Table 4). Moreover, two grass silica skeletons were found, one from an inflorescence and one from a leaf/culm. It is worth highlighting the presence of one small (ca. 10 µm) globular echinate, characteristic of palms (Arecaceae).

Of the 20 grinding stones samples, only four could be discussed quantitatively (<20 phytoliths were encountered on the remaining samples; Table 6). Ten grass silica skeletons were encountered, including one from a panicoid grass. Leaf/culm grass long cells predominated and short cells showed a relatively equal distribution among grass subfamilies. Palm phytoliths as well as one possibly originating from a sedge achene were also observed, while dicotyledonous plants were marginally represented.

The starch assemblage from sediments and grinding stones (183 grains; Tables 4 and 6) was clearly dominated by Type 2/3 Panicoideae grains, with a minor presence of Triticeae, Faboideae, tubers, and one very large (>50 µm) ovoid grain with lamellae and a highly eccentric small hilum (Fig. 5) attributed to *Solanum tuberosum* (potato).

Soil pH values were slightly alkaline and relatively constant throughout the sequence (Table 4).

Table 6. Results of phytolith and starch grain analyses from grinding stones from Vaharvo Timbo. Phytolith concentration i
Insoluble Fraction). Starch concentration is expressed in grains per g of original sediment.

	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9	GS10	GS11	GS12	GS13	GS14
Phytoliths														
Monocotyledons														
Arecaceae	1	.	2	.	.	.	.	.	.	.	.	.	.	.
Cyperaceae (achene)	.	.	1	.	.	.	.	.	.	.	.	.	.	.
Poaceae														
Silica skeletons														
Leaf/culm														
Panicoideae	.	.	.	.	.	.	.	.	.	.	.	.	.	.
Undetermined	.	4	.	4	.	.	.	.	.	.	.	.	.	.
Undetermined	1	.	.	.	.	.	.	.	.	.	.	.	.	.
Single cells														
Long cells														
Inflorescence	5	3	6	.	.	.	.	.	.	.	.	.	.	.
Leaf/culm	46	49	48	23	.	3	2	.	.	.	.	3	1	.
Undetermined	8	5	7	3	.	.	.	.	.	.	.	.	.	.
Bulliform (leaf)	4	5	31	7	.	.	2	.	.	.	.	1	.	.
Short cells														
Chloridoideae	17	12	24	12	.	.	.	.	.	.	.	.	.	.
Panicoideae	17	17	16	19	.	2	2	.	.	.	1	.	2	.
Pooideae	25	20	17	5	.	.	.	.	.	.	.	.	.	.
Undetermined	17	4	9	4	.	.	.	.	.	.	.	.	.	.
Dycotyledons	7	5	.	1	1	.	.	.	1	.	.	.	1	.
Undetermined taxa	102	180	143	76	.	9	9	.	3	.	1	7	1	.
Unidentified phytoliths	97	67	49	31	.	3	1	.	1	.	.	4	1	.
Total silica skeletons	1	4	.	4	.	.	.	.	.	.	.	.	.	.

	GS1	GS2	GS3	GS4	GS5	GS6	GS7	GS8	GS9	GS10	GS11	GS12	GS13	GS14
Total cells in SS	4	14	.	12	.	.	.	.	.	.	.	.	.	.
Total single cells	346	367	353	181	1	18	16	.	5	.	2	15	6	.
Phytolith concentration	35	12	5	8	0	1	1	0	.5	0	.4	2	.3	0
Starch grains														
Fabaceae														
Faboideae	.	.	2	.	.	1	.	1	.	1	.	.	1	.
Poaceae														
Panicoideae														
Type 2 (10-20 µm)	1	5	1	3	3	20	1	6	2	6	3	5	8	12
Type 3 (>20 µm)	.	1	.	.	3	5	1	3	.	1	1	3	7	2
Pooideae														
Triticeae	.	.	1	.	1	3	1	.	1	.	.	.	.	.
cf. Triticeae spherical	.	.	.	.	.	.	.	.	6	.	.	.	.	.
Undetermined	.	.	.	.	.	2	.	.	.	.	.	.	.	1
Damaged unidentified	1	1	.	1	.	.	.	.	.	.	.	.	.	.
Total starch grains	2	7	4	4	7	31	3	10	9	8	4	8	16	15
Starch concentration	66	196	63	102	576	2,163	168	661	685	368	366	349	821	640

Discussion

Before considering the archaeobotanical assemblages from Loteshwar and Vaharvo Timbo, we discuss the possible effect of taphonomical processes. Subsequently, hunter-gatherer and agro-pastoral plant exploitation strategies are discussed and a model for mid-Holocene pastoral land use strategy is proposed. Finally, we focus on the case for a centre of primary plant domestication in Gujarat.

The effect of taphonomy

A series of depositional and post-depositional processes affected the archaeobotanical assemblages from these sites: a) the abrasion on phytoliths and starch grains due to grinding, b) the effect of soil alkalinity and peaks of humidity on phytoliths, c) the mixing of archaeological deposits belonging to different episodes of the dunes occupation, and d) the possible contamination during the laboratory processing of the samples.

The effect of grinding on starch grains is well attested experimentally (Henry et al. 2009; Yang and Perry 2013). Several starch grains from Loteshwar grinding stones have many characters of damage, including loss of birefringence, fissures in the hilum, swelling and, occasionally, loss of all diagnostic traits (damaged unidentified grains). Silica skeletons from both sites, having small number of cells, also suggest mechanical breakage due to milling.

Soil alkalinity facilitates post-depositional chemical dissolution of phytoliths, especially in the presence of water (Madella and Lancelotti 2012; Piperno 2006), such as during the monsoon at Loteshwar and Vaharvo Timbo. Moreover, the consecutive occupational episodes at Loteshwar (the initial hunter-gatherer occupation and the excavation of pits during the Anarta period) resulted in the formation of a stratum with Chalcolithic and Mesolithic material (mixed level).

The presence of a potato starch grain in one sample from Vaharvo Timbo suggests contamination. The purportedly powder-free gloves used in Vaharvo extractions tested positive in laboratory checks for possible corn (Type 2/3 Panicoideae grains), which is the most common source of commercial starch (Crowther et al. 2014). Since the whole residues were processed, we were not able to repeat the extractions. Thus, we do not further discuss the starch samples from Vaharvo Timbo in this work.

In Loteshwar extractions we used a different brand of gloves, which tested negative for starch contamination, as did other control samples from laboratory supplies (García-Granero et al. submitted). Nonetheless, the presence of Triticeae starch grains in Mesolithic Loteshwar is surprising. This grass tribe includes major cereals such as wheat and barley that were introduced in North Gujarat from the Indus Valley during the Urban Harappan period (ca. 2500 BC) or possibly earlier, at the end of the fourth millennium BC (Pokharia et al. 2011). The grains (representing only 0.96% of the total) might therefore be related to local grass species producing starch similar to wheat/barley (Yang and Perry 2013). Pooid grasses are very rare in this region today (Parmar et al. 2012), but the high concentration of Pooideae-type phytoliths in Mesolithic deposits seems to suggest a wider presence during the early-mid Holocene (see below).

Hunter-gatherers plant exploitation during the early-mid Holocene

Palaeoclimatic models show a slow but constant weakening of the Indian Summer Monsoon after the early Holocene wet phase, ca. 10,000 to 7000 years ago, with a certain degree of variability at regional level (Gasse et al. 1996; Gupta et al. 2006; Hu et al. 2008; Liu et al. 2003; Overpeck et al. 1996; Wei and Gasse 1999). Preliminary data from interdunal depressions in the vicinity of Loteshwar and Vaharvo Timbo suggest that perennial water bodies existed until ca. 7000 years ago (NoGAP's unpublished data), contrary to present day conditions where most depressions dry up during the winter (Conesa et al. 2014b).

The similar temporal and ecological ranges, together with comparable lithic assemblages (Gadekar et al. 2014 and C. Gadekar pers. comm.), suggest that the sites were frequented by groups of hunter-gatherers with similar economic strategies. The archaeobotanical record from Vaharvo Timbo is poor but the presence of *Digitaria* sp., *Dactyloctenium aegytium* and spikelet bases from at least four different species suggests gathering of wild grasses. Palm and sedge phytoliths indicate the possible exploitation of wild palms (e.g. *Phoenix sylvestris*) (Barh and Mazumdar 2008; Davis and Johnson 1987; de Zoysa 1992; Khare 2007; Pandey et al. 2007) and of other plants from the more humid interdunal areas. Genetic evidence indicates that sesame was domesticated in South Asia (Bedigian 2003), but the exact centre of domestication is unknown and the recovery of wild sesame seeds highlight the presence of this plant in North Gujarat from the early-mid Holocene.

The archaeobotanical evidence from Mesolithic Loteshwar shows a high presence of dicot phytoliths, suggesting that hunter-gatherers exploited woody plants more than agro-pastoral people. It is also interesting to note the relatively high presence of pooid morphotypes –mainly rondels. Previous palaeoecological research in Gujarat suggests phases of higher winter precipitation during the Holocene (Prasad et al. 2007; Singh et al. 2007), which might have facilitate a higher presence of pooid grasses. The pooid morphotypes, however, may also derive from a so far unidentified rondel-producing panicoid grass, as in other areas of the world (e.g. *Panicum turgidum* in West Africa, Radomski and Neumann 2011: Table 3). Indeed, several species of Panicoideae were exploited in Mesolithic Loteshwar, as suggested by starch grains from this group. The starch assemblage also indicates the exploitation of wild pulses.

Overall, the archaeobotanical evidence from Mesolithic Loteshar and Vaharvo Timbo suggests the exploitation of a wide range of plants originating from (semi)permanent water bodies, creating marshy microenvironments in the dune-interdune area. When combined with the zooarchaeological analysis from Loteshwar (Patel 2009), these data show that hunter-gatherers inhabiting the semi-arid North Gujarat during the early-mid Holocene were relying on a broad-spectrum economy.

Millet cultivation and semi-nomadic pastoralism: a model of adaptive strategy

The boundary between food procurement (plant gathering) and food production (plant cultivation) has been drawn at the human intentionality to disrupt the life cycle of a plant population to encourage growth (Ford 1985: 2; Harris 1996: 446). The intentional cultivation of plant populations might or might not end in a domestication event and, in any case, the appearance of domestic traits would be delayed by at least 1000-2000 years (Fuller and Allaby 2009). Despite the lack of domestic traits in archaeobotanical remains, the human intervention in a plant life cycle can be identified in the archaeological record trough the analysis of cultivation-related artefacts (e.g. hoes) or the presence of weeds in the plant assemblage (Jones 1992).

The integration of our archaeobotanical data and earlier research is the basis for a model of mid-Holocene agro-pastoral land use strategy in North Gujarat (Fig. 6) by a semi-nomadic group with a low-level food producing economy (Smith 2001). The current regime of interdunal water availability was established ca. 7000 years ago and the human population had to adapt to new ecological settings, with reduced humidity and interdunal water bodies during the pre-monsoon season (Conesa et al. 2014b). Zooarchaeological data advocate for the adoption of semi-nomadic pastoralism (*sensu* Khazanov 1984: 19) from neighbouring herders (Fuller 2006) or as a locally developed process of cattle domestication (Patel 2009). Plant remains from Anarta Loteshwar suggest that livestock was complemented with cultivation of local small millets and probably other *kharif* crops, such as Job's tears, horsegram and sesame. The presence of weeds associated with cultivation (*Trianthema* spp. and *Chenopodium* sp.) supports the idea that these plants were not simply gathered as wild.

The integration of millet cultivation and semi-nomadic pastoralism has been (and still is) a successful subsistence strategy for populations in semi-arid regions worldwide, including for instance the Central Eurasian steppes during the Final Bronze Age and the Early Iron Age (Chang et al. 2003; Lightfoot et al. 2014; Murphy et al. 2013; Svyatko et al. 2013) and present-day FulBe groups in the Sahel (Thébaud and Batterbury 2001). The cultivation of fast-maturing small millets, harvested 60-90 days after sowing (Weber and Fuller 2008), is compatible with the seasonal migration cycles of mobile pastoral groups, enabling them to take advantage of several ecological niches (Di Cosmo 1994). Semi-nomadic agro-pastoral groups inhabiting North Gujarat during the mid-Holocene would have scheduled plant-related activities according to the highly seasonal monsoon regime, maximising mobility during periods of scarce resource availability.

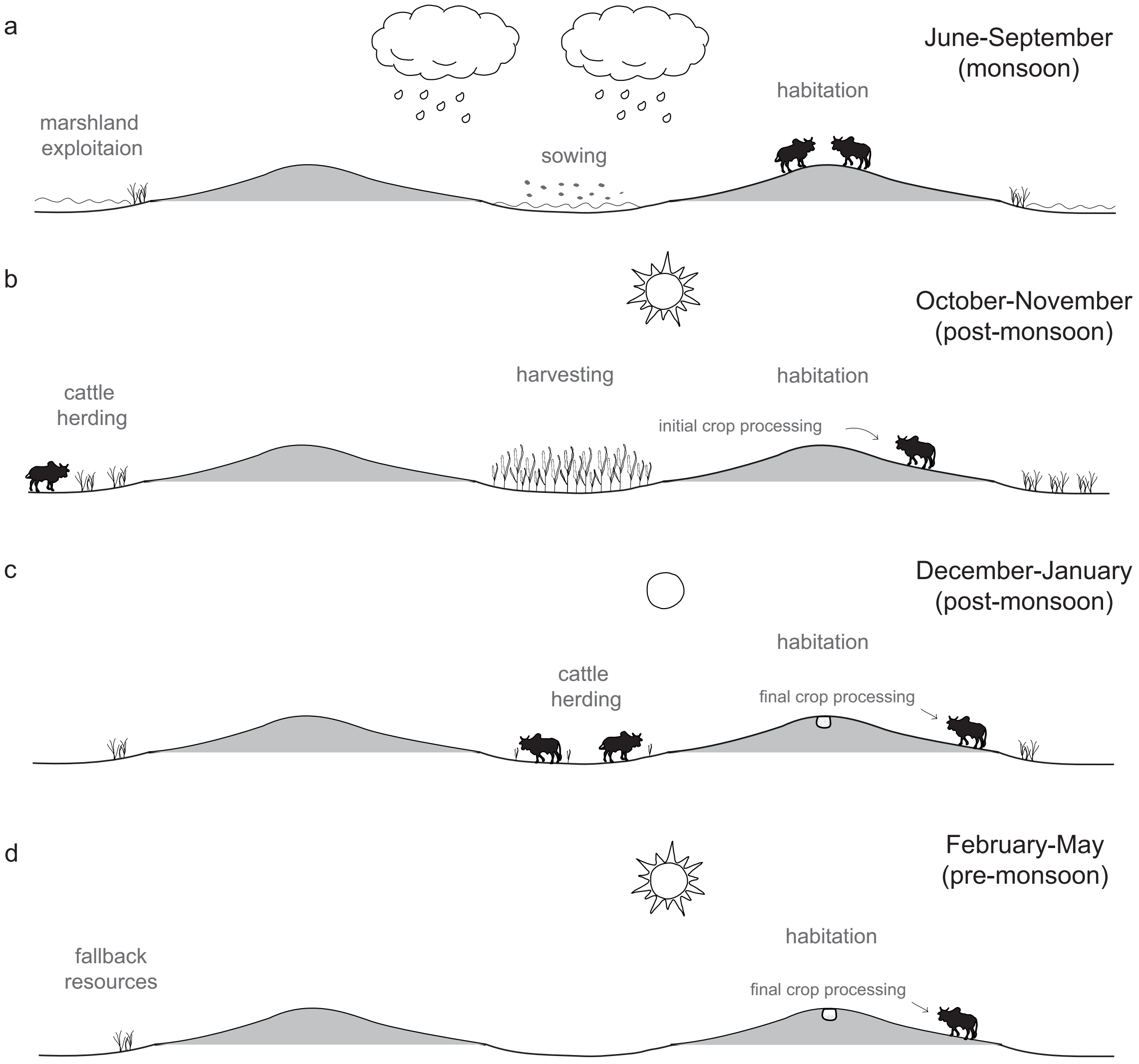

Figure 6. Model of the land use strategy of semi-nomadic populations in North Gujarat during the mid-Holocene. a) monsoon period, b-c) post-monsoon period and d) pre-monsoon period.

Monsoon (June-September)

Pastoral groups sowed small millets and other *kharif* crops in the more fertile interdunal depressions (soils with higher humidity and clay) with the first monsoon rains (between June and July) (Fig. 6a) and a certain degree of land clearance was probably part of the pre-sowing land preparation (cf. Singh 2010). During the period of crop growth and maturation (August-September), these groups would dwell in the area, feeding cattle on the green open scrublands and gathering plants from the marshy areas. Some degree of crop weeding might have occurred, although small millets do not need much work investment (Fogg 1983; Kimata et al. 2000; Weber and Fuller 2008). The presence of big millet starch grains (Panicoideae Type 3) and pseudocarps of Job´s tears suggest the possibility of a mixed cultivation strategy. Job's tears, originating in Southeast Asia, became ubiquitous in Gujarat and Rajasthan during the mid-late Holocene; it was mostly used as ornaments but it probably also had some role in people's diet (García-Granero et al. 2015; Pokharia et al. 2011 and references therein). Fast-maturing sesame, grown for its high oil content, could have been cultivated in mixed stands with pulses, similarly to current traditional agriculture in Kachchh (Singh 2010). *Sesamum indicum* was well established as a *kharif* crop during the Urban Harappan phase (ca. 2500-1900 BC) of the Indus Valley Civilisation (Tengberg 1999), from where it spread to southwest Asia (Bedigian 2004; Fuller 2003).

Post-monsoon (October-January)

Between October and November crops would be harvested (Fig. 6b). Due to different inter- and intra-species maturation rates plants were probably harvested on multiple episodes (Fogg 1983; Kimata et al. 2000; Weber and Fuller 2008), and millets as immature spikelets to avoid major seed loss (Fuller and Allaby 2009). Inflorescence structure in small millet species can sometime be loose, requiring a cutting at the base of the plants that results in the incorporation of a large quantity of weeds and the need for labour intensive crop processing (Reddy 1997). During post-harvest (December-January; Fig. 6c) cattle would be fed on leaves/culms leftovers. Grass fodder was probably important throughout the year as highlighted by the isotopic analyses from domestic cattle remains at Loteshwar (B. Chase pers. comm.). Part of the grains would have been preserved for next year sowing and plant macroremains (weeds of similar size as small millets and mineralised inflorescences) suggest that small millets were stored hulled, probably to protect them (Bouby et al. 2005; Reddy 1997). Millet grains can be stored for up to three years (Weber and Fuller 2008) but a technological study of one of the Anarta pits uncovered at Loteshwar in 2009 highlights that the storage structures were used only during the dry season (lack of waterproofing by plastering; Balbo et al. 2014b), thus indicating that crops were not likely to be stored for long periods and probably mostly set aside during the months following the harvest. Final crop processing (de-husking and grinding) was most likely carried out on a daily basis on site, as suggested by the microbotanical evidence from grinding stones.

During years of scarce yields, wild grasses could have supplemented the cultivated grains. The presence of crowfoot grass in the macrobotanical assemblage suggests such a possibility, and also it would explain the relatively high presence of saddle phytoliths in sediments and grinding stones. This plant is widely distributed throughout the tropics, subtropics, and warm temperate regions of the Old World (Manidool 1992) and it is generally considered a weed. Ethnographic record from modern Rajasthan illustrates that it can be consumed as a famine crop, either alone, mixed with semi-ground pulses to prepare Keech or ground with millet for bread-making (www.hort.purdue.edu).

