

BY THE CAMPFIRE. PYROTECHNOLOGY AND MIDDLE STONE AGE HEARTHTHS AT SIBUDU CAVE

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A thesis submitted to the Faculty of Science, University of the Witwatersrand,
Johannesburg, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, 2014.

DECLARATION

I declare that this Thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

Johannesburg, / /2014

(Signature of candidate)

ABSTRACT

The Middle Stone Age rock shelter site Sibudu contains abundant evidence of pyrotechnology (the controlled use of fire) such as combustion features, ashy layers and lenses and burned bone. I study the use, reuse and discard of fire at Sibudu and the layers Brown/Grey mix and Brown under Yellow Ash 2(i) from the post-Howiesons Poort (post-HP) industry (c. 58 000 years BP) and the layers Pinkish Grey Sand and Pinkish Grey Sand 2 from the Howiesons Poort (HP) techno-tradition (c. 65 000 years BP) are selected for detailed studies. I describe properties of selected combustion features, such as size, form, number of hearth strata, contents (bone, charcoal and stone) and pH values. The post-HP combustion features generally contain a higher proportion of charcoal and are more acidic than the HP combustion features, suggesting post-depositional differences.

Twenty actualistic experiments including 39 experimental fires constitute the largest component and contribution of this thesis. The experiments were conducted in two cycles; the first cycle of experiments burned (in different fires) one each of the wood taxa *Casuarina equisetifolia*, *Dichrostachys cinerea*, *Eucalyptus globulus* or *Acacia erioloba* and the second cycle of experiments burned *Dichrostachys cinerea* exclusively. Variables such as wood mass, topsoil horizon and number of sequential fires were carefully controlled. The surface and subsurface temperatures of the experimental fires were recorded. The experimental hearths were excavated using similar techniques as those used at Sibudu. Surface temperatures vary greatly even under similar environmental conditions, but subsurface temperatures are more predictable. Five kilograms of wood is sufficient to produce high temperatures for several hours, and slowly adding logs to a fire ensures even temperatures.

Sibudu's hearths have a basal black layer with charcoal, but experimental fires do not. Instead they produced 2 – 5 distinct strata, and long-burning fires produced more strata than short-burning ones. Experimental ash dumps lack strata. Areal extent of a hearth is

dependent on the wood mass burned, but its depth is dependent on the wood taxon burned.

I present spatial analysis of charcoal, bone and knapped stone from the selected Sibudu layers using Kernel density estimation. Higher densities of bone, charcoal and stone are present in the post-HP layers than in the HP. Specialist studies of wood taxa, micromorphology and organic petrology are also included. No specific firewood taxa were preferred, but herbaceous plants were burned at 65 000 years ago, suggesting short fires.

This thesis provides a foundation for future research on fire-related behaviour at Sibudu and other Middle Stone Age sites. For example, higher acidity was recorded in the post-HP than in the HP combustion features; this could be caused by different diagenesis and geoarchaeological studies need to be conducted to resolve the issue.. In addition, all the primarily deposited archaeological combustion features in this study were underlain by a basal black layer rich in charcoal, but such layers did not develop in the experimental combustion features and I cannot explain this difference. Thus it is necessary to conduct more studies of the variables affecting the formation and preservation of combustion features. One aspect to study experimentally is the range of attributes controlling surface temperatures of campfires. Amongst the experiments described here, experimental fires burning five kg wood produced maximum surface temperatures in the range of 132 - 848°C, which demonstrates that surface temperatures are unpredictable. The implication is that producing particular temperatures of a fire is not straight-forward and that prehistoric fire users needed planning abilities and a thorough knowledge of pyrotechnology. Both these skills require mental abilities like those of modern people and they also require a sophisticated understanding of environmental conditions.

Front page illustration: *Experimental fires and archaeological combustion features and layers. Cut outs from pictures illustrate (from left to right): Start of experimental fire E4.3; Glowing phase of the fire (experimental fire E4.2); Cold ashes (experimental hearth E4); H. Kempson documenting hearth in layer Brown/Grey mix 01.11.2008; Detail from picture of layer Brown/Grey mix 03.11.2008; Detail from east wall stratigraphy at Sibudu, square B4. All photos taken by Silje Evjenth Bentsen and the east wall stratigraphy used by courtesy of Lyn Wadley.*

ACKNOWLEDGEMENTS

It takes a village to support a PhD candidate. I am forever grateful to everyone who helped me on the long and winding road of my PhD, and some deserve a special mention. My supervisor, Lyn Wadley, was always available with good advice and quick feedback. I am indebted to her for errors corrected, suggestions made, questions asked, financial support for specialist analysis and expenses at conferences and in the field and much more. Many thanks to the 'Sibudu crew'; Helen Kempson, Tammy Hodgskiss, Christine Sievers and Jamie Clark. I have thoroughly enjoyed working, discussing and laughing with all of them. I thank my collaborators for their time and cooperation, and in particular Christopher Miller, who has spent much time on our collaboration. The reviewers of my papers, the editors in the journals that received my manuscripts and the researchers giving me feedback on conference presentations contributed to improving my research and I thank them for that. Thanks also to the Badenhorst family and M. and B. Agliotti for allowing me to conduct fire experiments in their gardens.

I wish to thank PAST – Palaeontological Scientific Trust and their Scatterlings of Africa programme for financial support 2009 – 2011 and Eivind Sannes' legat for studerende ungdom fra Fauske kommune in Norway for a grant in 2011. I also thank ASAPA (Association of Southern African Archaeology) and the Wenner-Gren Foundation for financial support to attend the ASAPA conference in Swaziland in 2011. I funded the last years of my PhD as a freelance translator. I extend my thanks to the many translators and project managers who helped me in this business.

A million thanks to Renier Esterhuizen for his invaluable support and patience and to my parents and brothers for always backing me. Thanks to all my friends in South Africa for discussions, advice and open ears when I needed it and in particular to Geeske Langejans, Gerrit Dusseldorp and Jerome Reynard. Thanks to Elise Åland for fresh perspectives, all my friends all over the world for listening to monologues about the weird South Africans and to everyone for their help, advice and support after my hospital visit last year. IOU

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PAPER 1

Bentsen, S. E.