Pre-monsoon (February-May)

During the summer months (February-May), the gathering of other plant resources such as sedges and tubers would have increased to complement the dwindling grains (Fig. 6d). Macrobotanical and phytolith evidence at Loteshwar suggests the use of sedges, possibly also for consumption, collected from the marshy interdunal depressions. Moreover, carbonised parenchymatic tissue and starch grains indicate the consumption of tubers. Plant remains from Urban Harappan Shikarpur in Kachchh (García-Granero et al. 2015) and several Neolithic sites in southern India (Fuller et al. 2004) imply a more important role than previously acknowledged of tuberous plants in the prehistory of the subcontinent. To overcome pre-monsoon scarcity, semi-nomadic groups in North Gujarat could have also traded with neighbouring Harappan communities, and the minor presence of wheat (a winter crop) at Loteshwar can be interpreted as such. Further evidence for contacts, in this case outside the Indus Valley, was highlighted by the presence of *Musa* sp. phytoliths in a previous study from Loteshwar (García-Granero 2011; García-Granero et al., in press).

With the arrival of the monsoon, the interdunes would have been sown again with the option of exploiting the same depressions for a few years and then move to non-exploited grounds within the dune-interdune area.

Was North Gujarat a centre of plant domestication?

Cultivation of small millets and tropical pulses was well established in Gujarat by the Urban Harappan period (Fuller 2006). The local character of the prehistoric Gujarati crop package suggests the existence of an indigenous plant domestication process (Fuller 2006, 2011; Fuller and Murphy 2014; Purugganan and Fuller 2009). The archaeobotanical evidence from Loteshwar and Vaharvo Timbo reveals a continuous history of plant gathering and then pre-domestication cultivation of at least three different groups: small millets, pulses and sesame. The cultivation is unequivocal from the archaeobotanical record, but defining North Gujarat as a primary centre of domestication requires an assessment of the 'domestic' character of these plants. Some of the morphological and genetic traits that characterise a plant as 'domestic' are the loss of seed dispersal mechanisms, the loss of germination inhibition, changes in seed size, and the appearance of seasonality control (Fuller and Allaby 2009).

Germination inhibition (loss of seed dormancy) and changes in seed size would occur during pre-domestication cultivation and should therefore be the first observed archaeobotanically, especially in the case of size change. South Asian small millets do not show an increase in seed size after domestication and most of them are still found wild or as weeds nowadays (Fuller 2011: Table A5). The small millets recovered from Anarta Loteshwar and later Harappan settlements in Gujarat are no exception to this, hindering the possibility of making inferences on their domestication status *sensu stricto*. A similar case can be made for pulses, which were recovered at Loteshwar from the macro (horsegram) and microbotanical (Faboideae starch) assemblages, suggesting exploitation since the seventh millennium BC. Tropical pulses are commonly found in Harappan settlements in Gujarat and Rajasthan, and wild stands of *Macrotyloma* and *Vigna radiata* (mung bean) are still present in the region (Fuller and Harvey 2006).

The native character of these plants and their long-term presence (hundreds to thousands of years) in the archaeological records, including the occurrence of other taxa considered associated weeds, all advocate for North Gujarat as a centre of small millet and pulses (probably horsegram) domestication. Dating the origins of small millet and horsegram exploitation and cultivation in North Gujarat is however difficult because of the challenging archaeological deposits. Indeed, the lack of clear stratigraphy and significant pre- and post-depositional taphonomic processes in most Anarta sites create a scant macrobotanical assemblage. Similar processes of combined small millets and pulses domestication occurred in southern India (Fuller et al. 2004). Horsegram has been cultivated in southern India since ca. 2500 BC (Fuller and Harvey 2006) and small millets from ca. 2000 BC (Fuller 2011), therefore later than the mid third millennium BC Anarta remains from Loteshwar.

The seeds of domestic sesame from Anarta Loteshwar are among the earliest recovered in South Asia (see Fuller 2003 for a review). The presence of wild sesame seeds at Vaharvo Timbo suggests that the plant was already exploited by hunter-gatherer groups during the early-middle Holocene, and possibly became locally domesticated during the mid-Holocene. However, further evidence and a more robust chronology are needed to establish North Gujarat as *the* centre of sesame domestication.

Conclusions

The archaeobotanical data from Loteshwar and Vaharvo Timbo, in the wider context of North Gujarat, is an illustrative example of human adaptation to climatic and environmental changes in semi-arid regions. The end of the hunter-gatherer occupation at these sites roughly coincides with the weakening of the precipitations (ca. 7000 BP) and the retreat of the interdune marshland environments. This evidence suggests that food production emerged in North Gujarat as a response to weakening rains (monsoon) to ensure resource predictability, as it seems to have been the case in other semi-arid areas of the world such as the African Sahel (Marshall and Hildebrand 2002). In our area, human populations adopted a strategy that involved semi-nomadic pastoralism, the cultivation of fast-maturing crops and the gathering of wild plants. We consider that our data support a local origin of plant domestication and that North Gujarat can be seen as a primary centre of origin, regardless to a local development of animal domestication (Patel 2009) or through adoption from neighbouring areas such as the southern Indus Valley (Fuller 2006).

Acknowledgments

Fieldwork at Loteshwar and Vaharvo Timbo was funded by the Spanish Ministry of Education, Culture and Sport (Programa de Ayudas para Proyectos Arqueológicos en el Exterior 2009 and 2011) and the Catalan Government (Programa EXCAVA 2009). Laboratory work was funded by the Spanish Ministry of Economy and Competitiveness

(Programa I+D, HAR2010-16052). We are grateful to the members of the NoGAP for their help during the fieldwork and for discussion, to G. Orlando (Università degli Studi di Salerno) for his assistance during the sorting of floatation samples, to the Archaeological Survey of India for granting excavation permissions and to the MS University of Baroda. JJGG acknowledges funding from a JAE-PreDOC doctoral research grant (Spanish National Research Council and European Social Fund). Finally, we would like to acknowledge the comments from several anonymous reviewers as well as M Aldenderfer who helped improving the original manuscript.

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García-Granero JJ, Gadekar C, Esteban I, Lancelotti C, Madella M, Ajithprasad P (submitted) What’s on the craftsmen’s menu? Plant consumption at Datrana, a 5000 years old lithic blade workshop in North Gujarat (India). Archaeol Anthropol Sci

What's on the craftsmen's menu? Plant consumption at Datrana, a 5000 years old lithic blade workshop in North Gujarat (India)

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Paper submitted to Archaeological and Anthropological Sciences on 27 March 2015

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Abstract

The exploitation of lithic resources was an important aspect of prehistoric resource exploitation strategies and adaptation. Research has mostly focused on technological and spatial aspects of lithic factory sites, often overlooking how these sites were integrated within local socio-ecological dynamics in terms of food acquisition and consumption. The aim of this paper is to study plant consumption at Datrana, a 5000 years old lithic blade workshop in North Gujarat, India, in order to understand its occupants' subsistence strategies. The results of archaeobotanical, mineralogical and soil pH analyses show that the occupants of this factory site were consuming local crops but not processing them, suggesting either that a) food was being processed in other areas of the site or b) it was acquired in a 'ready-to-consume' state from local food-producing communities. This study highlights the integration of a lithic factory site within its surrounding cultural and natural landscape, offering an example of how the inhabitants of a workshop interacted with local communities to acquire food resources.

Keywords: lithic workshop; craft specialisation; archaeobotany; mineralogy; subsistence strategies; South Asia

Introduction

The appearance of craft specialisation has been traditionally linked with the emergence of stratified societies and powerful elites (Peregrine 1991). However, the existence of a specialised production centre is the result of a variety of processes, and a certain degree of specialisation occurs in all societies (Kenoyer et al. 1991). Moreover, the level of production is often controlled by the craftsmen and women themselves, and not necessarily by the ruling elite (Shafer and Hester 1991).

The term 'craft specialist' refers to "an individual who repeatedly manufactures a craft product for exchange" (Shafer and Hester 1991: 79). Archaeologically, craft-specialised communities are recognized by the production of one (or a few) standardised item in excess of household needs, and the appearance of this item beyond its centre of production.

The most ubiquitous examples –both spatially and temporally– of craft production centres in archaeological contexts are lithic workshops (e.g. Beck et al. 2002; Biagi and Cremaschi 1991; Johnson 1984; Laughlin and Marsh 1951; Sanger et al. 2001; Sankalia 1967; Shafer and Hester 1991; Snarskis 1979; Stiles et al. 1974; Subbarao 1955). The archaeological record of lithic workshops varies according to their size, the time-span of their occupation and the nature of the activities carried out within the site. Indeed, the activities performed at a particular workshop depend on how it is articulated within the landscape in terms of distance to the residential base, raw material sources and trading networks, and the local ecology (Beck et al. 2002; Johnson 1984; Sanger et al. 2001).

One vital aspect of lithic factory sites that has often been overlooked is how these sites were integrated within local and regional socio-ecological dynamics in terms of food acquisition and consumption. Food acquisition strategies depend on the nature of the occupation (permanent, seasonal, etc.) and the level of interaction with local populations. Three hypothetic scenarios can be considered:

a) The workshop is occupied only by specialised craftsmen and women, who carry their own food supply from their residential base. This strategy would probably take place if the workshop were exploited during short periods of time. Archaeologically, it would result on the high presence of storage containers and bioarchaeological remains from the region of origin.
b) The workshop is occupied only by specialised craftsmen and women, who obtain food through exchange with local hunter-gatherer and/or agro-pastoral populations. This strategy could take place regardless of the length of the occupation and would imply a high level of interaction between the occupants of the workshop and the local populations. Archaeologically, it would result on the presence of local ecofactual remains at the workshop and the spread of crafts throughout its hinterland.
c) The workshop is occupied by specialised craftsmen and women but also people who carry out food-procurement activities. This strategy would take place if the workshop was occupied permanently or for relatively long periods of time, and implies a deep knowledge of the local ecology. Archaeologically, it would result on the presence of semi-permanent architectural settings and the ecofactual remains of a food-procuring economy.

The aim of this paper is to study plant consumption at Datrana, a 5000 years old lithic workshop in North Gujarat, India, in order to understand the plant acquisition and consumption strategies and the socio-economic organisation of their occupants at a local and regional level.

Datrana, a 5000 years old lithic workshop in North Gujarat, India

North Gujarat is a semi-arid (400-600 mm) ecotone located between the Thar Desert and the semi-humid South Gujarat (Fig. 1). The region is characterised by a monsoon regime (Indian Summer Monsoon) in which most of the rainfall occurs between June and September, shaping agricultural and pastoral activities. Datrana IV (23^{o} 46’ 41.7” N, 71^{o} 07’ 26.2” E), locally known as Hadka valo Timbo, is located on a large crescent-shaped stabilised sand dune about 2 km north east of Datrana village, Patan district.

This site is part of a large (40 ha) archaeological complex formed by discrete clusters of artefacts spread through ten mounds around a large interdunal depression.

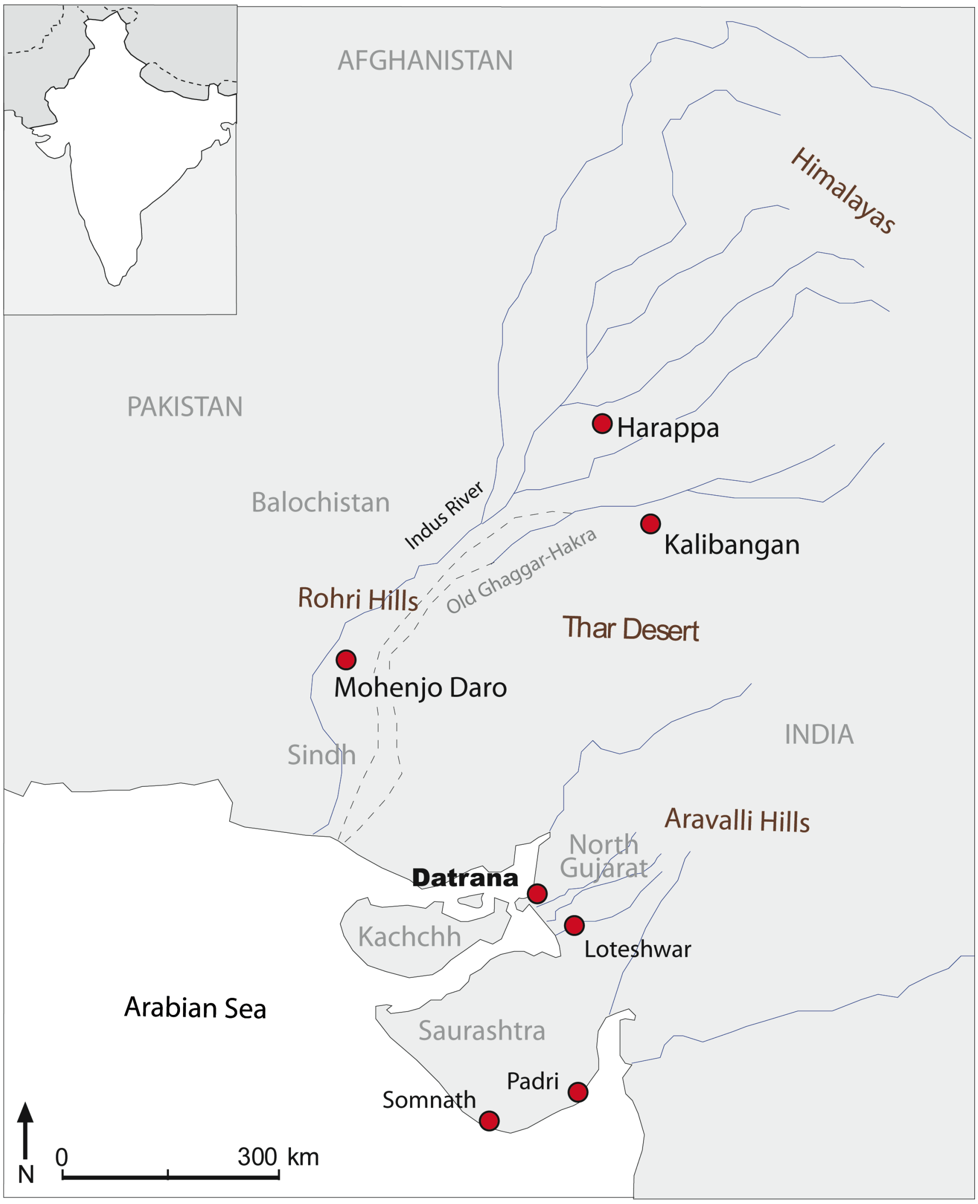

Figure 1. Map of Gujarat showing the location of Datrana IV and other sites mentioned in the text. Image by Francesc C. Conesa.

The excavations conducted by the Department of Archaeology and Ancient History of the M. S. University of Baroda (MSUB, India) at Datrana IV between 1993 and 1995 uncovered a Mesolithic hunter-gatherer occupation with superimposed Chalcolithic deposits (IAR 2000a, 2000b). Otoliths from the Mesolithic level were AMS dated to the mid eighth millennium cal BC (unpublished data). The majority (>95%) of the ceramic assemblage from the Chalcolithic deposits is characterised as Pre-Prabhas, a handmade pottery previously recovered only at Somnath on the Saurashtra coast (400 km south of Datrana, Fig. 1) and dated to the early third millennium cal BC (Ajithprasad 2002, 2011; Rajesh et al. 2013; Sonawane and Ajithprasad 1994). Pre-Prabhas pottery was also recovered during explorations at neighbouring Datrana V and Datrana IX, but it has not been found at any other Chalcolithic occupation in North Gujarat (Ajithprasad 2002, 2011). The ceramic assemblage from Datrana IV further included a minor (<5%) presence of Early Harappan Sindh (Indus Valley, ca. 2800-2600 cal BC) and Anarta pottery (North Gujarat, ca. 3700-2200 cal BC) (Ajithprasad 2002). Moreover, the evidence found at Datrana IV suggested the production of beads from agate, carnelian, chert and amazonite using a technology not attested in other Chalcolithic sites in North Gujarat (Madella et al. 2012). The exceptionality of its pottery and bead assemblages highlights the uniqueness of Datrana among the Early Chalcolithic occupations in North Gujarat. However, the subsistence strategy of the inhabitants of Datrana and how they interacted with other hunter-gatherer and agro-pastoral groups are poorly understood and require further research.

The North Gujarat Archaeological Project (NoGAP), a collaboration between the MSUB (India) and the IMF-CSIC (Spain), excavated a 4x4 m trench at Datrana IV in 2010 in the richest area in terms of surface material –particularly lithic tools. The new excavation aimed at understanding site formation processes and obtaining more information on the subsistence strategies of its occupants. The excavation revealed a 50 cm cultural deposit belonging to the Chalcolithic occupation, AMS dated ca. 3300-3000 cal BC and thus preceding the Pre-Prabhas occupation at Somnath (Table 1). Unlike the previous excavations, no hunter-gatherer occupation was uncovered during the 2010 field season (Madella et al. 2012). The artefacts recovered included lithic implements, pottery, copper/bronze punch points, stone beads and bead rough-outs, a cluster of burned carnelian nodules, stone drill bits, facetted crayons, hammer stones and grinding tools. No structural remains, hearths or ash concentrations were found. During the excavation we did not encounter any evidence of an activity floor, but several clusters of animal bones, potsherds and lithic tools ('trash pits') were encountered. Faunal remains were very fragmented, and some were partially charred.

An exhaustive study of the lithic assemblage revealed over 10,000 stone blades, few geometric and non-geometric tools and over 77,000 pieces of lithic debitage, mostly made of chalcedony (Gadekar et al. 2013). Two nearby sources of chalcedony nodules were encountered during an exploratory survey, both located about 20 km from the site (Madella et al. 2012). Blades were removed by crested guiding ridge technique, a practice associated with Chalcolithic settlements of the Indus Civilisation (Cleland 1977). In addition, the lithic assemblage included a few examples of Rohri chert blades from the Rohri Hills in Sindh, Pakistan (Biagi and Cremaschi 1991), over 500 km northwest of Datrana. The absence of Rohri chert debitage indicates that these blades were not locally produced but imported (Gadekar et al. 2013).

The Indus or Harappan Civilisation flourished throughout the Indus Valley in northwest South Asia between ca. 3300-1300 cal BC, extending from modern northeast Afghanistan to Pakistan and northwest India (Kenoyer 1991a; Possehl 2002; Wright 2010). Indus Civilisation sites are characterised by the appearance of a relatively homogenous corpus of material culture, including handicrafts (pottery, beads, seals, lithic tools) and metallurgy (Chase et al. 2014; Wright 2010). The recovery of Early Harappan Sindh pottery in mortuary and residential contexts in Gujarat suggests that the interaction between the Indus Valley and Gujarat began during the early third millennium BC (Ajithprasad 2002, 2011). However, it is during the Urban Phase of the Indus Civilisation (ca. 2500-1900 BC) that the Harappan influence is most evident in Gujarat, with the appearance of a series of walled urban settlements with the characteristic Harappan city plan and associated material culture along trade and travel corridors (Chase et al. 2014).

The use of the crested ridge technology for local blade production and the presence of imported Rohri chert blades suggest that the inhabitants of Datrana interacted with the Indus Valley during the late fourth millennium BC, at the beginning of the pre-Urban or Early Harappan Phase of the Indus Civilisation (ca. 3300-2600 BC). Such early interaction is unprecedented in Gujarat, and suggests that Datrana may have functioned as a lithic workshop occupied by pre-Urban Harappan communities from Sindh to exploit local chalcedony outcrops. These same groups would have later exploited chalcedony outcrops in the Saurashtra coast during the early third millennium BC, as attested by the presence of crested ridge blade technology and Pre-Prabhas pottery at Somnath (Ajithprasad 2002, 2011; Sonawane and Ajithprasad 1994). Alternatively, the origin of the Pre-Prabhas ceramic communities at Datrana can be traced back to the hunter-gatherer occupation of the site (Rajesh et al. 2013). However, this hypothesis seems unlikely under the light of the temporal gap between both occupations (over four thousand years) and the uniqueness of the Chalcolithic lithic and ceramic assemblages from Datrana.

The agricultural system during the pre-Urban Harappan Phase in Sindh was characterised by Near Eastern winter crops such as wheat (*Triticum* sp.), barley (*Hordeum vulgare* L.), peas (*Pisum sativum* L.), lentils (*Lens culinaris* L.) and chikpeas (*Cicer arietinum* L.); whereas the subsistence strategy of the inhabitants of North Gujarat relied on native summer crops such as small millets and tropical pulses (Fuller and Madella 2002; García-Granero et al. in press). The markedly different nature of the subsistence strategies in the region of origin of the craft specialists (Sindh) and the area were the lithic workshop was located (North Gujarat) offers a unique opportunity to study how the plant-related subsistence strategies of the inhabitants of Datrana were incorporated into the local socio-ecological dynamics.

Materials and Methods

We carried out archaeobotanical, mineralogical and pH analyses on samples collected during the 2010 field season, in which a systematic sampling strategy for macro and microbotanical remains was performed. Samples from the general archaeological deposits and several clusters of animal bones, potsherds and lithic tools –‘trash pits’–

were analysed for plant macro (wood charcoal, seeds and fruits) and microremains (phytoliths and starch grains), Fourier Transform Infrared Spectroscopy (FTIR) and soil pH (Table 1). Moreover, microbotanical remains were analysed from grinding stones (Table 2).

Table 1. Sediment samples analysed in this study and radiocarbon estimations from wood charcoal provided by the Centro Nacional de Aceleradores, Sevilla, Spain.

Sample ID	Description	^{14}C-age (yr BP)	2-σ cal. age (yr BC)	Lab code
DTR 9	General archaeological deposit	-	-	-
DTR 10	Cluster of remains (‘trash pit’)	-	-	-
DTR 11	Cluster of remains (‘trash pit’)	-	-	-
DTR 12	Cluster of remains (‘trash pit’)	-	-	-
DTR 13	Cluster of remains (‘trash pit’)	4465 ± 35	3339-3204, 3197-3023	2227.1.1
DTR 25	General archaeological deposit	4505 ± 35	3353-3096	2229.1.1
DTR 27	General archaeological deposit	-	-	-
DTR 30	Cluster of discarded carnelian	-	-	-
DTR 34	General archaeological deposit	-	-	-
DTR 44	General archaeological deposit	-	-	-

Table 2. Grinding stones analysed in this study. Descriptive terms after Wright (1992).

Sample ID	Description	Context
GS 1	Frag. basin grinding slab	DTR 10
GS 2	Frag. saddle-shaped grinding slab	DTR 12
GS 3	Frag. saddle-shaped grinding slab	DTR 12
GS 4a	Frag. saddle-shaped grinding slab, face a	DTR 12
GS 4b	Frag. saddle-shaped grinding slab, face b	DTR 12
GS 5	Frag. saddle-shaped grinding slab	DTR 12
GS 6a	Frag. saddle-shaped grinding slab, face a	DTR 12
GS 6b	Frag. saddle-shaped grinding slab, face b	DTR 12
GS 7	Frag. saddle-shaped quern	DTR 12
GS 8	Unifacial discoidal handstone	DTR 12
GS 9	Frag. saddle-shaped grinding slab	DTR 10
GS 10	Frag. saddle-shaped grinding slab	DTR 9
GS 11a	Frag. saddle-shaped grinding slab, face a	DTR 12
GS 11b	Frag. saddle-shaped grinding slab, face b	DTR 12
GS 12a	Frag. saddle-shaped grinding slab, face a	DTR 13
GS 12b	Frag. saddle-shaped grinding slab, face b	DTR 13
GS 13	Frag. saddle-shaped grinding slab	DTR 13
GS 14	Frag. saddle-shaped grinding slab	DTR 13
GS 15	Frag. saddle-shaped grinding slab	DTR 13
GS 16	Frag. saddle-shaped grinding slab	DTR 13
GS 17	Frag. saddle-shaped grinding slab	DTR 27

Bulk samples (20 l) were collected from each excavation spit (ca. 10 cm) of the 2x2 m grid to recover macrobotanical remains through bucket flotation with a 0.25 mm mesh. All macroremains in the fraction >0.5 mm were recovered and observed using a Leica EZ4 D stereoscope. Taxonomical identification of all plant remains relied on the plant reference collection of the BioGeoPal Laboratory (IMF-CSIC, Barcelona) and seed atlases (Cappers and Bekker 2013; Cappers et al. 2009; Neef et al. 2012).

Microbotanical remains from sediments and grinding tools were extracted following the protocols described in García-Granero et al. (2015) and observed with a Leica DM 2500 microscope equipped with a Leica DF 470 camera for microphotography. All phytolith samples were quick-scanned at 200x magnifications. Due to the scarcity of phytoliths only seven samples –two sediment samples and five grinding stones– were fully scanned at 630x magnifications. Multi-cell phytoliths (silica skeletons) were counted independently. Phytolith concentration was calculated per g of AIF (Acid Insoluble Fraction) according to Albert and Weiner (2001), and phytoliths were described using the International Code for Phytoliths Nomenclature (ICPN – Madella et al. 2005).

All starch samples were analysed. Slides were fully scanned at 200x magnifications and all the observed starch grains were photographed under transmitted and cross-polarised light at 630x magnifications. Starch concentration was calculated per g of processed sediment, and starch grains were described according to the International Code for Starch Nomenclature (ICSN 2011).

Infrared spectroscopy was used to identify the gross mineral components of the sediments. Infrared spectra were obtained using KBr pellets at 4 cm^{-1} resolution with a Nicolet iS5 spectrometer. In order to assess the origin of the calcite we applied the infrared grinding curve method developed by Regev and Poduska (Regev et al. 2010; Poduska et al. 2011) based on the measurement of the ratio of v_2/v_4 heights (1,420 cm^{-1} and 713 cm^{-1}, respectively) normalised to a v_3 height (874 cm^{-1}). Clays exposed to high temperatures were identified using specific absorptions in the clay spectrum following Berna et al. (2007). Soil pH was measured using a Combo pH & EC HI98129 by HANNA® instrument to understand how soil acidity/alkalinity might have affected the preservation of plant remains.

Results

Archaeobotanical remains

The anthracological analysis could not be carried out due to the scarcity and small size (mostly 0.5-1 mm) of the charred wood recovered from all contexts (Table 3). Charred seeds and fruits were also scarce (Table 3). The macrobotanical assemblage includes wild seeds and grains –crowfoot grass (*Dactyloctenium aegyptium* (L.) Willd.), Cyperaceae (sedges) and Caryophyllaceae–, a weed usually associated with small millet cultivation (*Chenopodium* sp.) and a barley rachis (Fig. 2).

Table 3. Results of the macrobotanical analyses.

	DTR 9	DTR 10	DTR 11	DTR 12	DTR 13	DTR 25	DTR 30	DTR 34	DTR 44
Sediment volume (l)	60	20	20	20	80	80	40	60	100
Charred seeds									
Amaranthaceae									
Chenopodium sp.	.	.	.	.	1	.	.	.	.
Caryophyllaceae	1	.	.	.	.	.	.	.	.
Cyperaceae	5	.	.	.	.	.	.	.	.
Poaceae									
Dactyloctenium aegyptium	.	.	.	.	1	1	.	.	.
Hordeum sp. rachis	.	.	.	.	1	.	.	.	.
Charred wood (mg/l)	0.5	0.7	2.9	1.1	12.3	2.9	4.7	1.3	0.2

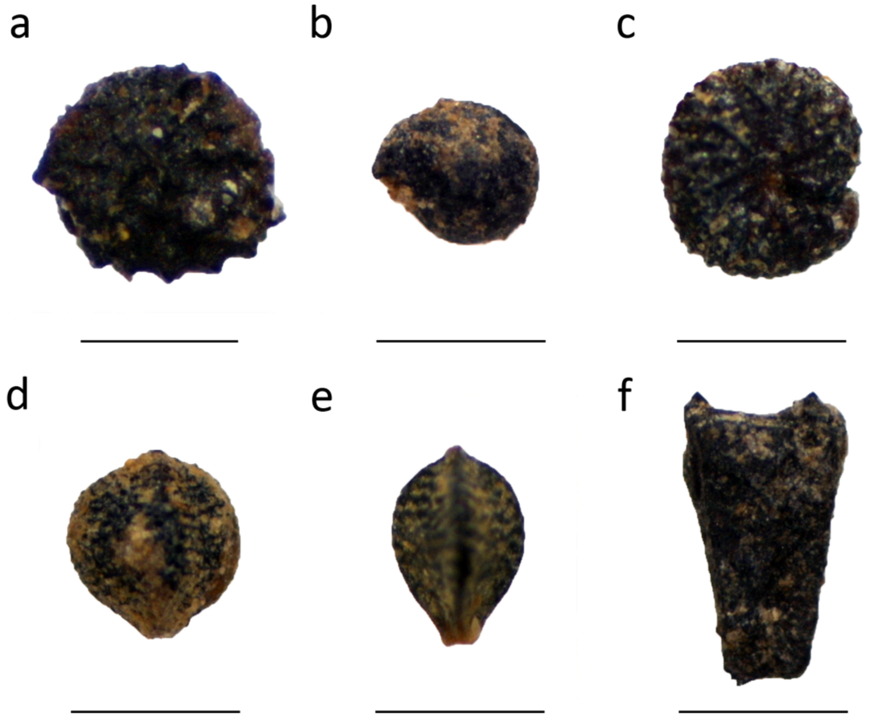

Figure 2. Charred seeds and fruits recovered from Datrana IV. a) *Dactyloctenium aegyptium* caryopsis, b) *Chenopodium* sp. seed, c) Caryophyllaceae seed, d-e) Cyperaceae seeds, f) *Hordeum vulgare* rachis. Scale bars 0.5 mm in a and 1 mm in b-f.

Phytoliths were very scarce in all samples (Tables 4 and 5), and silica skeletons were only found in sediment samples. Some phytoliths showed signs of chemical dissolution, but this trait was not generalised (Fig. 3).

Table 4. Results of phytolith, starch, soil pH and mineral component (FTIR) analyses from sediment samples. Phytolith concentration is expressed in phytoliths per g of AIF (Acid Insoluble Fraction). Starch concentration is expressed in grains per g of original sediment. - = sample not analysed. NB = not burned. B? = possibly burned. P = present. MP = marginally present.

	DTR 9	DTR 10	DTR 11	DTR 12	DTR 13	DTR 25	DTR 27	DTR 30	DTR 34	DTR 44
Phytoliths										
Silica skeletons										
Inflorescence	1	-	-	.	-	-	-	-	-	-
Leaf/culm	1	-	-	1	-	-	-	-	-	-
Total silica skeletons	2	-	-	1	-	-	-	-	-	-
Total cells in silica skeletons	5	-	-	2	-	-	-	-	-	-
Single cells										
Poaceae										
Long cells										
Leaf/culm	22	-	-	6	-	-	-	-	-	-
Undetermined	5	-	-	1	-	-	-	-	-	-
Bulliform (leaf)	4	-	-	2	-	-	-	-	-	-
Short cells										
Chloridoideae	2	-	-	2	-	-	-	-	-	-
Panicoideae	6	-	-	1	-	-	-	-	-	-
Pooideae	4	-	-	2	-	-	-	-	-	-
Undetermined	6	-	-	2	-	-	-	-	-	-
Dicotyledons	2	-	-	.	-	-	-	-	-	-
Undetermined taxa	84	-	-	37	-	-	-	-	-	-
Unidentified phytoliths	26	-	-	9	-	-	-	-	-	-
Total single cells	161	-	-	62	-	-	-	-	-	-
Phytolith concentration	598	-	-	157	-	-	-	-	-	-
Starch grains										
Fabaceae										
Faboideae	1	.	.	.	.	1	.	.	.	.
Poaceae										
Panicoideae										
Type 2	4	.	2	.	.	.	.	2	2	.
Type 3	.	.	1	.	.	.	.	1	.	.
cf Panicoideae	.	.	.	.	.	.	.	1	.	.
Pooideae										
Triticeae	.	.	1	.	.	1	.	.	1	.
Tuber undetermined 1	1	.	.	.	.	.	.	.	1	.
Damaged unidentified	.	1	.	.	.	.	.	1	.	.
Total starch grains	6	1	4	.	.	2	.	5	4	.
Starch concentration	14	2	11	.	.	5	.	13	10	.
Soil pH	8.61	8.55	8.59	8.46	8.46	8.63	8.47	8.56	8.34	8.49
Mineral components										
Clay	NB	B?	NB	NB	NB	NB	NB	B?	NB	NB
Quartz	P	P	P	P	P	P	P	P	P	P
Calcite	MP	MP	MP	MP	MP	MP	P	P	P	P

Table 5. Results of phytolith and starch analyses from grinding stones. Phytolith concentration is expressed in phytoliths per concentration is expressed in grains per g of original sediment. - = sample not analysed.

	GS 1	GS 2	GS 3	GS 4a	GS 4b	GS 5	GS 6a	GS 6b	GS 7	GS 8	GS 9	GS 10	GS 11a	GS 11b	GS 12a
Phytoliths															
Single cells															
Poaceae															
Long cells															
Leaf/culm	-	-	-	3	-	-	-	-	-	-	.	1	-	-	
Undetermined	-	-	-	.	-	-	-	-	-	-	.	1	-	-	
Bulliform (leaf)	-	-	-	3	-	-	-	-	-	-	.	1	-	-	
Short cells											.				
Chloridoideae	-	-	-	1	-	-	-	-	-	-	.	.	-	-	
Panicoideae	-	-	-	2	-	-	-	-	-	-	.	3	-	-	
Pooideae	-	-	-	5	-	-	-	-	-	-	.	4	-	-	
Undetermined	-	-	-	1	-	-	-	-	-	-	.	.	-	-	
Dicotyledons	-	-	-	.	-	-	-	-	-	-	.	1	-	-	
Undetermined taxa	-	-	-	6	-	-	-	-	-	-	.	5	-	-	
Unidentified phytoliths	-	-	-	8	-	-	-	-	-	-	.	3	-	-	
Total single cells	-	-	-	29	-	-	-	-	-	-	0	19	-	-	
Phytolith concentration	-	-	-	588	-	-	-	-	-	-	0	973	-	-	
Starch grains															
Fabaceae															
Faboideae	.	1	.	.	1	2	2	.	.	.	1	.	.	2	
Poaceae															
Panicoideae															
Type 1	1	.	1	.	.	.	8	.	.	.	1	.	.	.	
Type 2	2	2	1	3	.	.	44	.	.	1	1	1	.	2	
Type 3	.	1	.	.	.	1	.	2	.	2	.	.	.	1	
cf Panicoideae	.	.	1	.	.	.	1	.	.	.	2	.	.	.	

	GS 1	**GS 2**	**GS 3**	**GS 4a**	**GS 4b**	**GS 5**	**GS 6a**	**GS 6b**	**GS 7**	**GS 8**	**GS 9**	**GS 10**	**GS 11a**	**GS 11b**	**GS 12a**
Pooideae															
Triticeae	.	1	1	.	.	.	.	.	.	1	.	.	1	.	
cf Triticeae (spherical)	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
cf Triticeae (bell-shaped)	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Zingiberaceae	.	.	.	.	1	.	.	.	.	.	.	.	.	.	
Tuber undetermined 1	.	.	.	.	.	.	.	.	.	.	.	.	.	.	
Tuber undetermined 2	.	.	.	.	.	.	1	.	.	.	.	.	.	.	
Damaged unidentified	.	13	.	.	1	.	.	1	.	.	.	.	1	.	
Total starch grains	3	18	4	3	3	3	56	3	.	4	5	1	2	5	1
Starch concentration	679	816	303	56	132	319	4,079	294	.	134	773	46	375	263	22

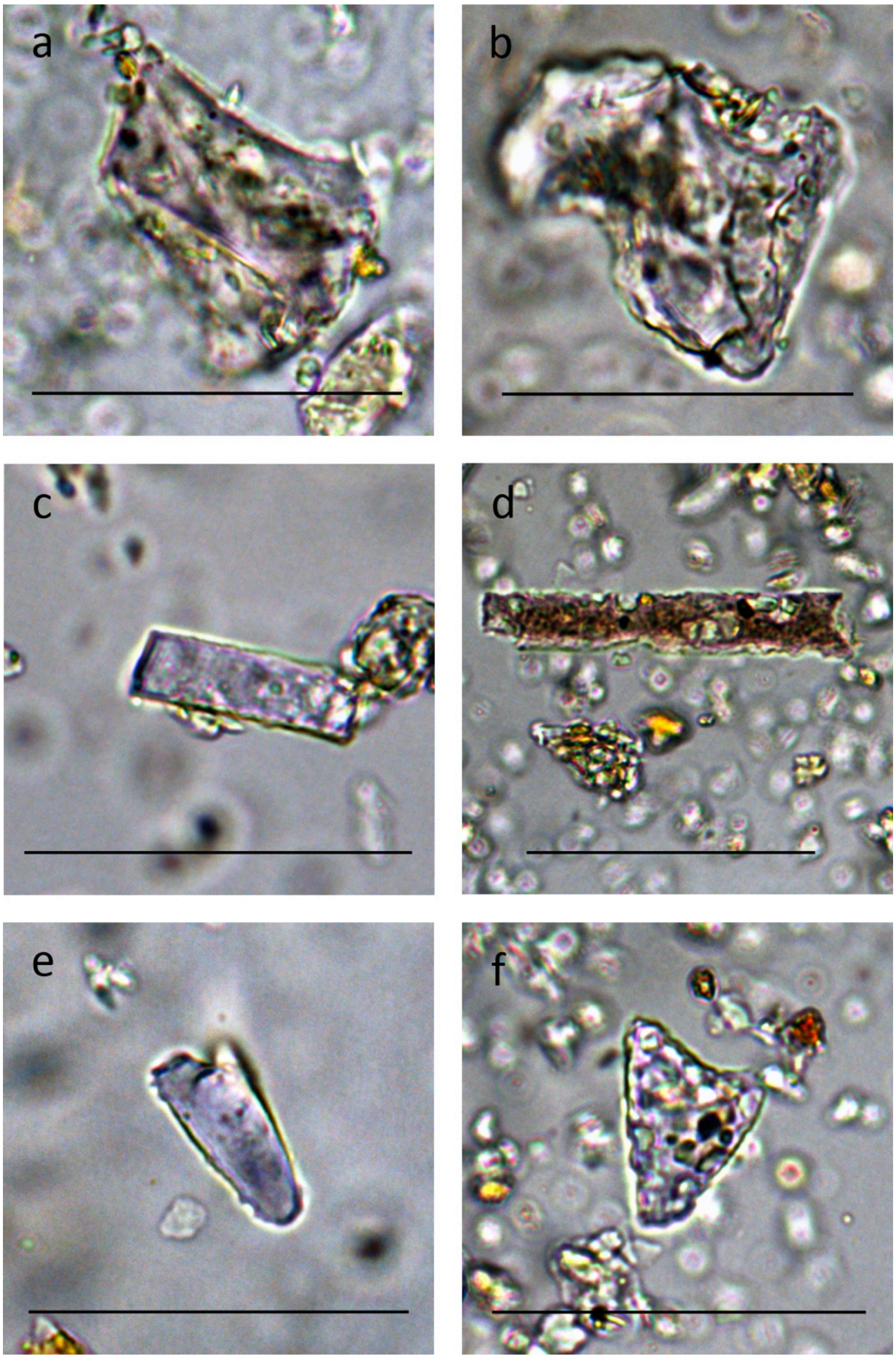

Figure 3. Phytoliths recovered from Datrana IV. a) bulliform cuneiform, b) taphonomised bulliform cuneiform, c) elongate psilate, d) taphonomised elongate psilate, e) trichome and f) taphonomised trichome. Scale bars 50 µm.