2012 Size matters: Preliminary results from an experimental approach to interpret Middle Stone Age hearths. *Quaternary International* 270, pp. 95-102.

PAPER 2

Bentsen, S. E.

2013 Controlling the heat: An experimental approach to Middle Stone Age pyrotechnology. *South African Archaeological Bulletin* 68, pp. 137-145.

PAPER 3

Bentsen, S. E.

2014 Using pyrotechnology: fire-related features and activities with a focus on the African Middle Stone Age. *Journal of Archaeological Research* 22, pp. 141-175.

PAPER 4

Bentsen, S. E., Miller, C. M., Ligouis, B., Allott, L. & Wadley, L.

In prep Combustion features and fire-related behaviour at Sibudu: Results from a multidisciplinary study.

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1 INTRODUCTION

Pyrotechnology, or the use and control of fire, has been an important part of human life for hundreds of thousands of years. Whereas the modern campfire is mainly associated with food and a social setting, prehistoric fires were, in addition, important tools that were essential for a wide range of tasks that require different temperatures. For example, meat can be roasted even at low temperatures such as 95°C (Wandsnider, 1997), some silcrete rock types can be heat treated in temperatures up to 400°C to improve knapping properties (e.g., Brown et al., 2009; Domanski & Webb, 1992; Flenniken & White, 1983; Mercieca, 2000; Purdy & Brooks, 1971), temperatures up to 600°C might be required for other silcretes (Schmidt et al., 2012, 2013) and the heat from a fire can help dry adhesives when hafting tools (Wadley, 2005a; Wadley et al., 2009).

Ethnographic studies of modern fire-users have also demonstrated that hearths can be instrumental in the organisation of hunter-gatherer camps (e.g., Binford, 1983; Gamble, 1991; Yellen, 1977). For example, the !Kung divide their camps into private areas, containing individual family hearths where most activities take place, and a central public area, which may contain a communal hearth (Yellen, 1977). Other studies show that modern fire users can have clear preferences for the taxon or taxa used or not used as firewood (e.g., Abbot et al., 1997; Archer, 1990; Tabuti et al., 2003). Informants from Malawi's Central Region, for example, distinctly prefer *Julbernardia paniculata* as firewood (Abbot & Lowore, 1999) and Vhavenda groups in South Africa traditionally have a taboo against using *Burkea africana*, *Kirkia acuminata* and *Kirkia wilmsii* as firewood because these taxa are believed to attract lightning (Mutshinyalo & Siebert, 2010).

Prehistoric fire use manifests itself at sites through combustion features, burnt artefacts or other burnt material. Accidental burning events caused by natural agents, such as lightning strikes, are not discussed in this thesis because the Sibudu deposits and combustion features are anthropogenic (see e.g., Goldberg et al., 2009; Schiegl & Conard, 2006; Schiegl et al., 2004). 'Combustion feature' is a generic term for an archaeological feature created through fire use. The term includes both primarily deposited features consisting of ash, organic matter and heat-affected sediments, such as hearths, and secondarily deposited fire-related material, such as dumped ash (see also discussion of the terms 'combustion feature' and 'hearth' in Mentzer, in press). Table 1.1 contains an overview of combustion features relevant in this thesis. I shall in this thesis refer to the strata in primarily deposited combustion features as 'hearth strata' and to combustion features produced in experiments as 'experimental hearths' or 'experimental ash dumps'.



Figure 1.1 View from Sibudu towards the river (south).

Table 1.1 Definitions of fire-related terms relevant to this thesis.

Term	Description	Associated processes	Literature examples
Ash dump	Secondarily deposited and mixed fire-related material, such as ash, charcoal and burnt bone. Usually grey in colour.	Site maintenance. scraping out ash from hearths	Goldberg et al., 2009
Ash feature	A feature rich in ash, similar to an ash dump.	Site maintenance, badly preserved hearths	Goldberg et al., 2009
Burned bedding	A feature similar to a hearth, but contains laminated lenses or strata of fibrous plant material and charcoal. Often only distinguished from hearths through micromorphology.	Burning of plant material used for surface preparation	Goldberg et al., 2009; Wadley et al., 2011
Hearth	Primarily deposited combustion features containing an upper stratum of ash (usually white), organic matter (usually a blackish stratum rich in charcoal) and heat-affected (rubified) sediments.	Domestic fireplaces, cooking etc.	Dibble et al., 2009; Schiegl et al., 1996
Superimposed hearths	Multiple hearths stacked on top of each other.	Repeated fire use in the same area.	Wadley, 2012a

1.1 AIMS

I aim to examine, describe and discuss the characteristics of MSA pyrotechnology by studying the use, reuse and discard of selected combustion features at Sibudu. The sample is not sufficient for a thorough understanding of all aspects of MSA pyrotechnology, nor for an understanding of all fire-related behaviour at Sibudu. Nevertheless, this work aims to provide insights into a part of this technology during specific occupation phases at the site, and thus produce a wider foundation for further pyrotechnological research on Sibudu as well as other MSA sites. The properties of selected combustion features will be described and discussed not just in terms of their formation and use, but also to gain an understanding of how fire-related behaviour at

Sibudu contributed to the formation of the site. This is important because the sediments at Sibudu are largely made up of ash, combustion features, burnt bone and charred plant remains. Lastly, this project aims to make predictions about prehistoric fire use and site formation through actualistic studies of pyrotechnology. This experimental component of the research is conducted in controlled environments in open air, and not in a laboratory, to replicate the type of situation applicable during the MSA.

1.2 THE STRUCTURE OF THE THESIS

A literature survey of MSA pyrotechnology is provided in Chapter 2. Pyrotechnology in the MSA is seen in the context of early fire use, and fire-related behaviour and features at Sibudu are described and discussed in relation to archaeological evidence for fire use from 33 other MSA sites. The current status of knowledge about MSA pyrotechnology demonstrates the benefits of applying new methodological approaches, facilitates comparisons with earlier and later archaeological periods, and is an important reminder of the benefits of a multi-disciplinary approach. This is a paper that is currently in press in the *Journal of Archaeological Research*, and I am the sole author of the paper.

Sibudu is introduced in more detail in Chapter 3. The chapter provides information on excavation techniques as well as dating and previous research at the site. Some of this information is repeated in the chapters published as papers, but Chapter 3 provides a convenient overview and reference for the rest of the thesis.