Starch grains were scarce in sediment samples but abundant on grinding stones (Tables 4 and 5, Fig. 4). In particular, samples GS 6a, GS 14 and GS 17 contained a high amount of Type 1 (3-10 µm) and Type 2 (10-20 µm) Panicoideae (Poaceae), most likely from small millets (Madella et al. 2013). A few Type 3 (>20 µm) Panicoideae and cf. Panicoideae grains were also recovered. The starch assemblage further included grains from the Triticeae tribe (Pooideae, Poaceae) –probably from wheat and/or barley (Yang and Perry 2013)– and the Faboideae subfamily (Fabaceae). Faboideae starch grains cannot be identified to genus or species level, and therefore they could belong either to local pulses –such as horsegram (*Macrotyloma uniflorum* (Lam.) Verdc.) or mung bean (*Vigna radiate* (L.) R.Wilczek)– or to Near Eastern crops such as lentils. Two morphotypes (tuber undetermined 1 and 2) could not be assigned to any specific taxonomic group but their morphology suggests they are most probably originating from underground storage organs (rhizomes/tubers), as does one grain belonging to the Zingiberaceae family (the ginger family). Finally, several starch grains could not be identified due to severe damage.

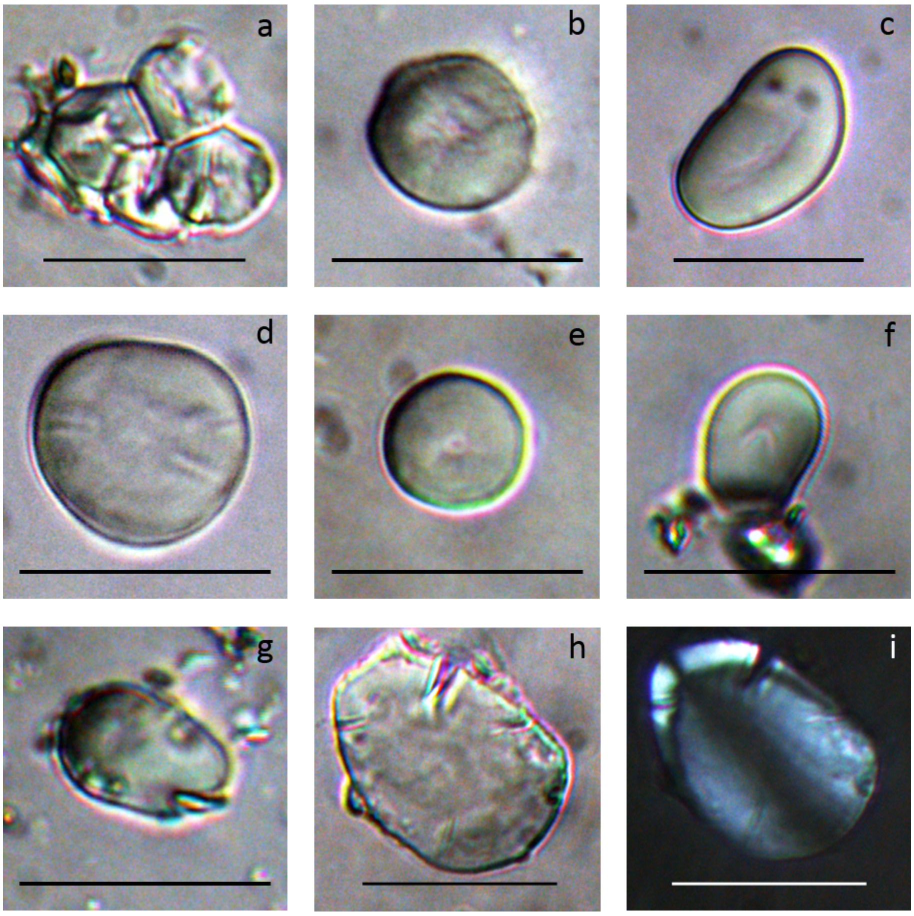

Figure 4. Starch grains recovered from Datrana IV. a) Panicoideae Type 2 grains, b) cf. Panicoideae grain, c) Faboideae grain, d) Triticeae grain, e) cf. Triticeae (spherical) grain, f) cf. Triticeae (bell-shaped) grain, g) tuber undetermined 1 grain, h-i) Zingiberaceae grain under transmitted (h) and cross-polarised light (i). Scale bars 20 µm.

Mineralogical and pH analyses

All sediment samples were mainly composed by quartz and clay, with a minor presence of calcite (Table 4). Overall, sediments from trash pits contained less calcite than those from general archaeological layers. Wood ash was the source of the calcite in samples DTR 25, 27, 30, 34 and 44, whereas it was not possible to assess the origin of the calcite in the remaining samples. Samples DTR 10 (trash pit) and 30 (cluster of burned carnelian) contained possibly burned clays. Soil pH values were moderately high throughout the sequence (Table 4), indicating the presence of slightly alkaline soils.

Discussion

Plant processing and consumption at Datrana IV

The scarcity of archaeobotanical remains at Datrana IV is to be interpreted in terms of the depositional and post-depositional processes that would have made possible their preservation. Plant remains are incorporated into the archaeological record as by-products of plant processing and consumption activities. The nature of such activities determines which plant remains are preserved and thus recovered in the archaeobotanical assemblage. The different types of plant remains analysed in this study represent diverse processing and consumption activities and have different preservation pathways (García-Granero et al. 2015). Therefore, understanding the depositional and post-depositional processes that may have affected their preservation allows for the reconstruction of the plant-related activities that took place at the site.

The local ecological settings –high soil salinity and alkalinity, wet-dry monsoon cycles– may have negatively affected the preservation of certain plant remains. Macrobotanical remains are usually preserved charred as a result of fire activities related to plant processing (roasting, parching, cooking), fuel use and cleaning episodes (van der Veen 2007). The scarcity of wood charcoal, charred seeds and fruits and phytoliths from woody taxa might indicate that a) fire was not an important element of the daily life of the inhabitants of this lithic workshop, b) post-depositional processes have prevented their preservation or c) this activities were carried out in a different part of the site. The absence of hearths and ash concentrations and the predominance of unburned clays support the former hypothesis. However, the presence of charred faunal remains, burned carnelian nodules and wood ash calcite indicates the existence of some sort of combustion. Overall, this evidence suggests that fire was present but its use was not widespread throughout the site, and therefore the scarcity of charred macrobotanical remains might be due to a) high soil alkalinity (e.g. Braadbaart et al. 2009; Cohen-Ofri et al. 2006; Schiegl et al. 1996), b) the repetitive occurrence of water run-off during the heavy rains of the Indian Summer Monsoon that might have exposed the occupational surfaces or c) anthropogenic factors such as trampling, re-working and cleaning episodes.

Phytoliths are mostly produced in non-edible plant parts and are therefore indicative of plant processing activities, mainly grasses (Harvey and Fuller 2005; Piperno 2006). Several post-depositional processes may affect the preservation of phytoliths (Madella and Lancelotti 2012 and references therein). In particular, soil alkalinity and burning may cause phytolith dissolution (Cabanes et al. 2011; Fraysse et al. 2006), although phytoliths have been recovered from highly alkaline soils and charred deposits (Piperno 2006). Phytoliths were very scarce at Datrana IV, and some of them presented signs of dissolution. A plausible cause of phytolith dissolution is the repetitive occurrence of monsoonal water run-off, particularly if the site was unoccupied for long periods of time. This possibility is suggested by the similarity of the mineralogical composition of a control sample from a nearby interdunal deposit (Balbo et al. 2014) with sample DTR 9, the top-most archaeological layer. This layer would be exposed for long periods of time, thus maximising the effect of post-depositional processes on plant remains. However, sediment alkalinity and water flow, and hence dissolution, cannot be considered as the only cause for the absence of phytoliths since phytoliths have been recovered from archaeological contexts in North Gujarat with equally alkaline soils (García-Granero et al. in press). Moreover, the presence of wood ash calcite in some of the samples attests for the good state of preservation of sediments, and therefore the absence of phytoliths –particularly from trash pits– cannot be solely explained as a result of post-depositional processes and must be interpreted in terms of past human activities. Thus, the scarcity of phytoliths suggests that non-edible plant parts were not being processed at Datrana IV. Another plausible explanation is that crop-processing activities took place in another area of the site, and the area excavated in 2010 was devoted exclusively to craft production.

The scarcity of phytoliths contrasts with the relative abundance of starch. Starch grains are mostly produced in edible plant parts, such as seeds, fruits and roots (Torrence 2006), and their presence in grinding tools indicates that they were used for grinding food. Starch grains are less resistant to taphonomic processes than phytoliths, and their presence further reinforces the hypothesis that the absence of phytoliths is the result of human practices. The relative abundance of starch grains in grinding tools and their scarcity in sediment samples can be explained by the preferential preservation of starch in artefacts (Haslam 2004).

Overall, the evidence from Datrana IV suggests that the inhabitants of this lithic workshop consumed mostly local summer crops such as small millets, the staple of contemporaneous food-producing communities in North Gujarat (García-Granero et al. in press). Near Eastern winter crops, probably cultivated in the Indus Valley, were also a marginal part of the diet. The scarcity of phytoliths from both summer and winter cereals indicates that either a) crops were processed in other area of the site or b) they were not processed on site but acquired de-husked. De-husked cereals are more prone to be affected by pests when stored for long periods of time (Bouby et al. 2005; Reddy 1997), and therefore food would have been acquired in a ‘ready-to-consume’ state.

The first hypothesis is concomitant with a well-structured division of working space for diverse routine daily activities. The inhabitants of Datrana IV would engage not only on specialised craftsmanship but also on food production (third hypothetic scenario). Monsoon-adapted small millets could have been cultivated in the large interdunal depression adjacent to the dune, which is a naturally fertile ground due to water retention after the monsoonal rains (Conesa et al. 2014). It is worth highlighting that the area excavated in 2010 presented the highest concentration of surface lithic material, an it is thus possible that craftsmen and women worked in this area while other daily routines were carried out elsewhere. Archaebotanical samples from a larger extension of the site should be analysed in order to understand possible spatial division of labour.

Unfortunately, this is no longer possible because an extension of the Narmada canal in 2014 cut across the Datrana archaeological complex, completely destroying it (S.V. Rajesh pers. comm.).

The second hypothesis fits with the second hypothetic scenario, in which only specialised craftsmen and women migrated from Sindh, and food was obtained through exchange with local hunter-gatherer and agro-pastoral groups. Plant foodstuffs could have been acquired from neighbouring millet-producing communities, such as the inhabitants of the Chalcolithic settlement of Loteshwar (ca. 3700-2200 cal BC). This model implies a high level of interaction between the inhabitants of Datrana and the native inhabitants of North Gujarat, a situation in which two communities would occupy the same ecological niche but different economic niches, carrying out complementary activities: food production and specialised craftsmanship.

As a result of such interaction crafts produced at Datrana IV (blades and stone beads) should appear in the archaeological record of contemporary occupations in North Gujarat. The archaeological record of the later fourth millennium BC in North Gujarat (and Gujarat in general) is, however, scant. Only two radiocarbon-dated sites fall into this chronology –Loteshwar in North Gujarat and Padri in the eastern Saurashtra coast–, and the kind of crafts produced at Datrana IV were not encountered at either of them (Ajithprasad 2002, 2011). The only site with similar material culture (including Pre-Prabhas pottery) is Somnath, in southern Saurashtra, which was radiocarbon dated to the early third millennium BC, suggesting a migration process from Datrana to Saurashtra.

At present we lack enough evidence to favour one hypothesis over the other. Moreover, they are not mutually exclusive: plant foodstuffs could have been acquired through on site production and also traded with local populations. In any case, it seems clear that craftsmanship and food acquisition were independent but somehow integrated activities at Datrana IV.

Datrana in a regional perspective

The archaeological record found at Datrana IV clearly advocates for its function as a specialised production centre. The workshop is located in the centre of the natural corridor between Sindh and Gujarat and near the seasonally navigable Ranns of Kachchh, advocating for trade as the major purpose driving specialised production. However, chalcedony blades are seldom reported from Early Harappan sites in Sindh or Baluchistan (Pakistan) (Cleland 1977). Instead, chert from the Rohri hills was exploited from the very beginning of the Early Harappan period using the crested ridge technique (Biagi and Cremaschi 1991). The only exception to this is Kalibangan (Haryana, India), where the Early Harappan lithic industry incorporates local chert, chalcedony and jasper due to the inaccessibility of Rohri chert and the availability of local raw material in the region (Lal et al. 2003).

Carnelian beads, on the other hand, are found throughout the Indus Valley (Kenoyer 1991b; Law 2011), suggesting that Datrana may have functioned as a bead-production centre. However, a preliminary assessment of the beads produced at Datrana IV indicates that the technique employed for their production is somehow different than the technique used to produce the beads usually found in Harappan sites. Therefore, until an in-depth study of the bead-production technique is carried out, the presence of beads produced at Datrana IV beyond this site cannot be ascertained.

The lack of a clear distribution network suggests that the production was probably not controlled but ruling elites but by the craftsmen and women themselves (Shafer and Hester 1991). However, the final destination of such massive production (particularly of chalcedony blades) is currently unclear. Further studies are needed to fully understand the function of Datrana at a local and regional level. Future research needs to address the mineralogical origin of carnelian beads found throughout Indus Civilisation sites to test the hypothesis that the crafts produced at Datrana were part of interregional trade networks. Moreover, the study of faunal remains and residue analyses on pottery, both ongoing, will help to further understand the subsistence strategies developed by these craftsmen and women over 500 km from their region of origin, and how were they integrated in the local socio-ecological dynamics.

Conclusions

Lithic tools were fundamental for most prehistoric societies, and thus the exploitation of lithic resources was an important aspect of prehistoric land use and adaptation. The importance of lithic materials has long been acknowledged by archaeologists, who have studied several characteristics of the lithic technology –the use of different raw materials and quarrying techniques, the spatio-temporal spread of lithic tools, etc.– for over a century. However, research has often underestimated the impact of lithic workshops at a smaller (local) scale. This study highlights the integration of a lithic workshop within its surrounding cultural and natural landscape. Moreover, the evidence from Datrana IV highlights the need for taking into account the effect of taphonomic processes when interpreting archaeobotanical assemblages, as well as the benefits of a multi-proxy approach when studying past plant exploitation strategies. In this study, the integration of charred macroremains, phytoliths and starch grains helped overcoming taphonomic biases, thus offering a broad picture of the food acquisition strategy at Datrana IV.

Acknowledgements

Fieldwork at Datrana IV was funded by the Spanish Ministry of Education, Culture and Sport (Programa de Ayudas para Proyectos Arqueológicos en el Exterior 2010), and laboratory work was funded by the Spanish Ministry of Economy and Competitiveness (Programa I+D, HAR2010-16052). We are grateful to the members of the NoGAP for their help during fieldwork, to Débora Zurro and Jorge Caro-Saiz for numerous discussions, and to the Archaeological Survey of India for granting excavation permission. JJGG acknowledges funding from a JAE-PreDOC doctoral research grant (Spanish National Research Council and European Social Fund).

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García-Granero JJ, Lancelotti C, Madella M (submitted) Grinding for survival: a microbotanical approach to Holocene subsistence strategies in semi-arid northern Gujarat (India). Veget Hist Archaeobot

Grinding for survival: a microbotanical approach to Holocene subsistence strategies in semi-arid northern Gujarat (India)

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Paper submitted to Vegetation History and Archabotany on 26 January 2015

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Abstract

The thorough reconstruction of subsistence practices throughout human history remains one of the most challenging questions in archaeological research. Analyses of microbotanical remains recovered from archaeological artefacts have greatly contributed to our knowledge of past livelihood strategies. The aim of this paper is to study the changes in plant-related subsistence strategies in northern Gujarat (NW India) throughout the Holocene through the analysis of phytoliths and starch grains from grinding stones. Moreover, this paper addresses a series of methodological issues of the analysis of microremains from grinding stones, including the integration of multiple proxies, the comparison between samples and the interpretation of control samples. A total of 80 samples from grinding tools from four archaeological occupations were analysed. The results were compared with 26 control samples from the same sedimentary matrix from which the tools were recovered and 12 control samples from laboratory consumables. Multivariate statistics were applied to a) compare samples from different sites, b) compare control samples with grinding stones to assess sample contamination and representativeness, and c) identify tool clusters within a site. The results show that the inhabitants of northern Gujarat continuously exploited small millets throughout the Holocene and that pulses, secondary at first, became a fundamental part of their subsistence strategy with the advent of settled life. Moreover, this study stresses the importance of the integrated analysis of phytoliths and starch grains and the application of multivariate statistics, which allow for stronger interpretations on the use and post-depositional trajectories of grinding stones, thus offering a solid framework for the reconstruction of past subsistence strategies.

Keywrods: grinding stones; phytoliths; starch grains; methods; archaeobotany; South Asia

Introduction

The study of archaeological artefacts has often focused on the identification of different chrono-typological categories. However, the development of novel approaches in archaeobotany, residue (e.g. lipids) and use-wear analyses is opening major inroads for a better understanding of artefact use (see e.g. Barton et al. 1998; Craig et al. 2000; Kealhofer et al. 1999). This knowledge is crucial to identify choices regarding food collection and preparation (gathering/harvesting, processing and cooking) that can inform about human behaviour, cultural preferences and socio-ecological dynamics of past human populations.

Plant microremains such as phytoliths and starch grains are often preserved in archaeological contexts (see Piperno 2006 for phytoliths; and Torrence 2006: Table 1.1

for starch grains). During the last two decades (bio)archaeologists have turned their attention to these proxies as potential indicators of human and animal diet (e.g. Henry and Piperno 2008), agricultural practices (Madella et al. 2009; Rosen and Weiner 1994), plant domestication processes (e.g. Perry et al. 2007; Piperno and Flannery 2001), non-dietary plant exploitation strategies (Albert et al. 2003; Balbo et al. 2012; Lancelotti and Madella 2012; Lancelotti et al. 2014; Madella et al. 2002), the use of domestic space (e.g. Balme and Beck 2002; Portillo et al. 2009) and the reconstruction of palaeoenvironmental conditions (e.g. Boyd et al. 1998; Lentfer et al. 2002).