I describe and discuss the experimental component of my project in Chapters 4 to 8. Chapter 4 provides a background for the following chapters and introduces previous fire experiments and the aims and method for my experiments, such as the thermometer chosen for recording temperatures, the wood taxa used in my experiments and the topsoil horizon of the experiments. I also provide a brief summary of the results. Some experimental results important to the use of fire are presented in Chapter 5, where I use

results from my experiments to argue that controlling and using a fire is not straightforward. There are many variables that need to be taken into account, and it appears from my experiments that it is difficult to predict the development of surface temperatures in a fire even when controlling variables such as wood taxon, fuel mass and topsoil horizon. Chapter 5 was published in the South African Archaeological Bulletin, volume 68 (198) (December 2013) and I am the sole author. I include both surface and subsurface temperatures from all my experiments in Chapter 6, and I conduct statistical analyses of the data to examine the use of fire. One of the results is that the number of logs used in a fire can affect the maximum surface temperatures of a fire. Site maintenance such as cleaning ashes from a hearth before starting a new fire can also contribute to higher maximum surface temperatures, although the texture of the topsoil horizon does not seem to affect fire temperatures.

Experimental data on the formation of combustion features are presented and discussed in Chapters 7 and 8. Chapter 7 gives results from ten fire experiments and discusses them in relation to combustion features at Sibudu. It is argued that variation in hearth area implies variation in hearth use. This paper was published in *Quaternary International* volume 270 (2012) and I am the sole author on this paper. Chapter 8 elaborates on some of the results from Chapter 7. I include more data in Chapter 8, and I also perform statistical analyses of the data. I show that few experimental hearths contain a distinguishable black stratum rich in charcoal under the top white ash stratum. My experiments also suggest that more hearth strata are produced in long lasting fires and that the ash depth is related to fuel load for some wood taxa.

In Chapter 9, I combine micromorphological, organic petrological and anthracological results from other researchers with a spatial analysis of Sibudu. This collaborative paper examines combustion features, fire-related behaviour and diachronic changes in layers dating to ~65 ka and ~58 ka, which are the same layers introduced in Chapter 3. The micromorphological analysis by Dr. C. Miller implies that many combustion features at Sibudu are the result of burning bedding, and the organic petrological analysis by Dr. B.

Ligouis suggest tightly controlled fires at Sibudu and that herbaceous plants were burned in many of the fires. The charcoal identification by Dr. L. Allott and the botanical analysis by Prof. L. Wadley imply that about half the taxa burned at Sibudu are suitable as firewood or wooden implements. I digitised site plans drawn by L. Wadley, weighed material from selected layers and entered the maps and weights into ArcMap. The spatial analysis of weights of bone, charcoal or stone, using the Kernel density estimation, suggests that clusters of material were more contained, and perhaps less trampled, in the younger than in the older layers. This paper is currently in preparation and will shortly be submitted to the *PaleoAnthropology Journal*.

Chapter 10 provides pH readings from sediments in archaeological features and layers as well as experimental fires. It appears that there is a relationship between the lithic industry in a layer and the pH value of a layer, but the sample size is very small. I also report on the ratio of bone, charcoal and stone in archaeological combustion features and layers and charcoal from experimental fires.

I summarise and discuss the results of my research in Chapter 11. My thesis provides implications for the study of Middle Stone Age pyrotechnology at Sibudu as well as at other sites. I have demonstrated in experiments that maintenance techniques such as adding logs to the fire at regular intervals and raking out ashes before starting a new fire in a hearth can be important to control the surface temperatures of a fire. The spatial analysis suggests dumping areas at Sibudu, and the contents of the combustion features suggest that different post-depositional processes were important to different layers at Sibudu. Chapter 11 also contains suggestions for future studies. New fire experiments could, for example, be conducted to examine maintenance techniques that help control the development of a fire. More detailed studies of the sizes of bone, charcoal and stone could be conducted to further examine diachronic differences at Sibudu and a more detailed spatial analysis including specialist analysis of bone fragments and stone could help distinguish between activity areas at dumping areas at Sibudu as well as other sites.

2 FIRE-RELATED FEATURES AND ACTIVITIES IN THE MSA

The paper presented in this chapter is a literature survey of MSA pyrotechnology in the context of early fire use. The paper is published in the Journal of Archaeological Research 22, pp. 141 – 175.

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Using Pyrotechnology: Fire-related Features and Activities with a Focus on the African Middle Stone Age

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Published online: 22 November 2013
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Abstract Pyrotechnology was important in prehistory and has been a research topic for decades, in particular, the origins of controlled and habitual use of fire. The earliest putative evidence of fire use is from the African sites of Swartkrans (1,500,000–1,000,000 years ago) and Koobi Fora (1,500,000 years ago). In contrast, researchers working with European sites debate whether habitual use of fire occurred before 400,000 years ago. This paper provides a brief introduction to early fire use and then focuses on the African Middle Stone Age. Published evidence on fire use is available for 34 sites in southern Africa. Combustion features yield much evidence about human behavior, not only in regard to technical skills but also concerning social activities. Several activities using fire, symbolic behavior, spatial structuring, and group size in the Middle Stone Age are inferred from bone and lithic data, ash discard, site maintenance, and hearth size. The current status of knowledge on Middle Stone Age pyrotechnology demonstrates the benefits of applying new methodological approaches, facilitates comparisons with earlier and later archaeological periods, and is an important reminder of the benefits of a multidisciplinary approach.

Keywords Southern Africa · Middle Stone Age · Pyrotechnology · Hearths

Introduction

Pyrotechnology, the use of fire as a tool, was an important part of prehistoric life and has been a research topic for decades (e.g., Brain and Sillen 1988; Clark and Harris 1985; Goldberg et al. 2001; Gowlett 2006; Oakley 1961; Wrangham and

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Carmody 2010). Research generally focuses on the origins of the control and habitual (i.e., regular and fully controlled) use of fire. Recent publications include, for example, an announcement of “the earliest secure evidence for burning in an archaeological context” at Wonderwerk Cave, South Africa (Berna et al. 2012), a review of early fire use that concludes that Europe was colonized without the habitual use of fire (Roebroeks and Villa 2011a), and a study that questions whether Neanderthals were able to make their own fire (Sandgate et al. 2011). The control and use of fire enabled the production of warmth and light, cooking and other activities; focusing on how and when this happened illuminates important research issues such as the development of complex technologies (e.g., making ceramic pots or metal tools) through time. Yet the development from the origins of fire use through various technological advances to the use of pyrotechnology as an advanced tool remains poorly understood (Brown et al. 2009, p. 861). This article provides a brief introduction to early pyrotechnology before focusing on fire use in the Middle Stone Age (MSA) of southern Africa.