The potentials of microresidue studies from stone tools have long been recognised (Briuer 1976). However, analyses of microbotanical remains from grinding stones only recently started to be carried out routinely as part of the archaeobotanical research within archaeological projects. Notwithstanding the relatively recent development of this research area, analyses of plant microremains recovered from grinding stones have greatly contributed to the understanding of plant-related subsistence strategies worldwide (see e.g. Liu et al. 2011 in East Asia; Field et al. 2009 in Oceania; Piperno and Holst 1998 in the Americas; Radomski and Neumann 2011 in Africa; and Aranguren et al. 2007 in Europe). Despite the current proliferation of phytolith and starch grain studies from grinding stones, only few analyse both proxies in an integrated approach –i.e. aiming at answering the same research questions and with a combined extraction from the same sample (Dickau et al. 2012; Pearsall et al. 2004; Perry et al. 2006; Piperno et al. 2009; Zarrillo et al. 2008). An integrated analysis enables the identification of a wider range of plants and plant parts and offers the possibility to overcome some taphonomic biases that affect either phytoliths or starch grains, resulting in a higher representativeness of the original input (García-Granero et al. 2015; Piperno 2009).

Northern Gujarat (northwestern India) is a semi-arid (400-600 mm of annual rainfall) ecotone located between the Thar Desert and the semi-humid South Gujarat (Fig. 1). Holocene plant-related subsistence strategies in the region are poorly understood, especially the transition from gathering to cultivation (Fuller 2006; Sonawane 2000). The local ecological conditions –high soil salinity and dry-wet monsoon cycles– hamper the preservation of macrobotanical remains (seeds, fruits and wood charcoal), resulting in an incomplete archaeobotanical record. The scarcity of macrobotanical remains, particularly in Early-Middle Holocene contexts, impedes a diachronic analysis of subsistence strategies. However, grinding stones are ubiquitous in the archaeological record, allowing for the recovery and analysis of microbotanical remains and thus offering a comparable framework to study subsistence shifts during the Holocene.

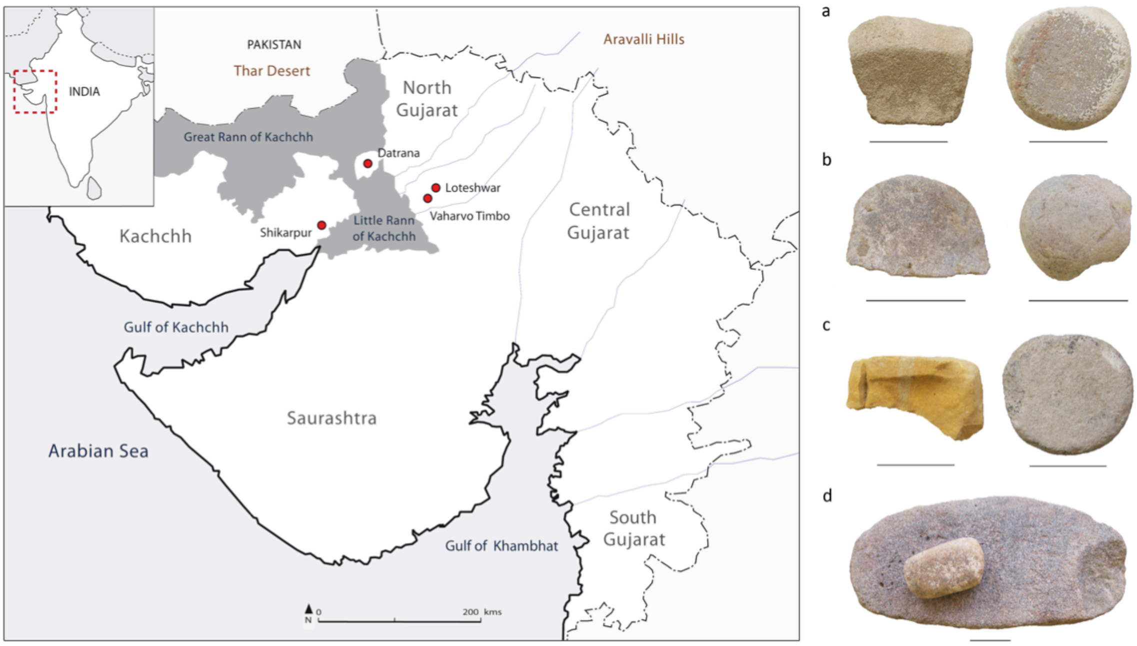

Figure 1. Map of Gujarat showing the location of the sites and examples of grinding stones analysed in this study. a) Vaharvo Timbo, b) Loteshwar, c) Datrana IV and d) Shikarpur. Scale bars 5 cm. Map by Francesc. C. Conesa.

The aim of this paper is to study the changes in plant-related subsistence strategies in northern Gujarat during the Holocene by analysing phytoliths and starch grains from grinding stones. Moreover, we address the following methodological issues, which can contribute to a better understanding of the produced data and its interpretation:

1. The integration of phytolith and starch grain analyses.
2. The comparison between different types of tools/sites.
3. The interpretation of control samples.

Materials and Methods

Grinding stones were collected from four archaeological deposits excavated between 2009 and 2012 in northern Gujarat, with a chronology spanning most of the Holocene: Vaharvo Timbo (VHV), Loteshwar (LTS), Datrana IV (DTR) and Shikarpur (SKP) (for information about the sites see Balbo et al. 2014; Bhan and Ajithprasad 2008; Gadekar et al. 2013, 2014a, 2014b; García-Granero et al. 2015, in press; Madella et al. 2010; Patel 2009; Rajesh et al. 2013). Samples from VHV, DTR and SKP are from a single occupational period; whereas samples from LTS span from hunter-gatherer (HG) to agro-pastoral (AP) occupations, with a mixed deposit between the two (MIX) (Table 1).

The morphology of a grinding tool cannot be used as a diet indicator; however, it can suggest the overall strategy of food processing (Wright 1994). In northern Gujarat, the different types of tools reflect the nature of the occupations from which they were recovered. Thus, the assemblages from VHV, LTS and DTR are composed by small, portable tools, characteristic of seasonal camps occupied by hunter-gatherers and semi-nomadic agro-pastoralists; whereas the tools recovered at SKP, an Urban Harappan centre, are relatively large implements characteristic of agricultural settlements (Fig. 1).

Table 1. Context of the archaeological samples analysed in this study.

Site	Code	Chronology (ca cal BC)	Type of occupation	# of artefacts	# of samples	# of control samples
Vaharvo Timbo	VHV	ca 5600-5000	Hunter-gatherer camp	19	20	4
Loteshwar (hg)	LTS	ca 7500-5500	Hunter-gatherer camp	4	5	1
Loteshwar (mix)	LTS			4	5	1
Loteshwar (ap)	LTS	ca 2700-2300	Agro-pastoral camp	5	9	4
Datrana IV	DTR	ca 3300-3000	Agro-pastoral camp	17	21	5
Shikarpur	SKP	ca 2200-1900	Urban settlement	18	20	11

Microbotanical remains were extracted and analysed from 67 grinding stones for a total of 80 samples –multiple surfaces and broken pieces from the same tool were analysed separately (Table 1). In addition, an aggregate of 26 control samples from archaeological contexts and 12 test samples from laboratory consumables were analysed. A morphotypological description of the 67 grinding stones analysed in this study, following the descriptive terms proposed by Wright (1992), can be found in the supplementary material (Table S1).

Field sampling

In order to minimise the possibility of contamination during the recovery of artefacts, direct touching of the used surface/s of the grinding stones with bare hands was avoided and powder-free gloves were used when available. After retrieval, the single artefact was bagged in a zip-lock plastic bag and sealed. The bag containing the artefact together with a label tag was placed into a second bag.

Small zip-lock plastic bags with approximately 25 g of sediment from the context related to the artefact –the area surrounding the artefact, but not the sediment directly in contact with it– were collected as control samples. In order to average the signal and avoid the possibility of unintentionally recover sediment representing a specific activity area, control samples were gathered from different spots all around the artefact. When two or more artefacts were recovered from the same archaeological context, a single control sample was collected for all of them.

Microremains recovery

The recovery of plant microremains took place in a controlled environment –a clean, closed room with no airstream– at the Department of Archaeology and Ancient History, M. S. University of Baroda (India). To create a clean working surface, laboratory paper was used and disposed after each sample processing. The instruments were cleaned between artefacts and rinsed with distilled water. A new set of powder-free gloves was used for each step of the procedure.

The residue was recovered by dry and wet brushing as described by Chandler-Ezell and Pearsall (2003). When dealing with artefacts too big to be single-handled (e.g. querns), a pipette was used to recover and transfer the wet sediment directly into a previously weighed centrifuge tube. Sonication was not carried out because some grinding stones were too big to fit in the ultrasound –thus impeding protocol standardisation– and several had two used surfaces (Table S1). To facilitate transportation, wet samples were left to settle for at least 24h and then decanted. All further extraction steps and analysis were carried out at the BioGeoPal Laboratory (IMF-CSIC, Barcelona, Spain).

The likeliness of contamination from the archaeological sediments is higher in the first layer of sediment attached to the artefact (dry sample), and once this layer is removed it decreases considerably (Hart 2011). Thus, comparing the wet sample with the control sample offers a more robust framework to understand if the residue recovered from the grinding stones resulted from the actual use of the tool and not from a posterior contamination. Therefore, we decided to process and analyse only the wet and control samples, whereas the dry sample was stored for future reference.

Microremains extraction

To minimise contamination, and similarly to previous stages, clean equipment was used at all times, as well as new Pasteur pipettes for each sample. Recently, Crowther et al. (2014) called attention to the likelihood of starch contamination from laboratory consumables (e.g. gloves). In this study, laboratory consumables were tested *a posteriori*. The methods employed to collect and analyse control samples from laboratory consumables were designed to allow for comparability with the archaeological samples (see Supplementary Information).

One of the aims of this study was to extract both phytoliths and starch grains from the same initial sediment sample (following the example of Chandler-Ezell and Pearsall 2003), thus the same protocol –a combination of those published by Horrocks (2005) and Madella et al. (1998)– was used for grinding stones and control samples (Table 2). Chemicals were applied in a pre-set sequence in order to prevent any damage to the starch grains, which are degraded or destroyed by HCl and H_2O_2 (Chandler-Ezell and Pearsall 2003; Coil et al. 2003). Furthermore, before starch recovery the temperature was always kept below 40 ˚C to prevent starch gelatinisation (Gott et al. 2006).

Table 2. Protocol for the combined extraction of phytoliths and starch grains from grinding stones.

Step	Process	Aim
1	Top up the tubes with distilled H_2O, centrifuge for 5’ at 3000 rpm and decant. Dry into the oven (<40°C) and weigh the tube with the residue.	Weigh residue
2	Top up the tubes containing the samples with a 5% weight solution of Sodium Hexametaphosphate, shake and leave overnight.	Deffloculate clays
3	Shake the samples and then centrifuge for 3’ at 1500 rpm and discard the supernatant. Top up with distilled H_2O and repeat this step at least three more times (more if the supernatant is still not clear). Dry into the oven (<40°C).	
4	Add 5 ml of Sodium Polytungstate (SPT) with a specific gravity of 1.8 g/cm^3, shake and centrifuge for 3’ at 1500 rpm.	Recover starch grains
5	Recover the floating fraction with a Pasteur pipette and transfer to labelled new tubes.	
6	Top the recovered floating fraction up with distilled H_2O and centrifuge for 3’ at 3000 rpm.	Remove SPT
7	Decant pouring just half of the content of the tubes. Top up with distilled H_2O, shake gently and centrifuge for 3’ at 3000 rpm four more times. Do not decant the tubes after the last centrifuge. Instead, pipette out the supernatant leaving about 5-10 ml in the tube.	
8	Transfer the starch residue to a labelled glass vial with distilled H_2O and dry into the oven (<40°C). Starch samples are ready to be mounted or stored.	Store starch residue
9	Top the original tubes up with distilled H_2O, centrifuge for 3’ at 1500 rpm and discard the supernatant. Top up with distilled H_2O and repeat this step at least three more times (more if the supernatant is still not clear).	Remove SPT
10	Add up to15 ml of a 5% solution of HCl. Place the tubes with the samples in a water-bath at approx. 40°C until the reaction stops (i.e. no more bubbling occurs when adding a drop of HCl). Do not seal the tubes to allow for gas releasing. Stir occasionally.	Eliminate carbonates
11	When the reaction stops, top up with distilled H_2O, shake gently and centrifuge for 3’ at 1500 rpm and discard the supernatant. Repeat this step at least three more times (more if the supernatant is still not clear).	Remove HCl
12	Add up to 15 ml of 33% volume H_2O_2. Place the tube in a water-bath at approx. 40°C until the reaction stops (i.e. no more bubbling occurs when adding a drop of H_2O_2). Do not seal the tube to allow for gas releasing. Stir occasionally.	Eliminate organic matter
13	When the reaction stops, top up with distilled H_2O, shake gently and centrifuge for 3’ at 1500 rpm and discard the supernatant. Repeat this step at least three more times (more if the supernatant is still not clear). Dry and weigh the tube with the Acid Insoluble Fraction (AIF) of the sample.	Remove H_2O_2
14	Add 10 ml of a solution of SPT with a specific gravity of 2.35 g/cm^3, shake gently and centrifuge for 3’ at 1500 rpm.	Recover phytoliths
15	Recover the floating fraction with a Pasteur pipette and transfer it to a labelled new tube. Shake gently and centrifuge the remaining suspension for 3’ at 1500 rpm and recover again. The entire floating fraction has to be recovered.	
16	Top the recovered floating fraction up with distilled H_2O and centrifuge for 3’ at 2000 rpm.	Remove SPT
17	Pour out the supernatant leaving only the residue at the bottom. Top up with distilled H_2O, shake gently and centrifuge for 3’ at 2000 rpm three more times.	
18	Label and weigh a glass vial. Transfer the silicates to the vial with distilled H_2O and dry.	Store phytolith residue
19	Weigh the vial with the silicates. Phytoliths samples are ready to be mounted or stored.	

Phytolith analysis

To prepare phytoliths for observation, ca. 1 mg of residue was placed on a microscopy slide and mounted with Entellan®. Slides were first quick-scanned at 200x magnifications to obtain an estimate of the phytolith concentration and to identify possible diagnostic morphotypes (Piperno 2006: 102). Counting was carried out at 630x magnifications using a DM 2500 microscope equipped with a Leica DF 470 camera for microphotography. When possible, 300 identifiable single-cell phytoliths were counted. Since phytoliths do not distribute uniformly on the slide (Zurro 2011), different areas were randomly scanned during counting. In samples with very low phytolith concentrations the whole slide was scanned, and those with less than 100 phytoliths per slide were considered sterile. When present, multi-cell phytoliths (silica skeletons) were counted independently and photographed to allow further analysis, since they can be taxonomically diagnostic at genus or even species level (Ball et al. 1996, 1999, 2009; Madella et al. 2013; Portillo et al. 2006). Phytoliths forming each silica skeleton were individually counted and described using the International Code for Phytoliths Nomenclature (ICPN – Madella et al. 2005).

Concentration was calculated per g of AIF (Acid Insoluble Fraction) according to the formula proposed by Albert and Weiner (2001):

$$C = \frac{P\left(\frac{A}{a}\right)\left(\frac{S}{s}\right)}{AIF}$$

where P is the total number of phytoliths counted (including those phytoliths part of silica skeletons and unidentified phytoliths), A is the total area of the slide, a is the area of the slide effectively scanned (i.e. area of visited fields of view), S is the weight of total silicates in the sample (after recovery with 2.35 s.g. SPT), s is the weight of silicates mounted on the slide and AIF represents the fraction of the sample not dissolved by chemicals.

Starch grain analysis

To prepare a starch sample, 200 µl of distilled water were added to the vial containing the dry starch residue. A pipette tip was used to mix the residue and 20 µl of liquid were placed on a slide, covered with a Petrie dish to avoid contamination and allowed to dry under the fume cupboard. Once the residue was dry, a drop of 50% glycerol was added and transparent nail polish was applied to each corner of the cover to fix it to the slide. By measuring the exact quantity of liquid placed on a slide (20 µl) the percentage of starch residue analysed per sample is standardised (10%), thus allowing for a quantitative analysis of the results.

The whole slide was scanned under cross-polarised light at 200x magnifications, and grains were photographed and described under both transmitted and cross-polarised light at 630x magnifications. Grain features were described using a set of pre-established parameters (Table S2) according to the International Code for Starch Nomenclature (ICSN 2011).

The concentration of starch grains was calculated per gram of initial weight of the sediment processed for microremains extraction, either from artefact or sediment samples, through the formula:

$$C = \frac{SG * R}{initial\ sed}$$

where *SG* is the total number of starch grains encountered and *R* is the reciprocal of the fraction of residue effectively analysed –in this case 1/10, and therefore *R*=10. This formula allows for the comparison of samples regardless to the fraction of residue analysed simply modifying the value of *R*.

Data analysis

Statistical analyses, performed with the free software R (R Development Core Team 2014 – the scripts can be found in the supplementary material), aimed at:

1. Testing the correlation between the total number of microbotanical remains and initial sediment weight through simple regressions to understand how sample weight affects the likelihood of recovering phytoliths and starch grains.
2. Identifying patterns in data between sites and periods through Principal Component Analysis (PCA) to understand differences and similarities in the microbotanical assemblages.
3. Comparing the results of phytolith analyses from grinding stones and archaeological control samples through indices of compositional similarity based on morphotypes abundance to establish the primary context of the microremains.
4. Identifying groups of tools within the same site also through indices of similarity to recognise possible spatial patterns and understand the post-depositional trajectories of the artefacts.

Samples from the HG and MIX deposits from LTS are always plotted together due to the low number of samples from each context. For multivariate statistical analyses (PCAs and indices of similarity), phytolith morphotypes were grouped into 12 categories in order to reduce the number of variables, facilitate the interpretation of the results and allow for comparability between samples (Table S3). Starch grains were classified according to groups identified during the microscopic analysis (Table S4). For the PCAs, the phytolith and starch grain counts were normalised by log10 transformations, to minimise the impact of the variables variance. A plot with the two first Principal Components of the PCA (PC1 and PC2) is shown for visualisation, with ellipses around the 95% confidence interval of the mean.

The method used to calculate the compositional similarity indices includes the effect of unseen shared species, which makes it less biased than classic indices when a substantial proportion of species are missing from samples (Chao et al. 2005). This is particularly relevant when working with archaeobotanical data, where a particular taxon (a species or morphotype) may be absent from most samples. The compositional similarity indices were plotted as dendrograms, where the clusters were defined by the 0.95 percentile of the index score.

Results

Laboratory control samples

Among the four brands of powder-free gloves used in this study, only one contained a significant amount of starch grains (Table 3) –mostly Type 1b/c (Panicoideae), characteristic of corn (*Zea mays* ssp. *mays* L.), the most common source of commercial starch (Crowther et al. 2014). These gloves were used exclusively during the extraction of microbotanical remains from samples from VHV, where Type 1b/c starch grains were the most commonly recovered (García-Granero et al. in press). As we cannot exclude that the starch assemblage from VHV is not the result of contamination during laboratory processing, these samples have been excluded from the statistical analysis.

No significant amounts of starch grains (≤1) were recovered from the other laboratory consumables used during the different stages of this study, and no phytolith was encountered on any laboratory control sample.

Table 3. Starch grains encountered in control samples from laboratory consumables analysed in this study. A description of the types can be found in Table S4.