Recognizing early fire use

It has been suggested that human control of fire is the result of a complex evolutionary process that started with the cognitive ability to conceptualize fire, which has been observed in chimpanzees (Pruetz and LaDuke 2010). Even great apes seem to prefer cooked food, which implies that early hominins may have had the same preference and that cooking might have spread rapidly once people became aware of its transformative effect on food (Wobber et al. 2008). Wrangham (2009) highlights the evolutionary significance of fire in enabling cooked foods and estimates, based on morphological adaptations that indicate the quality of the diet, that *Homo erectus* was able to control fire and was the first species to deliberately cook food (Carmody and Wrangham 2009; Wrangham and Carmody 2010). It is difficult, however, to recognize early fire use based on hominin anatomical features; recognizing fire archaeologically also is not as straightforward as one might presume. Early anthropogenic fire use can, for example, be difficult to distinguish from natural fires at archaeological sites, which have been exposed to postdepositional processes for several hundreds of thousands years. Nevertheless, a few examples of early fire use and the methods used to recognize early pyrotechnology are available in the literature.

During excavations of the South African site of Swartkrans Cave, in layers that are about 1,500,000 to 1,000,000 years old, the researchers found 270 bones they thought were burned (e.g., Brain 1993a, b). Experimental studies supported this interpretation and indicated that the bones had been exposed to temperatures around 400–500 °C, which are consistent with temperatures in campfires (Brain and Sillen 1988). Skeptics have suggested that the bones were burned in wildfires (see Pickering 2012), but four burnt bones from the cave have butchery marks (Pickering et al. 2008). Uncooked bones at the site might have been burned in a wildfire or, just as likely, been dropped in fires maintained for purposes other than cooking (Pickering 2012). Some researchers thus emphasize that the data do not demonstrate

habitual fire use (e.g., Roebroeks and Villa 2011a). Pickering (2012), however, emphasizes the contextual value of the Swartkrans material and points to the lack of burnt bones in other depositional units in the cave, the occurrence and distribution of burnt bone within a specific set of layers, and the butchery marks on some of the bones. These data are still some of the earliest putative examples of the deliberate use of fire. The experimental work on bones from Swartkrans (Brain and Sillen 1988) also has contributed to other projects that have investigated the evidence of burning of bones (e.g., Nicholson 1993; Shipman et al. 1984; Stiner et al. 1995). Experimental studies have demonstrated, for example, that bone buried under the fire becomes carbonized and black, while bones on the surface of the fire are calcined and white (Stiner et al. 1995). This is a very useful insight for interpreting fire use at a site, although burnt bones are not considered by all archaeologists as an acceptable proxy for purposeful fire use by early hominins.

Burnt sediments also can indicate fire use, sometimes in combination with burnt artifacts. For example, patches of burnt sediments and thermally altered stone artifacts have been found at the Koobi Fora FxJj 20 site in northern Kenya, which is approximately 1,500,000 years old (e.g., Bellomo 1994; Clark and Harris 1985). As is the case at Swartkrans, there is some debate about whether these burnt traces could have been caused by wildfires. Micromorphological analyses, where thin sections from sediment blocks are studied under the microscope (e.g., Courty et al. 1989), can sometimes identify fire use that could not be distinguished during excavation. For example, micromorphological analyses of 1,000,000-year-old sediments from Wonderwerk Cave, South Africa, identified well-preserved ashed plant material and fragments of burnt bones in what appears to be in situ burning events (Berna et al. 2012). Samples for micromorphology can be taken from remaining stratigraphic sequences years after the original excavation, as was done at Wonderwerk Cave (Berna et al. 2012). This method thus presents potential for new studies of fire at sites where excavation has ceased but where stratigraphic columns survive and can be sampled.

Even when burnt sediments are not detected at a site, the spatial distribution of burnt artifacts can help identify use of fire at a site through the use of mapping and geospatial tools. If the distribution of burnt artifacts is spatially restricted, then there is a strong case supporting fire use. A well-known example is the 780,000-year-old site of Gesher Benot Ya'aqov in the Middle East. By mapping the distribution of burnt flint artifacts at the site, indications of several combustion features were found (e.g., Alperson-Afil and Goren-Inbar 2010; Alperson-Afil et al. 2007; Goren-Inbar et al. 2004). Mapping burnt lithics to identify fire use is, however, regarded with the same concerns as the use of burnt bone.

Combustion features, often referred to as “hearths,” are an important sign of fire use and are considered secure evidence by most researchers. What seems like well-defined features at a site, however, may sometimes have been deposited through nonanthropogenic processes. Two examples illustrate this problem: the Chinese site of Zhoukoudian and the Cave of Hearths in South Africa. Until quite recently Zhoukoudian was considered to have the earliest known secure evidence of fire use in layers dating to approximately 600,000 years ago. Micromorphological analyses of the site suggest, however, that the sediments include water-laid accumulations of

fine-grained, dark, organic-rich material and reworked loess, not hearths and ashes (Goldberg et al. 2001). The Cave of Hearths has occupation layers from the Earlier Stone Age (ESA) to historical times. Recent paleomagnetic analyses, which involve comparing known reversals of the earth's magnetic field to the direction and intensity of magnetism preserved in sediments or rocks from a site, suggest that the oldest occupation of the site dates to around 400,000–600,000 years ago (Herries and Latham 2009). Several hearths were initially described at the site (Van Riet Lowe 1954), though Oakley (1954) pointed to the lack of carbon in the features and suggested that guano could have been ignited by lightning strikes in the cave. Mason (1988) considered that the earliest inhabitants lit fires on top of the guano, thus igniting it. A recent archaeomagnetic study (Herries and Latham 2009) did not find convincing evidence for hearths in the cave. The researchers behind the study point out, however, that many areas with described hearths have already been excavated and that there is no remaining evidence for the features observed in these areas. Thus they do not rule out the possibility or probability of hearths in the cave (Herries and Latham 2009, p. 64), which leaves the question open.

The earliest fire use: Light, warmth, and protection

The first fire users may have used fire to keep predators at a distance (Brain 1993a). Clark and Harris (1985, p. 21) suggest that early fire users were opportunistic scavengers who transported fire and might even have used it to drive carnivores from their kills. Early fire users probably also used the fire for light and warmth. For example, a study of the spatial clustering of stone artifacts around combustion features at Koobi Fora FxJj 20 indicates that the primary use of fire at the site was for protection, as a light source, and/or as a heat source (Bellomo 1994). From an archaeological perspective it is difficult to evaluate the importance of these three properties of pyrotechnology to early fire users. The interpretations, while based on common sense, are often speculative.

Fire for light and warmth could have contributed to the expansion of home ranges (Clark and Harris 1985), exemplified by the discussion of human expansion into Eurasia. The Spanish site of Sima del Elefante has been proclaimed the oldest site with artifacts and human fossil remains in Europe, dating to 1,200,000–1,100,000 years ago (Carbonell et al. 2008). Other finds, such as the 1,800,000–1,600,000-year-old hominin fossils from Dmanisi in Georgia (e.g., Gabunia and Vekua 1995; Gabunia et al. 2000; Rightmire et al. 2006; Vekua et al. 2002), indicate an even longer occupational history. Although these sites are from periods consistent with early evidence of fire use in Africa, sites with indications of fire use in Europe are much younger. One example is Beeches Pit in the UK. The site is dated to about 400,000 years ago, and burnt flint, burnt bone, and fire-related features (hearths) were found (e.g., Gowlett 2006; Preece et al. 2006). At the Spanish site of Torralba, which dates to between 350,000 and 300,000 years ago, the presence of charcoal implies the use of fire at the site (Howell 1966). Another example of early fire use in Europe is Terra Amata. Dating of the site ranges from 350,000 to 200,000 years ago, and hearths, burnt flint, and burnt shell were observed (De Lumley 1969; Villa 1983; Wintle and Aitken 1977).

The lack of fire at the earliest European sites can be explained by poor preservation (Gowlett 2006). It also has been considered an indication of sporadic use of fire in the first half of the Middle Pleistocene rather than habitual and controlled use of fire (Roebroeks and Villa 2011a). Sites such as Gesher Benot Ya'aqov point to fire as an African tradition that was a trigger for migration into Eurasia (Alpersen-Afil and Goren-Inbar 2010, p. 97), but fire might not have been a prerequisite for colonizing Europe and might have been regularly used only from 400,000 to 300,000 years ago (Roebroeks and Villa 2011a). Sandgate et al. (2011) suggest that habitual fire use did not occur until much later, that Neanderthals did not know how to make fire, and that the use of fire was not a significant part of Neanderthal adaptation. Neanderthals, however, seem to have used fire for a wide range of tasks, which indicates that fire was indeed significant and self-sustained among these groups (e.g., Roebroeks and Villa 2011b).

The colonization of Europe has been researched from several perspectives, and researchers have looked at the speed of this process. It has previously been suggested that a large guild of carnivores prevented hominin occupation of Europe before 500,000 years ago (Turner 1992) or that the process was delayed by social constraints (Gamble 1999, pp. 421–422), but hypotheses about the process also have changed as new archaeological sites are discovered and excavated (e.g., Pavlov et al. 2004; Roebroeks 2001). Fire is just one of the factors that could affect this process. Sites such as Gesher Benot Ya'aqov (Alpersen-Afil and Goren-Inbar 2010; Alpersen-Afil et al. 2007; Goren-Inbar et al. 2004) do show that, whether habitual and self-sustained or not, pyrotechnology was definitely part of the cultural repertoire of early hominins in Eurasia.

Structuring space and symbolic behavior

Fire might have helped not only to expand the home base but, in a more narrow perspective, pyrotechnology and the construction of hearths may have created a base or meeting point in a camp. Ethnographic examples point to the social importance of the placement of fires. For example, Yellen (1977) showed how a hearth can represent a social unit and that these units can be arranged in a specific pattern according to customary practice. The social significance of early fire as a gathering point where hominins could interact has been suggested previously (e.g., Clark and Harris 1985; Gowlett 2006; Oakley 1961; Roebroeks and Villa 2011a), and the hearth has been considered an important sign of a *living site* (Van Riet Lowe 1954). I do not provide a review here of hypotheses concerning the social and cognitive development of hominins and the use of fire (see instead Twomey 2013 and references therein), but I do mention a few points relevant to fire-related features and MSA pyrotechnology.

Symbolic behavior, such as the structuring of space, can be related to the importance of fire or combustion features in the social sphere, but this is not limited to modern humans. For example, as mentioned above, there is a distinct spatial patterning of activities at Gesher Benot Ya'aqov (e.g., Alpersen-Afil and Goren-Inbar 2010). Studies of Neanderthal sites also show that these hominins repeatedly constructed combustion features at the same place, created specific activity areas

around hearths as well as away from hearths, maintained sleeping areas by hearths (pointing to social units and relationships), and created refuse areas away from their habitation areas (e.g., Albert et al. 2012; Bar-Yosef et al. 1992; Schiegl et al. 1996; Speth 2004, 2006; Vallverdú et al. 2010, 2012; Vaquero and Pastó 2001; Vaquero et al. 2001). Structuring space by adding a stone lining to the hearth does not seem to be a regular feature until the Upper Palaeolithic (e.g., Villa 2010, p. x), but containing the fire with rocks might have had a practical rather than a symbolic or social function. Different types of hearths have been classified by the appearance (or lack) of stone linings or foundations (e.g., Leroi-Gourhan and Brézillon 1972), and the value of refitting stone tools to examine relationships between spatial units at a site has been recognized (Cahen et al. 1979) for a very long time. Combinations of refitting, recognition of activity areas, and the construction of hearths can be used to interpret social organization. This is, for example, the case at the Dutch Late Palaeolithic site of Rekem, where spatial segregation of diverse stages in the maintenance of hunting tools can be interpreted as a sign of private or socially restricted contexts around certain hearths (Caspar and De Bie 1996).