ID	Type 1	Type 2	Type 4	Type 8	Unid	Total
Gloves (brands)						
Care Supply	.	.	.	.	1	1
Kimberly-Clark	.	.	.	.	.	0
Naturflex	.	.	.	.	.	0
Cuatrogasa	60	1	.	1	.	62
Tube 1	.	.	1	.	.	1
Tube 2	.	.	.	.	.	0
Paper	.	.	.	.	.	0
Beaker	.	.	.	.	.	0
Vial	.	.	.	.	.	0
Glycerine 50%	.	.	.	.	1	1
SPT 1.8	1	.	.	.	.	1
Calgon	.	.	.	.	.	0

Archaeological control samples

Phytoliths were abundant in control samples from LTS and SKP, whereas in VHV and DTR they were very scarce (Table 4). In the latter, only a few control samples were analysed due to the scarcity of phytoliths on grinding stones. Samples with <100 encountered phytoliths were excluded from the similarity analysis. Only a few samples were available from VHV and LTS, and therefore they were analysed and plotted together (Fig. S1). Samples from SKP were analysed and plotted independently (Fig. S2). The analyses confirmed that most grinding stones do not cluster with their corresponding control sample, except for samples LTS_GS1a, LTS_GS7b and SKP_Hand4, which were therefore excluded from subsequent analyses.

Starch grains were very scarce (0-6 grains) in most control samples, with the exception of some samples from SKP that contained up to 54 grains (Table 4). Control samples generally presented lower starch concentration than grinding stones (Tables 4 and 5).

Table 4. Results of the phytolith and starch grain analyses from archaeological control samples. Phytolith concentration per g of AIF (Acid Insoluble Fraction). Starch grain concentration per g of original sediment. - = sample not analysed.

Site	ID	Sediment weight (g)	AIF weight (g)	Phytoliths		Starch grains	
				count	concentration	count	concentration
VHV	Control 1	3.8750	2.9389	164	1,781	1	3
VHV	Control 2	4.1154	2.6981	-	-	3	7
VHV	Control 3	3.9771	2.2265	-	-	2	5
VHV	Control 4	4.1623	2.3317	-	-	3	7
LTS	Control 1	4.1047	3.5314	363	6,304,071	0	0
LTS	Control 2	3.8926	3.2360	373	15,121,158	5	13
LTS	Control 3	4.1524	3.4775	378	12,589,753	1	2
LTS	Control 4	4.0684	3.1576	339	582,561	2	5
LTS	Control 5	3.8050	2.5614	534	710,819	3	8
LTS	Control 6	4.1879	3.4963	323	3,905,329	3	7
DTR	Control 1	4.1894	3.5332	166	598	6	14
DTR	Control 2	4.1514	3.3565	-	-	1	2
DTR	Control 3	4.1539	3.6191	64	157	0	0
DTR	Control 4	3.9993	3.4678	-	-	0	0
DTR	Control 5	4.1301	3.2449	-	-	0	0
SKP	Control 1	4.1143	3.0780	319	1,820,230	6	15
SKP	Control 2	4.2425	3.1336	335	837,048	30	71
SKP	Control 3	3.9155	3.1191	310	1,530,812	6	15
SKP	Control 4	3.9929	3.1596	300	282,607	10	25
SKP	Control 5	3.8640	2.8502	309	607,404	2	5
SKP	Control 6	4.0670	2.9560	298	725,916	5	12
SKP	Control 7	3.9291	2.8521	313	649,305	0	0
SKP	Control 8	3.8521	2.6259	304	589,989	53	138
SKP	Control 9	3.8437	2.8208	303	1,062,273	54	140
SKP	Control 10	4.1046	3.2049	319	1,428,320	1	2

Site	ID	Sediment weight (g)	AIF weight (g)	Phytoliths		Starch grains	
				count	concentration	count	concentration
SKP	Control 11	4.0344	2.8577	306	433,430	3	7

Grinding stones

Phytoliths were present in all the samples from SKP, absent from all samples from DTR and variable in samples from VHV and LTS (Table 5). Samples from VHV showed a medium correlation (R^2=0.63) between the total number of phytoliths and the initial sample weight (samples <0.3 g are sterile), whereas samples from LTS did not show any correlation (Fig. 2a).

Grasses dominated the phytolith assemblage in all samples, with panicoids being the most common grass subfamily in VHV, LTS_AP and, especially, SKP (Fig. 3a). Non-grass phytoliths –including sedges (Cyperaceae) and dicotyledons– were marginally present in all sites, whereas palms (Arecaceae) were encountered only in samples from VHV and SKP. Taxonomically non-diagnostic (undetermined) and weathered, unidentifiable phytoliths (damaged UNID) were also present at all sites, being an important part of the assemblage from VHV.

Table 5. Results of the phytolith and starch grain analyses from grinding stones. Phytolith concentration per g of AIF (Acid Insoluble Fraction). Starch grain concentration per g of original sediment. - = sample not analysed.

Site	ID	Sediment weight (g)	AIF weight (g)	Phytoliths		Starch grains	
				count	concentration	count	concentration
VHV	GS 1	0.3022	0.1145	350	35,014	2	66
VHV	GS 2	0.3572	0.2056	381	12,338	7	196
VHV	GS 3	0.6390	0.3623	353	4,555	4	63
VHV	GS 4	0.3933	0.2276	193	7,717	4	102
VHV	GS 5	0.1216	0.0473	1	110	7	576
VHV	GS 6	0.1433	0.0569	18	981	31	2,163
VHV	GS 7	0.1781	0.0696	16	1,108	3	168
VHV	GS 8	0.1514	0.0573	0	0	10	661
VHV	GS 9	0.1313	0.0368	5	571	9	685
VHV	GS 10	0.2171	0.0752	0	0	8	368
VHV	GS 11	0.1093	0.0384	2	443	4	366
VHV	GS 12	0.2289	0.0455	15	2,176	8	349
VHV	GS 13	0.1950	0.0601	6	316	16	821
VHV	GS 14	0.2345	0.0698	0	0	15	640
VHV	GS 15	0.2307	0.0522	11	1,317	6	260
VHV	GS 16a	0.0949	0.0278	0	0	9	948
VHV	GS 16b	0.1022	0.0335	1	358	2	196
VHV	GS 17	0.0992	0.0455	9	1,241	15	1,512
VHV	GS 18	0.0949	0.0449	1	223	0	0
VHV	GS 19	0.2582	0.1231	4	299	4	155
LTS	GS 1a	0.0615	0.0351	365	3,604,553	27	4,390

Site	ID	Sediment weight (g)	AIF weight (g)	Phytoliths		Starch grains	
				count	concentration	count	concentration
LTS	GS 1b	0.0434	0.0186	220	119,462	36	8,295
LTS	GS 2a	0.0409	0.0209	327	2,440,953	15	3,667
LTS	GS 2b	0.0226	0.0121	2	893	11	4,867
LTS	GS 3a	0.0236	0.0134	465	239,606	8	3,390
LTS	GS 3b	0.0212	0.0136	558	125,707	11	5,189
LTS	GS 4	0.0779	0.0478	350	8,097,814	21	2,696
LTS	GS 5	0.0921	0.0467	316	536,699	14	1,520
LTS	GS 6a	0.0322	0.0203	2	717	19	5,901
LTS	GS 6b	0.0308	0.0099	30	11,869	12	3,896
LTS	GS 7a	0.1645	0.1060	4	260	7	426
LTS	GS 7b	0.0796	0.0298	356	1,143,761	17	2,136
LTS	GS 8	0.0560	0.0312	310	400,406	9	1,607
LTS	GS 9	0.0831	0.0463	19	3,009	54	6,498
LTS	GS 10	0.0550	0.0188	1	312	107	19,455
LTS	GS 11	0.2633	0.1447	324	7,042	23	874
LTS	GS 12a	0.0439	0.0182	0	0	230	52,392
LTS	GS 12b	0.0470	0.0140	0	0	27	5,745
LTS	GS 13	0.0995	0.0375	0	0	15	1,508
DTR	GS 1	0.0442	0.0243	-	-	3	679
DTR	GS 2	0.2207	0.1077	-	-	18	816
DTR	GS 3	0.1320	0.0699	-	-	4	303
DTR	GS 4a	0.5354	0.1529	29	588	3	56
DTR	GS 4b	0.2267	0.0698	-	-	3	132
DTR	GS 5	0.0939	0.0624	-	-	3	319
DTR	GS 6a	0.1373	0.0452	-	-	56	4,079
DTR	GS 6b	0.1022	0.0556	-	-	3	294
DTR	GS 7	0.1531	0.0713	-	-	0	0
DTR	GS 8	0.2991	0.1356	-	-	4	134
DTR	GS 9	0.0647	0.0249	0	0	5	773
DTR	GS 10	0.2196	0.1611	19	973	1	46
DTR	GS 11a	0.0534	0.0233	-	-	2	375
DTR	GS 11b	0.1900	0.0606	-	-	5	263
DTR	GS 12a	0.5919	0.1534	-	-	13	220
DTR	GS 12b	0.3246	0.0920	-	-	9	277
DTR	GS 13	0.0551	0.0313	1	141	9	1,633
DTR	GS 14	0.1719	0.1080	-	-	100	5,817
DTR	GS 15	0.3258	0.0911	-	-	2	61
DTR	GS 16	0.0691	0.0354	-	-	2	289
DTR	GS 17	0.1111	0.0364	20	1,099	31	2,790
SKP	Quern 1	0.2542	0.0706	299	4,634,268	7	275
SKP	Quern 2	0.3209	0.1386	304	4,182,827	5	156
SKP	Quern 3	0.5051	0.1928	332	3,090,134	98	1,940
SKP	Quern 4	1.1954	0.5273	298	1,683,901	24	201
SKP	Quern 5	0.3369	0.1406	310	4,400,743	69	2,048
SKP	Quern 6	0.6771	0.2058	299	1,896,012	19	281
SKP	Quern 7a	0.4997	0.1571	312	3,136,372	33	660

Site	ID	Sediment weight (g)	AIF weight (g)	Phytoliths		Starch grains	
				count	concentration	count	concentration
SKP	Quern 7b	0.5626	0.2187	307	2,138,836	12	213
SKP	Quern 8	1.2237	0.5793	303	4,511,346	45	368
SKP	Quern 9a	0.6777	0.1709	304	4,149,532	25	369
SKP	Quern 9b	0.1846	0.0878	309	1,912,030	29	1,571
SKP	Hand 1	0.5414	0.1888	310	3,596,088	32	591
SKP	Hand 2	0.9872	0.4692	299	1,066,864	50	506
SKP	Hand 3	0.2191	0.0844	358	29,872	9	411
SKP	Hand 4	0.8749	0.2906	302	2,191,360	23	263
SKP	Hand 5	0.4726	0.2160	302	2,052,040	57	1,206
SKP	Hand 6	0.5741	0.2386	302	1,211,538	31	540
SKP	Hand 7	1.6178	0.7256	301	1,224,839	24	148
SKP	Mortar	0.7707	0.2468	299	2,161,381	12	156
SKP	Pestle	0.3813	0.1993	331	12,316,703	46	1,206

Only samples with >100 identified phytoliths (n=34) were plotted in the PCA, which yielded 12 Principal Components (PCs) explaining 100% of the variance (Table S5). SKP clearly separated from VHV and LTS, with the exception of sample SKP_Hand3 (Fig. 4a). Samples from the AP deposits from LTS were also differentiated from VHV and LTS_HG. The variables affecting the distribution of samples from SKP were mainly grass short cells and grass inflorescence long cells, whereas samples from VHV and LTS were characterised by a higher presence of dicotyledons and grass leaf/culm phytoliths.

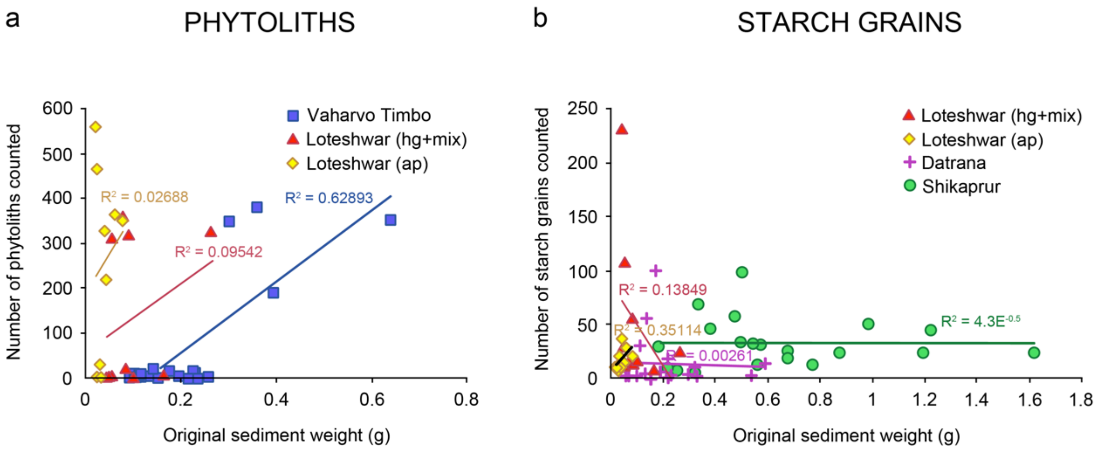

Figure 2. Total number plant microremains counted per sample against the initial sediment weight. a) phytolith samples from Vaharvo Timbo, Loteshwar and Shikarpur, and b) starch samples from Loteshwar, Datrana IV and Shikarpur.

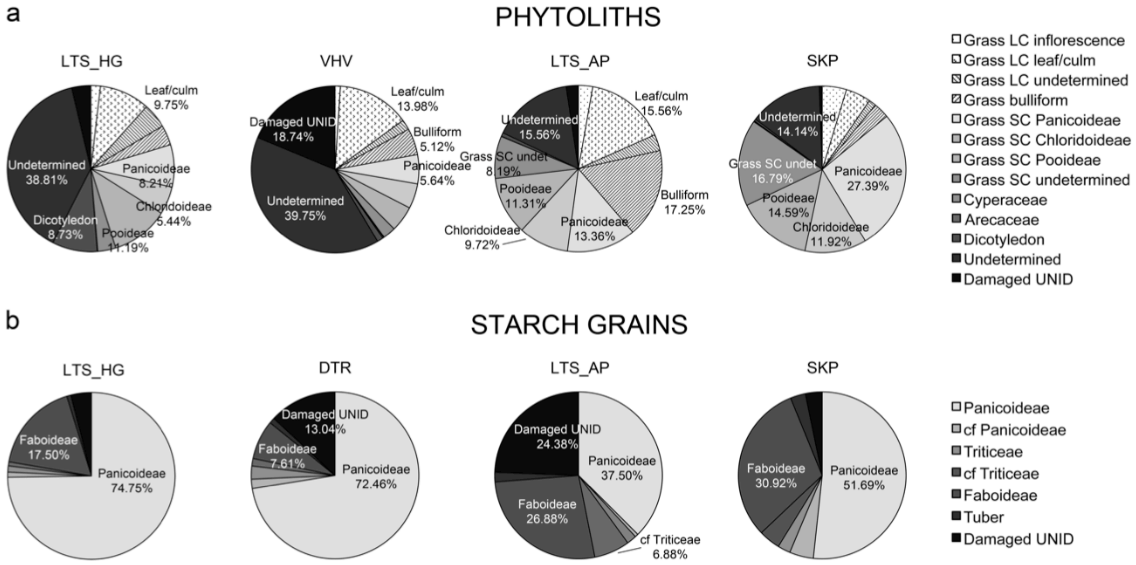

Figure 3. Percentages of microbotanical remains recovered from grinding stones. a) single-cell phytoliths from Vaharvo Timbo, Loteshwar and Shikarpur, and b) starch grains form Loteshwar, Datrana IV and Shikarpur. Only those categories representing >5% of the assemblage are indicated in the charts.

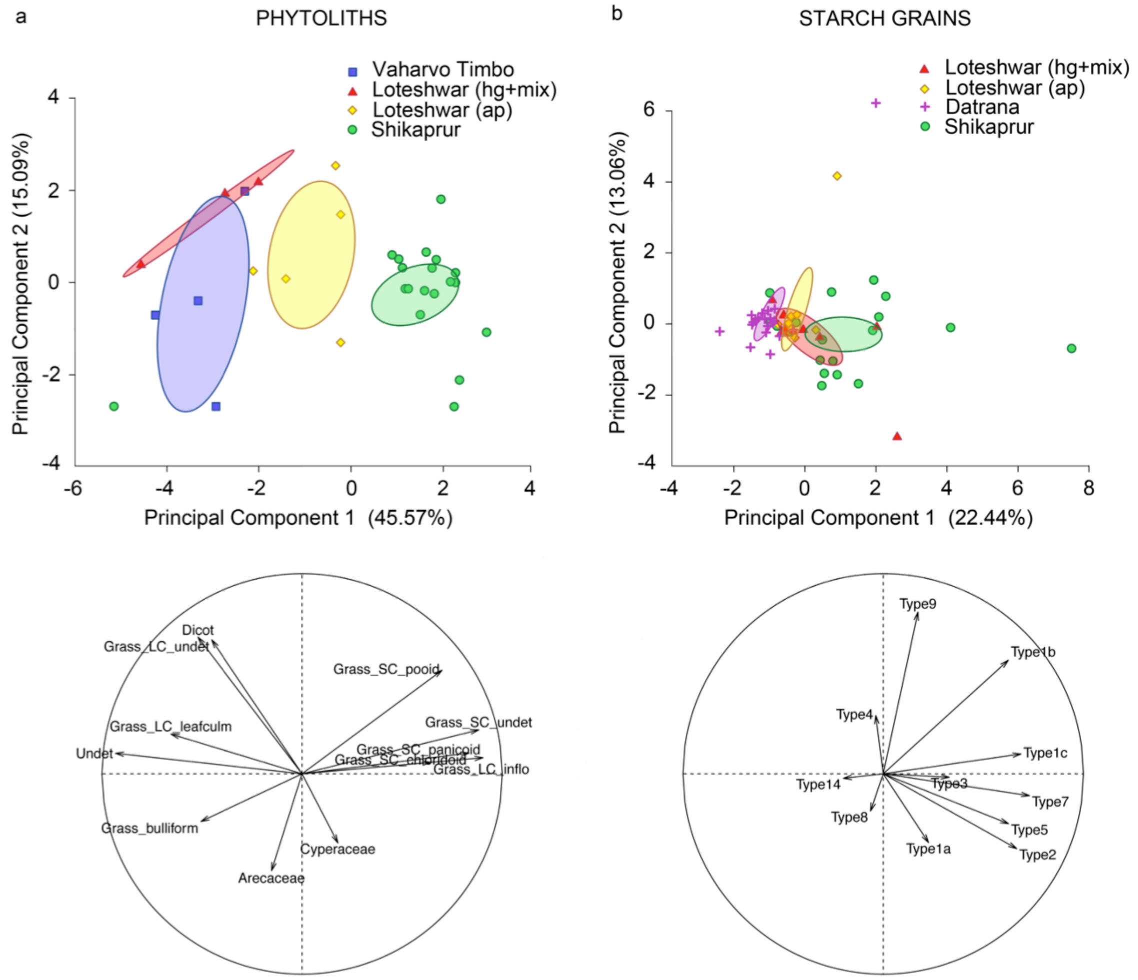

Figure 4. PC1 and PC2 scatterplots of the Principal Component Analyses (PCAs). a) phytolith samples from VHV, LTS and SKP, and b) starch samples from LTS, DTR and SKP.