Selecting fuel, cooking, and making tools

Before using pyrotechnology, one has to select the fuel for the fire. Variables such as locally available resources, the desired properties of a fire, rules for using the fire, and the principal user(s) of the fire can be important in the selection of firewood. The type and quality of firewood can influence the fire and its development. There are two main types of wood: hardwood from angiosperms and softwood from conifers. Hardwood has more hemicelluloses, a higher content of acetyl and methoxyl groups, and a more complex morphology than softwood (Braadbaart and Poole 2008, pp. 2434–2435; Shafizadeh and DeGroot 1976, pp. 2–3). Several other variables, such as moisture content, chemical composition, and wood density, affect how the wood burns (Munalula and Meincken 2009, p. 416), and each wood taxon has different properties that can affect the qualities of a fire. The expected completion and success of other tasks, such as the gathering of plants to be cooked or the selection of raw materials to be transformed, also can influence the gathering and preparation of firewood.

Studies of the fuel used in a fire can be important to interpretations of climatic variables and prehistoric knowledge of the available resources in an environment as well as prehistoric preferences for firewood properties. Modern fire users in Malawi, for example, select wood based on properties such as perceived drying rate, ability to produce embers, and a low moisture content or low dry weight; they prefer different properties for different tasks (Abbot et al. 1997). Prehistoric fire users may have had other preferences when selecting firewood, and identification of wood taxa from archaeological charcoal (e.g., Allott 2006; Cartwright and Parkington 1997; Cowling et al. 1999; Théry-Parisot et al. 2010) can help identify desired properties. Bones have been used as fuel at European Palaeolithic sites, which may have affected the properties of the fire (e.g., Théry-Parisot 2001, 2002). Dung is another possible fuel type, though it might not have been widely used before the keeping of livestock (Shahack-Gross 2011).

Cooking, that is, using heat to prepare food, helps people to digest it. Cooking itself can involve many processes and stages, e.g., cutting up and distributing meat, rinsing plants, and bathing food tissues in salty baths, before the actual heat treatment occurs (see Wandsnider 1997). The chemical processes involved during cooking not only change the texture and flavor of the food but also kill bacteria. Cooking can thus protect people against illnesses as well as preserve food and extend its storage time (Carmody and Wrangham 2009; Wandsnider 1997). Roasting and other cooking techniques can be performed in many different ways, e.g., roasting on rocks by the fire, smoking meat, and cooking food in pits under the fire. It has been suggested, however, that pit roasting of meat, which is widely documented in ethnographic contexts (e.g., Wandsnider 1997 and references therein), was established only about 30,000 years ago (Thoms 2009). A more detailed look at pyrotechnology might contribute to our understanding of how and when cooking techniques developed.

Pyrotechnology can be instrumental in transforming materials and making various tools. Thermal alterations of certain rock types to improve their knapping properties have been investigated through experiments and technological studies. For example, heating silcretes can have a positive effect on rock properties (e.g., Flenniken and White 1983; Purdy and Brooks 1971), possibly caused by recrystallization of the heated rocks (e.g., Domanski et al. 1994; cf. Schmidt et al. 2012). An experimental study also indicated that intentionally heat-treated silcretes (silicified sediment or rock) have fewer cracks than unintentionally, possibly postdepositionally, heat-fractured silcretes, and this can be used to distinguish between intentional and unintentional exposure to heat (Mercieca 2000). Pyrotechnology also can aid the hafting and mounting of tools. This is not a technique that is limited to groups of modern humans. For example, Neanderthals could use pyrotechnology to haft tools with birch-bark tar (Koller et al. 2001; Mazza et al. 2006).

A spotlight on MSA pyrotechnology

In the rest of this article I focus on MSA pyrotechnology. The MSA spans more than 250,000 years, ending at about 30,000 years ago (Jacobs et al. 2008; McBrearty and Brooks 2000; Tryon and McBrearty 2002). This is the period when *Homo sapiens* appeared and ultimately colonized the world. The cognitive differences between *Homo sapiens* and other species, as well as differences within *Homo sapiens*, are vast research areas that can only be briefly summarized here. The former conception of a cognitive sophistication of modern humans around 50,000 to 40,000 years ago has been critically questioned by several researchers during the last 10–15 years (e.g., Brooks et al. 2006; Henshilwood et al. 2002; Jacobs et al. 2008; McBrearty and Brooks 2000; Wadley 2001; Wadley et al. 2009). Excavations of MSA sites have contributed important archaeological data to this debate. Lithics (e.g., Brooks et al. 2006; Mourre et al. 2010; Soriano et al. 2007; Villa et al. 2005; Wurz 1999, 2012), bone tools (e.g., Backwell et al. 2008; d’Errico and Henshilwood 2007; Henshilwood et al. 2001a), ochre (e.g., d’Errico et al. 2012; Henshilwood et al.

2002, 2009; Hodgskiss 2012; Mackay and Welz 2008; Rifkin 2012; Wadley 2005, 2009; Watts 2002, 2010), and shell and marine resources (e.g., Avery et al. 2008; d’Errico et al. 2005, 2008; Klein et al. 2004; Langejans et al. 2012) are among the archaeological finds that provide a base for interpretations of the technological sophistication and symbolic behavior of *Homo sapiens* during the MSA. From a different perspective, other researchers have pointed out that the Neanderthals seem to have been more cognitively adept than previously assumed and exhibit traits that until recently were considered to be strictly modern (e.g., Albert et al. 2012; Speth 2004, 2006; Vallverdú et al. 2010; Vaquero et al. 2001; Zilhao 2007).

In a comment on the debate about modernity, Shea (2011) points out that all modern human behavior, as well as the behavior of extinct hominins, varies and that any development through time is reversible and, in any case, only recognizable after it has happened. He further calls for a construction of better models for the variability of human behavior through a focus on the costs and benefits of specific strategies in various contexts (Shea 2011, p. 14). I accept behavioral variability as a premise for the MSA part of this article, which focuses on the different fire-related features reported and interpretations of fire use rather than cognitive implications (but see Twomey 2013 and references therein for a discussion of cognitive behavior and fire use).