Starch grains were present in all but two samples (Table 5), ranging between 1 and 230, and were not correlated with the initial sample weight (Fig. 2b). Panicoideae grains (particularly Type 1a) predominated at all sites, followed by Faboideae, which were present mostly in LTS_AP and SKP (Fig. 3b). The PCA yielded 11 PCs explaining 100% of the variance (Table S5). There were no statistical differences in the starch assemblage composition among LTS and DTR, whereas samples from SKP had a different range of distribution, exhibiting the most positive values for PC1 (Fig. 4b).

The only site where phytoliths and starch grains were recovered from all the grinding stones is SKP, and therefore the indices of compositional similarity to identify groups of tools were analysed only in this site. Sample SKP_Hand3 was excluded due to the taphonomical processes that affected the phytolith assemblage, which resulted in the preferential preservation of certain morphotypes more resistant to dissolution, such as parallelepipedals (García-Granero et al. 2015), and its classification as an outlier in the PCS (Fig. 4a). The grinding tools were grouped in three clusters, whereas two querns (SKP_Quern3 and SKP_Quern5) were not part of any cluster (Fig. 5). Grinding stones identified in each of the clusters come from a variety of archaeological contexts, and grinding stones recovered from the same context were not necessarily grouped in the same cluster (Fig. 6).

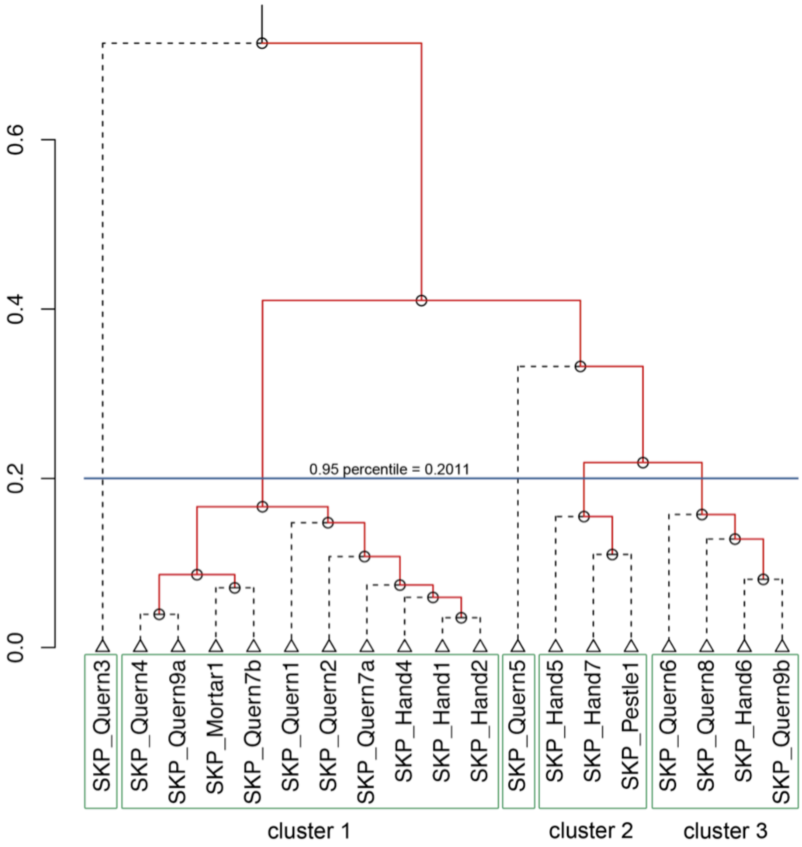

Figure 5. Dendrogram of the similarity analysis of grinding stones from Shikarpur. The blue line marks the 0.95 percentile of the index score, which defines the sample clusters (green boxes).

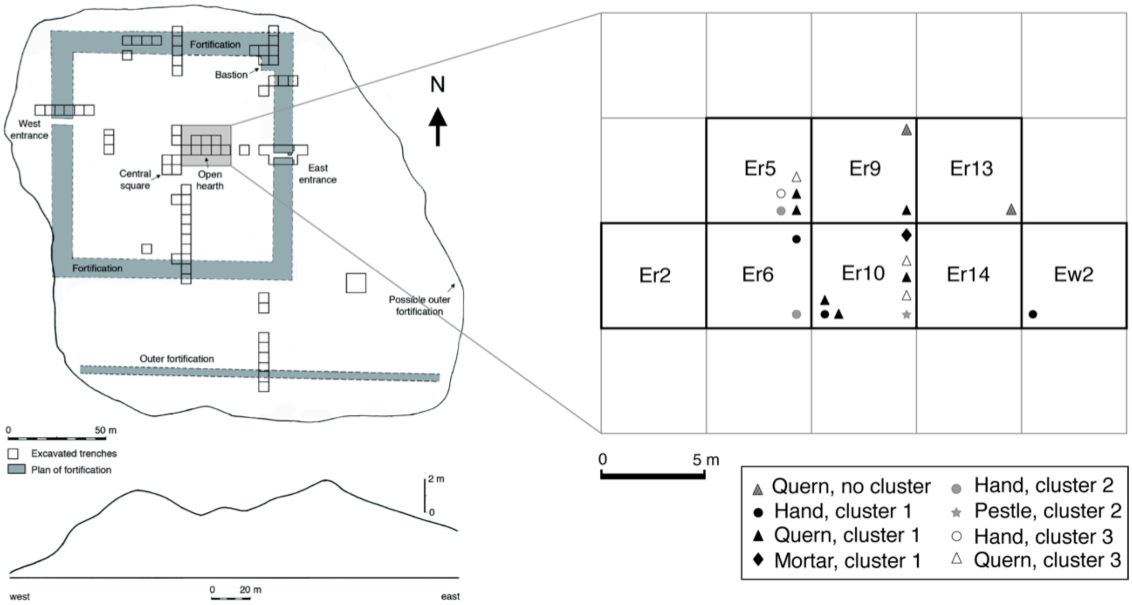

Figure 6. Spatial representation of the similarity analysis of grinding stones from Shikarpur. (site plan modified after Gadekar et al. 2014a).

Discusison

Holocene subsistence strategies in northern Gujarat

Northern Gujarat is a semi-arid region where resource availability is highly influenced by the Indian Summer Monsoon, resulting in a marked seasonality of plant resources. In spite of this, human groups have inhabited this region throughout most of the Holocene. Understanding how these populations dealt with resource scarcity and unpredictability is of great importance for understanding the strategies that people put in place to adapt to adverse conditions. This will help in developing our understanding of socio-ecological dynamics in semi-arid regions worldwide to face challenges in resource availability and sustainable exploitation.

Grinding stones, as the only ubiquitous artefact directly related to food production and consumption in this context, provide an ideal proxy to study plant-related subsistence strategies in a comparative diachronic framework. Moreover, the pores of grinding tools provide a protective environment for plant microremians (Haslam 2004). For this reason, the virtual absence of phytoliths from some tools is striking. The low number of phytoliths encountered at DTR suggests that at least some of the grinding tools might have been used for activities other than plant processing, such as polishing stone beads (Rajesh et al. 2013). An alternative explanation, also relevant to some of the LTS tools, is that cereals were de-husked and well cleaned prior to grinding, as suggested by the presence of a high amount of starch grains and the absence of phytoliths in some samples. This hypothesis is further supported by the scarcity of grass inflorescence phytoliths, suggesting that cereals were de-husked with other tools, such as wooden pestles (Kimata et al. 2000; Reddy 1997).

The microbotanical assemblage from northern Gujarat shows that during the entire Holocene plant-related subsistence strategies were based on local drought-tolerant crops such as small millets and tropical pulses. Panicoids predominate both the phytolith and the starch assemblage at all sites. Several small millets are native to this region, including little millet (*Panicum sumatrense* Roth), yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult), bristly foxtail (*S. verticillata* (L.) P.Beauv.) and, possibly, browntop millet (*Brachiaria ramosa* (L.) Stapf.) (Fuller 2006; García-Granero et al. in press). Although small Panicoideae grains may appear in several taxa within this subfamily (Madella et al. 2013 and references therein), the natural occurrence of several small millets in northern Gujarat strongly suggests that the Panicoideae starch assemblage resulted from their consumption. Silica skeletons encountered in grinding stones also show morphological features comparable to small millets (García-Granero et al. 2015, in press), further supporting the processing of these crops for consumption. The starch evidence also advocates for the importance of pulses (Faboideae) in the human diet. Two pulses are native to northern Gujarat or neighbouring areas: mung bean (*Vigna radiata* (L.) R.Wilczek) and horsegram (*Macrotyloma uniflorum* (Lam.) Verc.) (Fuller and Harvey 2006). Macrobotanical remains of these crops are routinely recovered from late Holocene urban settlements in Gujarat, including SKP (García-Granero et al. 2015). Their presence in the starch assemblage from all sites, including the HG deposits from LTS, highlights a long trajectory of pulse consumption. However, their importance in the human diet seems to increase significantly during the late Holocene, as indicated by the starch assemblage from SKP and the AP deposits from LTS.

Differences in plant consumption seem to be based on social organisation and the degree of mobility. As noted above, in northern Gujarat small climatic fluctuations have a deep impact on the available resources and thus on the human populations depending upon them. Hunter-gatherer and early agro-pastoral groups probably responded to adverse climatic conditions with a high degree of mobility and relied mostly on fast-maturing small millets and other grasses (García-Granero et al. in press). With the emergence of urban settlements such as SKP and other late Holocene Harappan sites, the strategy moved towards a more intense and complex agricultural system that enhanced productivity, and involved a focus on the cultivation of small millets and pulses and their rotation to improve soil fertility (García-Granero et al. 2015).

A methodological approach to the study of plant microremains from grinding stones

The reliable reconstruction of plant consumption from grinding tools requires the application of a specifically designed methodology to appraise their depositional and post-depositional trajectories.

Microremains recovery and extraction

The scarcity of phytoliths in most tools from VHV is probably related to the small quantities of initial sediment, as suggested by the correlation between initial sediment weight and number of phytoliths encountered. The amount of residue retrieved depends on the recovery method employed, the type of sediment (clays, silts or sands), the degree of humidity and the size of the tool. In this study, the two-step brushing method proposed by Chandler-Ezell and Pearsall (2003) was chosen over the spot sampling approach (e.g., Yang et al. 2013) because it allows for the recovery of a higher amount of residue and thus maximises the likelihood of recovering phytoliths. A possible alternative when sample weight is low is the employment of other extraction protocols, such as the microwave digestion proposed by Parr (2002). This method requires an initial sediment weight of as little as 0.25 g, enables the simultaneous extraction of both microremains and it is both quick and relatively inexpensive (e.g. Parr and Carter 2003). It does, however, require a high initial investment for the necessary equipment –a microwave sample preparation oven–, seldom present in archaeobotany laboratories. Another extraction protocol requiring a low initial sample (in this case 0.05 g) is the rapid phytolith extraction proposed by Katz et al. (2010). This protocol was not employed in this study because it does not allow for the simultaneous recovery of phytoliths and starch grains; however, when necessary, samples could be divided for the independent extraction of both microremains using Katz el al. (2010)'s protocol for phytoliths and the adaptation of Horrocks (2005)'s protocol employed in this study for starch grains.

Control samples

The need for control samples in order to ascertain that the microremains recovered from grinding tools accurately represent the results of tool use and are not a product of contamination is generally acknowledged in the literature (e.g. Yang et al. 2009). However, the recovery and analysis of control samples is not a common practice, as the guidelines for collecting them are not always clear. Phytolith contamination is more likely to originate from the archaeological sediment in which an artefact was buried, whereas starch contamination is more likely to occur during the laboratory processing as starch does not preserve well in sediments (Haslam 2004) but it is commonly used for commercial purposes (Crowther et al. 2014). The assessment of contamination must take into account these alternative pathways for each proxy. Thus, grinding stones and archaeological control samples should be compared to assess phytolith contamination, whereas laboratory consumables should be tested as possible sources of starch contamination. The present work confirms the potential contamination derived from laboratory consumables noted in previous studies (Crowther et al. 2014). Therefore, we stress the need for testing laboratory consumables in each study that involves starch analyses.

Data analysis

The need for statistical analysis of phytolith data was first noted by Power-Jones and Padmore (1993) and further developed when working with modern reference material (e.g. Ball et al. 1996, 1999; Lancelotti and Madella 2012; Mercader et al. 2010, 2011; Out et al. 2014) and in palaeoecological studies (e.g. Lu et al. 2006). Multivariate analyses are also commonly used to compare modern starch assemblages (Giovannetti et al. 2008; Liu et al. 2014; Peek and Clementz 2012; Torrence et al. 2004; Wilson et al. 2010). However, multivariate analyses of archaeological phytolith and starch assemblages are still not common. In this study, we used PCAs to identify patterns in data between sites and similarity analyses to classify samples according to statistically significant clusters. PCAs were fundamental to highlight the statistical significance of the differences identified between assemblages. Such differences were much less evident by simply looking at the relative abundance of each morphotype.

While PCAs are not uncommon in archaeobotanical studies, a fairly novel approach is the application of similarity indices. There are several similarity indices routinely applied in ecological studies. Chao index of compositional similarity is best suited for archaeobotanical samples because it takes into account the importance of unseen and underrepresented components (Chao et al. 2005). Grinding stones with similar assemblages were grouped within the same cluster, indicating the possibility of having been used for the same (or very similar) processing activity.

Human activities related to food production and transformation can be either communal or household-based (Fuller and Stevens 2009). Consequently, the archaeobotanical evidence resulting from these actions can be confined to a specific area or present over the entire residential site. At SKP, grinding stones that clustered in the same group were not all recovered from the same archaeological context, indicating that there was no spatial specialisation in the final food-processing stages. Indeed, in an urban site such as SKP, the final stages of food processing (e.g. grinding) were at household and not communal level.

Phytoliths from artefacts and archaeological control samples are usually compared by means of qualitative variables (presence/absence of a particular morphotype) or simple quantitative data (concentration per g of AIF/sediment). However, phytolith concentration depends on a number of issues –type of plants processed, type of context, taphonomical processes, etc.–, and this approach may yield inconclusive results. Kealhofer et al. (1999) proposed the use of multivariate statistics (Correspondence Analysis) to compare phytoliths extracted from obsidian artefacts and from the surrounding sediment matrix. The similarity analysis employed in this study offers a stronger framework for the comparison between samples since a) it takes into account all the variables, not just the two first eigenvalues; b) it includes the effect of unseen/uncommon morphotypes; and c) the clusters generated in the dendrogram are based on the statistical analysis of the data. Most grinding stones do not cluster together with their corresponding control samples, indicating that their assemblages are sufficiently different to be considered independent. This substantiates the hypothesis that phytoliths recovered from the grinding stones resulted from the actual use of the tool and not from a posterior contamination. Thus, the two-step brushing method effectively removed the potentially contaminated sediment, increasing the reliability of the microbotanical analyses and offering a solid framework for the interpretation of data.

Conclusions

This study shows that the analysis of microbotanical remains from grinding stones can offer a comparable diachronic framework for understanding shifts in subsistence strategies. The microbotanical assemblage from northern Gujarat presents both continuity and change throughout the Holocene as an expression of different adaptive responses to climatic adversity. The integrated analysis of these complementary microremains is not widespread, partly due to the lack of clear protocols for field and laboratory practices, devised for both archaeobotanists and non-archaeobotanists. This paper offered an example of an integrated approach that further explores methodological aspects of this research area, highlighting the need for specifically designed protocols to prevent and check for contamination, and the usefulness of multivariate statistics to further test research hypotheses. The interest in phytoliths and starch grain analyses from artefacts has increased during the last two decades; however, a comparable increase has not been witnessed in the methodological aspects of these studies.

Acknowledgements

This work has benefited from discussions with several researchers to whom we are thankful. Special thanks are due to P. Ajithprasad, D. Zurro, H. Barton, J. Ruiz-Pérez and the participants of the 9th International Meeting on Phytolith Research in Brussels (Belgium, September 2014). Fieldwork at LTS, DTR and VHV was carried out within the North Gujarat Archaeological Project (NoGAP) and funded by the Spanish Ministry of Education, Culture and Sport (Programa de Ayudas para Proyectos Arqueológicos en el Exterior 2009, 2010 and 2011) and the Catalan Government (Programa EXCAVA 2009). The Archaeological Survey of India funded fieldwork at SKP and the Spanish Ministry of Economy and Competitiveness funded laboratory work (Programa I+D, HAR2010-16052). We are grateful to the members of the NoGAP and the Department of Archaeology and Ancient History of The MSU Baroda (Gujarat, India) for their help during the field and laboratory work in India, and to the Archaeological Survey of India for granting excavation permissions. JJGG acknowledges funding from a JAE-Predoc PhD grant (Spanish National Research Council and European Social Fund).

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Grinding for survival: a microbotanical approach to Holocene subsistence strategies in semi-arid northern Gujarat (India), Supplementary Material

Methods

Control samples from laboratory consumables

The methods employed to collect and analyse control samples from laboratory consumables were designed to allow for comparability with the archaeological samples. Consumables used during all laboratory work (both at the Department of Archaeology and Ancient History of the MSU Baroda, India and the BioGeoPal Laboratory of the IMF-CSIC, Spain) were processed at the BioGeoPal Laboratory. All the process was carried out without wearing gloves to avoid possible starch contamination. Hands were thoroughly washed with starch-free detergent between each sample to avoid cross-contamination. Sample collection methods were adapted to each consumable:

Gloves

1. Introduce one glove into a glass beaker and top up with distilled H_2O. Sonicate for 15’. Cover the beaker while sonicating.
2. Transfer the distilled water to a new 50 ml centrifuge tube. Centrifuge for 5’ at 3000 rpm.
3. Pipette out the supernatant with a disposable pipette until only 5 ml are left in the tube. Transfer to a glass vial and dry into the oven (<40°C).
4. Add 200 µl of distilled H_2O to the vial using a precision pipette. Recover 20 µl and place on a microscopy slide. Cover with a Petrie dish and let dry under the fume.
5. Add a drop of 50% glycerol and cover with a cover slip. Apply transparent nail polish to each corner of the cover to fix it to the slide.

Beaker

1. Add 40 ml of distilled H_2O to a beaker. Sonicate for 15’. Cover the beaker while sonicating.
2. Repeat steps 2-5 from “Gloves”.

Tubes

1. Top up a new 50 ml centrifuge tube with distilled H_2O. Sonicate for 15’.
2. Centrifuge for 5’ at 3000 rpm.
3. Repeat steps 3-5 from “Gloves”.

Paper

1. Introduce paper sherds into a new 50 ml centrifuge tube and top up with distilled H_2O. Sonicate for 15'.
2. Centrifuge for 5' at 3000 rpm.
3. Repeat steps 3-5 from "Gloves".

Vial

1. Repeat steps 4-5 from "Gloves".

Glycerol 50%

1. Repeat step 5 from "Gloves".

Sodium polytungstate

1. Add a drop of sodium polytungstate on a microscopy slide and cover with a cover slip. Apply transparent nail polish to each corner of the cover to fix it to the slide.

Sodium hexametaphosphate

1. Add 20 µl of sodium hexametaphosphate on a microscopy slide. Cover with a Petrie dish and let dry under the fume.
2. Repeat step 5 from "Gloves".

Multivariate analyses

PCAs and similarity analyses were carried out with the free software R. The scripts and data files used to carry out each analysis can be downloaded from https://github.com/cl379/Rscripts/tree/master/papergrinding.

Supplementary Tables

Table S1. Morphotypological description of the grinding stones analysed in this study. (descriptive terms after Wright 1992).