Pyrotechnology was an important part of life in the MSA and constitutes an additional practice that can augment the knowledge of technological practices in the MSA. Building a holistic image of MSA pyrotechnology will create a productive base for comparisons with pyrotechnology in other periods and areas. There are some studies of fire use at individual sites in the MSA (Albert and Marean 2012; Allott 2005, 2006; Brown et al. 2009; Goldberg et al. 2009; Henderson 1992; Herries and Fisher 2010; Mason 1988; Mourre et al. 2010; Schiegl et al. 2004; Schmidt et al. 2013; Wadley 2005, 2009, 2012; Wadley et al. 2011), but a synthesis of pyrotechnology in the MSA has not yet been published. The following outline of MSA pyrotechnology provides that synthesis.

The MSA material: Recognition of fire use and fire-related features in the MSA of southern Africa

In the available literature on southern Africa, 34 MSA sites have preserved signs of fire use (Table 1). Burning events created through fire use can leave various signatures at a site, such as charcoal, burnt organic material and lithics, and combustion features. For several reasons, these or other attributes of fire use might not have been included in publications of sites, so some sites or attributes might be missing from Table 1, which includes only those sites where hearths, ash dumps/layers, burnt items, and the other categories were positively identified in a publication. It has been suggested that early methods of excavating MSA sites were not fine enough to recognize fire-related features (Klein 1970, p. 131). Indeed, my review of the literature reveals that many observations of the signs of fire have been recognized in more recent studies (Table 1). The data in Table 1 refer exclusively to MSA layers at sites where occupation layers preceding or postdating the MSA also occur.

Table 1 Southern African MSA sites with signs of fire use

No. on map	Site	Hearths/ combustion features	Ash features/ deposits	Ash layers/ lenses	Clusters of charcoal	Carbonized/ reddened substrata	Superimposed hearths	Charcoal	Carbonized plant/ seeds	Burnt seashell	Burnt bone	Burnt rocks/ stone tools	Burnt ostrich eggshell	References
1	Apollo 11	x		x	x			x	x		x		x	Vogelsang et al. (2010)
2	Blombos Cave	x	x			x	x	x	x	x	x	x		Henshilwood et al. (2001a, b, 2002), Jacobs et al. (2006), Mourre et al. (2010), Tribolo et al. (2006)
3	Boomplaas Cave	x		x		x								H. Deacon (1979, 1989)
4	Border Cave	x		x		x		x	x					Beaumont et al. (1978), Butzer et al. (1978), Grün and Beaumont (2001)
5	Bushman Rock Shelter			x		x		x	x					Louw (1969), Plug (1981)
6	Cave of Hearths	x		x				x						Mason (1988)
7	Die Kelders Cave	x	x	x		x	x	x	x	x	x			Avery et al. (1997), Goldberg (2000), Marean et al. (2000), Schweitzer (1970)

Table 1 continued

No. on map	Site	Hearths/ combustion features	Ash features/ deposits	Ash layers/ lenses	Clusters of charcoal	Carbonized/ reddened substrata	Superimposed hearthths	Charcoal	Carbonized plant/ seeds	Burnt seashell	Burnt bone	Burnt rocks/ stone tools	Burnt ostrich eggshell	References
8	Diepkloof Rock Shelter	x	x	x		x	x	x	x		x	x	x	Jacobs et al. (2008), Miller et al. (2013), Parkington and Poggenpoel (1987), Rigaud et al. (2006), Texier et al. (2010), Tribolo et al. (2009)
9	Florisbad	x			x			x			x	x		Kuman and Clarke (1986), Kuman et al. (1999)
10	Ha Suloja	x						x						Carter (1977)
11	Herolds Bay Cave	x												J. Deacon (1979)
12	Highlands			x				x						H. Deacon (1979)
13	Howiesons Poort	x			x			x		x				J. Deacon (1995)
14	Klasies River	x	x	x	x	x	x	x	x	x	x	x		Butzer (1978), Deacon (1989), Deacon and Geleijnse (1988), Henderson (1992), Jacobs et al. (2008), Singer and Wymer (1982)

Table 1 continued

No. on map	Site	Hearths/ combustion features	Ash features/ deposits	Ash layers/ lenses	Clusters of charcoal	Carbonized/ reddened substrata	Superimposed hearthths	Charcoal	Carbonized plant/ seeds	Burnt seashell	Burnt bone	Burnt rocks/ stone tools	Burnt ostrich eggshell	References
15	Klein Kliphuis							x						Mackay (2006)
16	Melikane Shelter				x			x						Carter (1977)
17	Montagu Cave	x		x				x						Keller 1966 in Klein (1970)
18	Mumbwa caves	x	x			x	x		x		x	x		Barham (2000), Barham et al. (2000)
19	Mwulu's Cave			x										Sampson (1972), Tobias (1949)
20	Nelson Bay Cave	x		x		x		x						Butzer (1973)
21	Ngalue Cave	x					x							Mercader et al. (2009)
22	Pinnacle Point Site 5-6	x		x		x		x				x		Brown et al. (2009)
22	Pinnacle Point Cave 13	x		x		x	x	x	x	x	x			Karkanas and Goldberg (2010), Marean et al. (2004, 2010)
23	Pomongwe	x		x				x						Cooke (1963)
24	Rhino Cave											x		Coulson et al. (2011), Robbins et al. (2000)

Table 1 continued

No. on map	Site	Hearths/ combustion features	Ash features/ deposits	Ash layers/ lenses	Clusters of charcoal	Carbonized/ reddened substrata	Superimposed hearths	Charcoal	Carbonized plant/ seeds	Burnt seashell	Burnt bone	Burnt rocks/ stone tools	Burnt ostrich eggshell	References
25	Rose Cottage Cave	x	x	x	x		x	x				x		Jacobs et al. (2008), Valladas et al. (2005), Wadley (2001, 2006)
26	Sehonghong	x	x	x			x	x						Carter (1977), Carter et al. (1988), Jacobs et al. (2008)
27	Sibudu Cave	x	x	x	x	x	x	x	x	x	x	x		Cain (2005), d'Errico et al. (2008), Goldberg et al. (2009), Schiegl et al. (2004), Sievers (2006), Wadley (2001, 2006, 2012), Wadley and Jacobs (2006)
28	Spitzkloof							x			x		x	Dewar and Stewart (2012)
29	Strathalan Cave B	x						x	x					Opperman (1996), Opperman and Heydenrych (1990)
30	Umhlaluzana Shelter							x						Kaplan (1989, 1990)