Site	Context	ID	Description	Control sample
VHV	Hg 1	GS 1	Frag. basin grinding slab	Control 1
VHV	Hg 1	GS 2	Frag. unifacial rectilinear handstone	Control 1
VHV	Hg 1	GS 3	Frag. basin grinding slab	Control 1
VHV	Hg 1	GS 4	Frag. basin grinding slab	Control 1
VHV	Hg 1	GS 5	Half unifacial ovate handstone	Control 1

VHV	Hg 2	GS 6	Frag. basin grinding slab	Control 2
VHV	Hg 2	GS 7	Frag. basin grinding slab	Control 2
VHV	Hg 1	GS 8	Frag. basin grinding slab	Control 1
VHV	Hg 2	GS 9	Frag. unifacial rectilinear handstone	Control 2
VHV	Hg 2	GS 10	Frag. unifacial rectilinear handstone	Control 2
VHV	Hg 2	GS 11	Frag. basin grinding slab	Control 2
VHV	Hg 2	GS 12	Frag. basin grinding slab	Control 2
VHV	Hg 2	GS 13	Frag. unifacial rectilinear handstone	Control 2
VHV	Hg 3	GS 14	Frag. unifacial rectilinear handstone	Control 3
VHV	Hg 3	GS 15	Unifacial discoidal handstone	Control 3
VHV	Hg 3	GS 16a	Frag. unifacial rectilinear handstone, frag. a	Control 3
VHV	Hg 3	GS 16b	Frag. unifacial rectilinear handstone, frag. b	Control 3
VHV	Hg 3	GS 17	Frag. basin grinding slab	Control 3
VHV	Hg 4	GS 18	Frag. basin grinding slab	Control 4
VHV	Hg 4	GS 19	Frag. unifacial rectilinear handstone	Control 4
LTS	Ap 1	GS 1a	Frag. bifacial discoidal/lens handstone, face a	Control 1
LTS	Ap 1	GS 1b	Frag. bifacial discoidal/lens handstone, face b	Control 1
LTS	Ap 1	GS 2a	Half bifacial ovate/oval handstone, face a	Control 1
LTS	Ap 1	GS 2b	Half bifacial ovate/oval handstone, face b	Control 1
LTS	Ap 2	GS 3a	Frag. bifacial handstone, face a	Control 2
LTS	Ap 2	GS 3b	Frag. bifacial handstone, face b	Control 2
LTS	Ap 3	GS 4	Frag. basin grinding slab	Control 3
LTS	Hg	GS 5	Frag. saddle-shaped grinding slab	Control 5
LTS	Ap 4	GS 6a	Broken handstone, used as grinding slab	Control 6
LTS	Ap 4	GS 6b	Unifacial ovate handstone	Control 6
LTS	Mix	GS 7a	Half basin grinding slab, face a (not used?)	Control 4
LTS	Mix	GS 7b	Half basin grinding slab, face b	Control 4
LTS	Mix	GS 8	Half basin grinding slab	Control 4
LTS	Mix	GS 9	Half bifacial ovate/oval handstone	Control 4
LTS	Mix	GS 10	Half unifacial rectilinear handstone	Control 4
LTS	Hg	GS 11	Half unifacial ovate handstone	Control 5
LTS	Hg	GS 12a	Frag. bifacial rectilinear/flat handstone, face a	Control 5
LTS	Hg	GS 12b	Frag. bifacial rectilinear/flat handstone, face b	Control 5
LTS	Hg	GS 13	Frag. basin grinding slab	Control 5
DTR	Ap 2	GS 1	Frag. basin grinding slab	Control 2
DTR	Ap 3	GS 2	Frag. saddle-shaped grinding slab	Control 3
DTR	Ap 3	GS 3	Frag. saddle-shaped grinding slab	Control 3
DTR	Ap 3	GS 4a	Frag. saddle-shaped grinding slab, face a	Control 3
DTR	Ap 3	GS 4b	Frag. saddle-shaped grinding slab, face b	Control 3
DTR	Ap 3	GS 5	Frag. saddle-shaped grinding slab	Control 3
DTR	Ap 3	GS 6a	Frag. saddle-shaped grinding slab, face a	Control 3
DTR	Ap 3	GS 6b	Frag. saddle-shaped grinding slab, face b	Control 3
DTR	Ap 3	GS 7	Frag. saddle-shaped quern	Control 3
DTR	Ap 3	GS 8	Unifacial discoidal handstone	Control 3
DTR	Ap 2	GS 9	Frag. saddle-shaped grinding slab	Control 2
DTR	Ap 1	GS 10	Frag. saddle-shaped grinding slab	Control 1
DTR	Ap 3	GS 11a	Frag. saddle-shaped grinding slab, face a	Control 3
DTR	Ap 3	GS 11b	Frag. saddle-shaped grinding slab, face b	Control 3
DTR	Ap 4	GS 12a	Frag. saddle-shaped grinding slab, face a	Control 4

DTR	Ap 4	GS 12b	Frag. saddle-shaped grinding slab, face b	Control 4
DTR	Ap 4	GS 13	Frag. saddle-shaped grinding slab	Control 4
DTR	Ap 4	GS 14	Frag. saddle-shaped grinding slab	Control 4
DTR	Ap 4	GS 15	Frag. saddle-shaped grinding slab	Control 4
DTR	Ap 4	GS 16	Frag. saddle-shaped grinding slab	Control 4
DTR	Ap 5	GS 17	Frag. saddle-shaped grinding slab	Control 5
SKP	Er10	Quern 1	Quern fragment	Control 3
SKP	Er9	Quern 2	Saddle-shaped quern	Control 8
SKP	Er9	Quern 3	Half saddle-shaped quern	Control 6
SKP	Er10	Quern 4	Half saddle-shaped quern	Control 3
SKP	Er13	Quern 5	Saddle-shaped quern	Control 10
SKP	Er5	Quern 6	Half saddle-shaped quern	Control 11
SKP	Er5	Quern 7a	Half saddle-shaped quern, face a	Control 11
SKP	Er5	Quern 7b	Half saddle-shaped quern, face b	Control 11
SKP	Er10	Quern 8	Saddle-shaped quern	Control 3
SKP	Er10	Quern 9a	Basin grinding slab, fragment a	Control 3
SKP	Er10	Quern 9b	Basin grinding slab, fragment b	Control 3
SKP	Ew2	Hand 1	Spherical handstone	Control 1
SKP	Er6	Hand 2	Oval, irregular handstone	Control 2
SKP	Ew10	Hand 3	Bifacial, rectilinear handstone	Control 4
SKP	Er10	Hand 4	Spherical handstone	Control 5
SKP	Er6	Hand 5	Spherical handstone	Control 7
SKP	Er5	Hand 6	Bifacial, rectilinear handstone	Control 11
SKP	Er5	Hand 7	Bifacial, rectilinear handstone	Control 11
SKP	Er10	Mortar	Boulder mortar	Control 9
SKP	Er10	Pestle	Bipolar cylindrical pestle	Control 3

Table S2. List of starch grain descriptors used in this study. (modified after Lentfer 2009).

Type		**Shape – 2D**		**Shape – 3D**		**Facet**		**Hilum - Position**	
S	simple	SR	sub-round	EHSP	elong hemisph	FL	flat	C	centric
C	compound	R	round	HSP	hemispherical	CC	concave	E	eccentric
SC	semi-comp	OV	ovate	SP	spherical	CV	convex	HE	highly ecc
Size		PL	polygonal	OV	ovoid	**Texture**		**Hilum - Type**	
		TR	triangular	GL	globose				
VS	<5 µm	IR	irregular	PL	polyhedral	WR	wrinkle	LV	large vacuole
S	>5-10 µm	CR	crescent	QU	quadrilateral	S	smooth	SV	small vacuole
M	>10-20 µm	BS	bell-shaped	IR	irregular	R	rough	CR	crystal
L	>20-50 µm			GLE	globose elong	RD	ridged	SL	slot
VL	>50 µm			TPR	tri-prismatic	**Lamellae**		**Hilum - Fissure**	
Extinction cross				WE	wedge				
				KI	kidney	Y	yes	L	linear
R	regular			CO	cone	N	no	Y	y-shaped
IR	irregular			DI	discoidal			ST	stellate
FL	flared			TO	torroid			OS	open simple
				BS	bell-shaped			OI	open irreg

Table S3. Phytolith groups used for multivariate statistics.

Group	Morphotypes
Grass LC inflorescence	elongate echinate, elongate dendritic, elongate crenate, elongate columellate
Grass LC leaf/culm	elongate psilate, elongate sinuate
Grass LC undetermined	elongate irregular, other grass long cells
Grass bulliform	cuneiform bulliform
Grass SC chloridoid	saddle
Grass SC panicoid	bilobate, trilobate, polylobate, cross
Grass SC pooid	rondel, trapeziform sinuate, trapeziform polylobate, trapeziform. ovate, trapeziform bilobate, trapeziform elongate
Grass SC undetermined	trapeziform, cork cell, short cell undetermined
Cyperaceae	tabular scrobiculate, tabular conical
Arecaceae	globular echinate
Dicot	globular psilate, globular granulate, schlereid, scalloped, irregular
Undetermined	parallelepipedal, trichome, trichome base, papillae, stoma, mesophil, tracheid, elongate undetermined

Table S4. Starch groups used for multivariate statistics. The list of descriptors can be found in Table S2.

Type	Size	Ext. cross	Shape	Facets	Texture	Lamellae	Hilum	Taxonomy
1a	VS/S	R	PL, PL	FL	WR	N	C, variable	Panicoideae
1b	M	R	PL, PL	FL	WR	N	C, variable	Panicoideae
1c	L	R	PL, PL	FL	WR	N	C, variable	Panicoideae
2	M/L	R	OV, OV	.	S	Y	C, L	Faboideae
3	M	R	R, SP	.	S	N	C, SV	cf. Trititceae
4	M/L	R	R, DI	.	S	Y/N	not visible	Triticeae
5	M/L	R	R, SP	.	RD	N	C, L	cf. Panicoideae
7	M	IR	OV, OV	.	S	N	EC, SV	tuber
8	M	R	BS, BS	FL	S	N	EC, L	cf. Triticeae
9	VL	R	OV, TPR	.	S	Y	HEC, L	tuber
14	L	R	OV, OV	.	S	N	HEC, L	Zingiberaceae

Table S5. Eigenvalues, percentage of variance and cumulative variance of the two Principal Components Analyses (PCAs) carried out in this study.

PC	Phytoliths			Starch grains		
	Eigenvalues	% var.	Cum. %	Eigenvalues	% var.	Cum. %
1	5.468516629	45.571	45.571	2.468884638	22.444	22.444
2	1.810794437	15.090	60.661	1.436760538	13.061	35.506
3	1.149986166	9.583	70.244	1.255272688	11.412	46.917
4	1.099231930	9.160	79.404	1.095162687	9.956	56.873
5	0.749347355	6.245	85.649	1.004903827	9.135	66.009
6	0.528767807	4.406	90.055	0.946481760	8.604	74.613
7	0.446331010	3.719	93.774	0.799315421	7.267	81.880
8	0.275449769	2.295	96.070	0.749450384	6.813	88.693
9	0.220911482	1.841	97.911	0.569721447	5.179	93.872
10	0.124872758	1.041	98.952	0.394072082	3.582	97.455
11	0.100683699	0.839	99.791	0.279974527	2.545	100.000
12	0.025106957	0.209	100.000			

Supplementary Figures

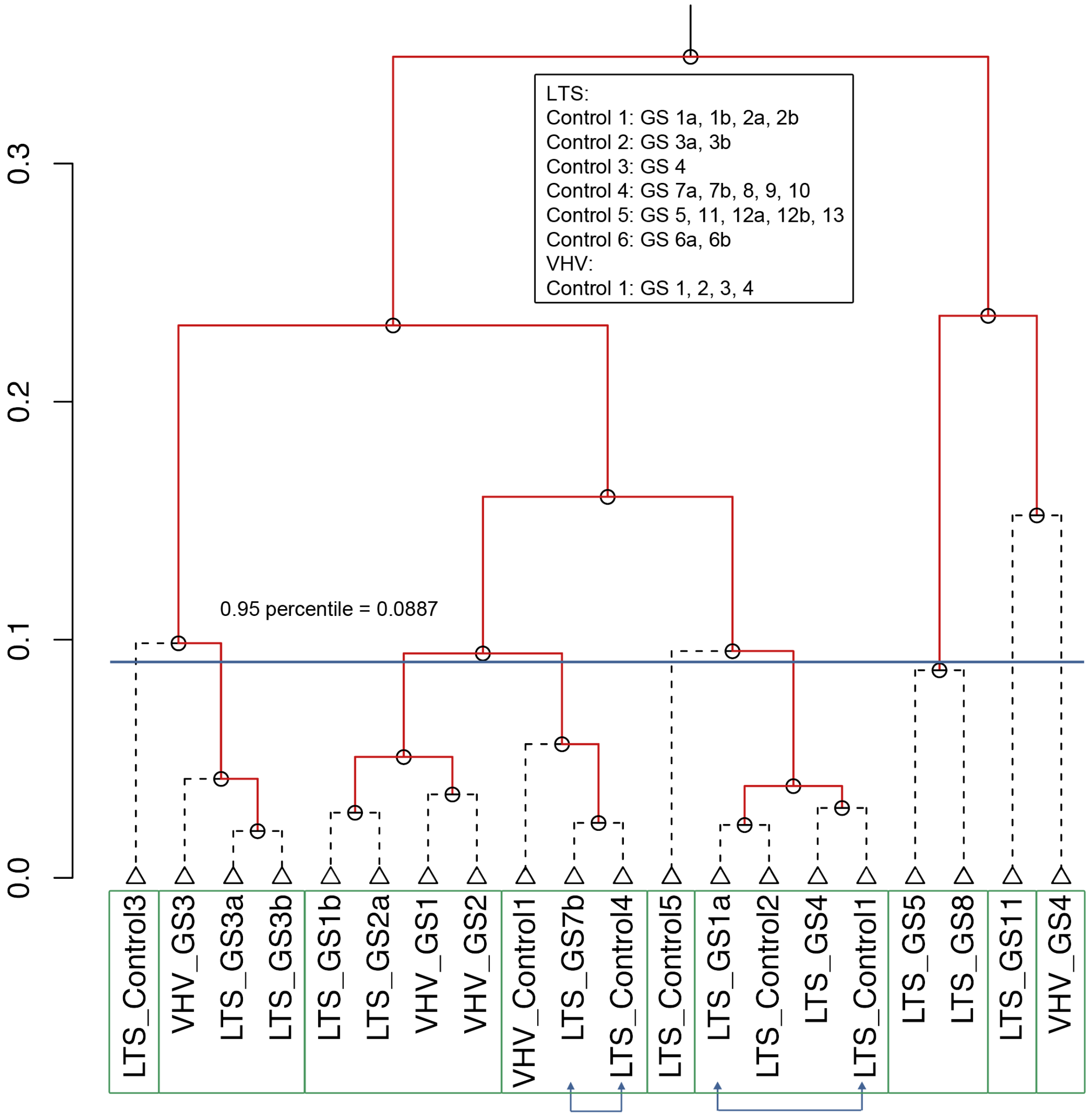

Figure S1. Dendrogram of the similarity analysis of grinding stones and control samples from VHV and LTS. The blue line marks the 0.95 percentile of the index score, which defines the sample clusters (green boxes). The blue arrows point to grinding stones clustered with their control sample.

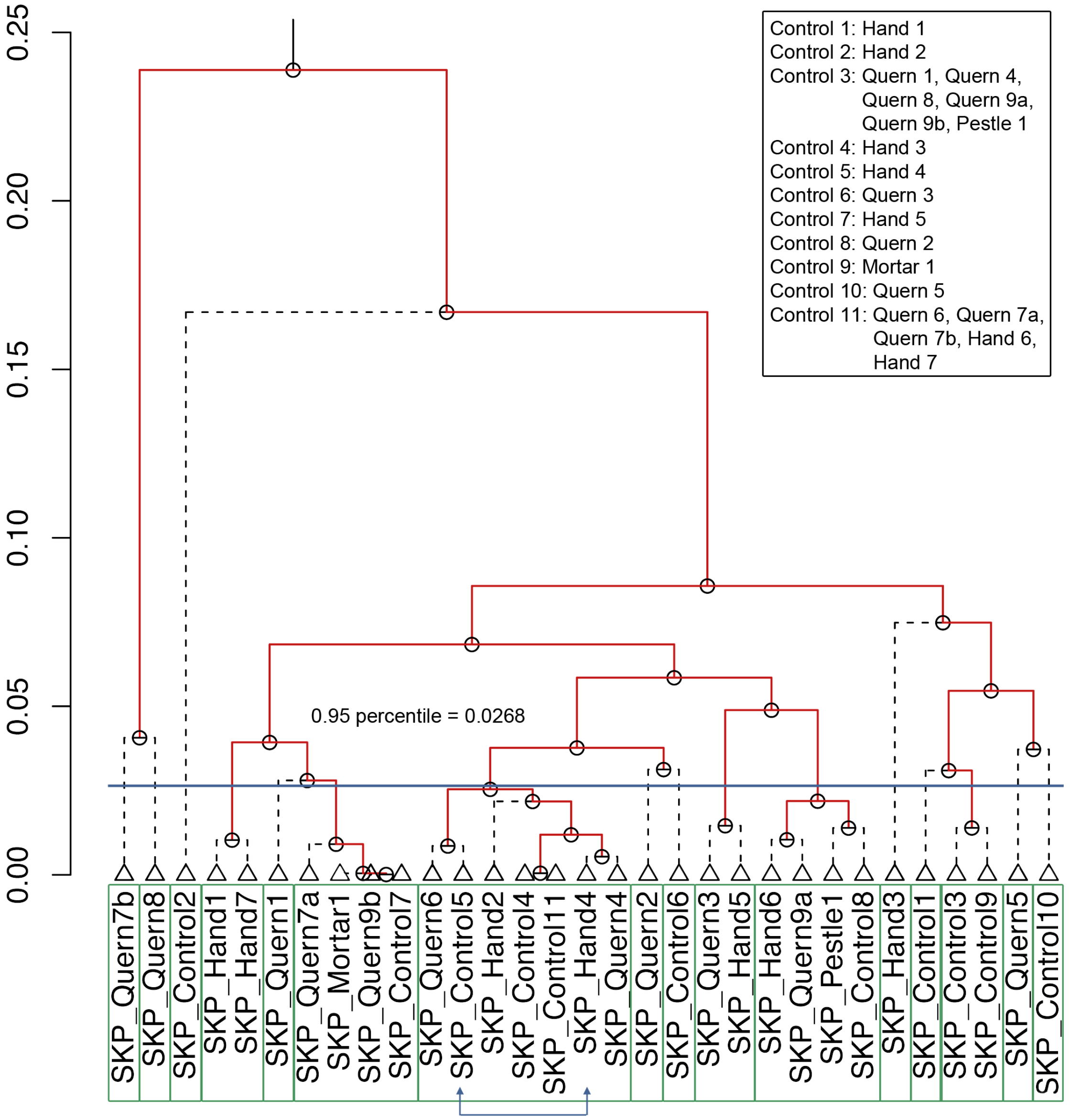

Figure S2. Dendrogram of the similarity analysis of grinding stones and control samples from SKP. The blue line marks the 0.95 percentile of the index score, which defines the sample clusters (green boxes). The blue arrows point to grinding stones clustered with their control sample.