Table 1 continued

No. on map	Site	Hearths/ combustion features	Ash features/ deposits	Ash layers/ lenses	Clusters of charcoal	Carbonized/ reddened substrata	Superimposed hearths	Charcoal	Carbonized plant/ seeds	Burnt seashell	Burnt bone	Burnt rocks/ stone tools	Burnt ostrich eggshell	References
31	Wonderwerk Cave			x							x			Beaumont and Vogel (2006), Chazan and Horwitz (2009), Malan and Cooke (1941)
32	Ysterfontein I	x				x	x	x						Avery et al. (2008), Halkett et al. (2003), Klein et al. (2004)
33	Zeekoegat 27										x			Sampson (1968)

An x indicates that a sign of fire is reported from a site

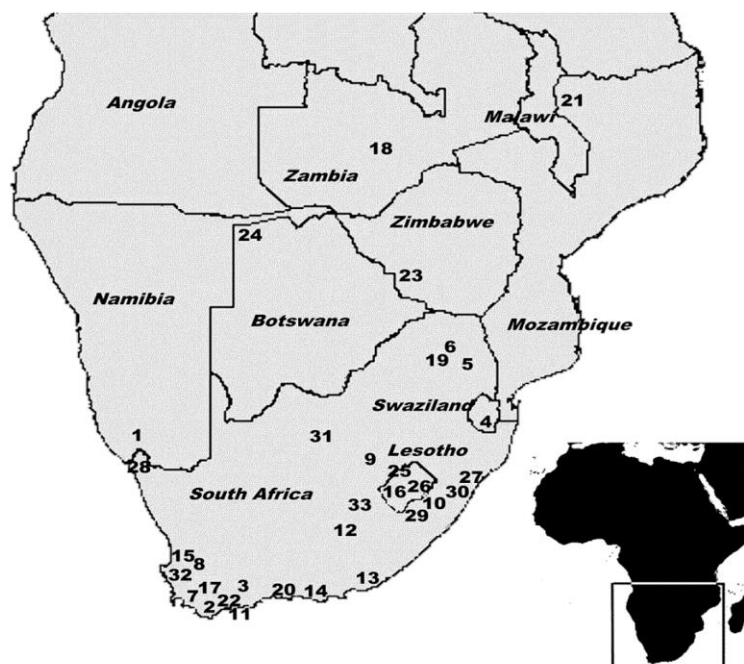


Fig. 1 Map of southern Africa showing the location of MSA sites with signs of fire use. Sites are marked as follows: 1 Apollo Cave, 2 Blombos Cave, 3 Boomplaas Cave, 4 Border Cave, 5 Bushman Rock Shelter, 6 Cave of Hearths, 7 Die Kelders Cave, 8 Diepkloof Rock Shelter, 9 Florisbad, 10 Ha Soloja, 11 Herolds Bay Cave, 12 Highlands, 13 Howiesons Poort, 14 Klasies River, 15 Klein Kliphuis, 16 Melikane Shelter, 17 Montagu Cave, 18 Mumbwa Cave, 19 Mwulu's Cave, 20 Nelson Bay Cave, 21 Ngalue Cave, 22 Pinnacle Point Site 5-6 and Cave 13, 23 Pomongwe, 24 Rhino Cave, 25 Rose Cottage Cave, 26 Sehonghong, 27 Sibudu Cave, 28 Spitzkloof, 29 Strathalan Cave B, 30 Umhlatuzana Shelter, 31 Wonderwerk Cave, 32 Ysterfontein 1, and 33 Zeekoegat 27. The map was made using a layer from www.maps-for-free.com, computed by Hans Braxmeier, as a template for the outline of the continent and the countries

Most of the sites featured are in South Africa (Fig. 1), which is a reflection of the amount of research carried out here. The reported data represent different phases of the MSA. Beaumont and Vogel (2006) place the start of the MSA at $\sim 270,000$ years ago at Wonderwerk Cave, but Chazan and Horwitz (2009) suggest that the MSA at the site is not that old. The earliest MSA occupation at Florisbad is dated to about $\sim 279,000$ years ago (Kuman et al. 1999). Other early MSA fire use occurred at Border Cave, possibly before $\sim 200,000$ years ago (Grün and Beaumont 2001), and Pinnacle Point at $\sim 164,000$ years ago (Marean et al. 2007). The youngest MSA layers represented are from $\sim 22,000$ years ago at Strathalan Cave B (Opperman 1996), $\sim 33,000$ years ago at Klein Kliphuis, and $\sim 30,000$ years ago at Sehonghong (Jacobs et al. 2008). Many of the MSA sites featured here were occupied during more than one phase of the MSA and can have fire-related features and indications of fire from all of these phases.

Charcoal and burnt material as proxies for fire use in the MSA

Charcoal and burnt materials provide the most common signs of fire use (Table 1). Charcoal is reported at 76 % ($n = 26$) of the sites reviewed. Charcoal is the only

indicator of fire use at two sites, Umhlatuzana and Klein Kliphuis. Hearths were visible in the upper Later Stone Age (LSA) layers at Umhlatuzana (Kaplan 1989, 1990) but not in the MSA layers, where there was no visible stratigraphy, perhaps due to acidic groundwater runoff (Kaplan 1989, p. 7). A similar difference in visual stratigraphy was reported at Klein Kliphuis (Mackay 2006, p. 182). Hearths are preserved at four of the nine sites where no charcoal was reported; documenting that combustion features can potentially be distinguished even when charcoal is not present. Neither charcoal nor defined hearths are reported from the MSA layers of Mwulu's Cave (Sampson 1972; Tobias 1949), Rhino Cave (Coulson et al. 2011; Robbins et al. 2000), Wonderwerk Cave (Beaumont and Vogel 2006; Chazan and Horwitz 2009; Malan and Cooke 1941), or Zeekoegat 27 (Sampson 1968); burning on elements such as bone and stone suggest otherwise invisible fire use at these sites.

Twelve sites report burnt bone as an indicator of fire. At Zeekoegat 27, charring of undiagnostic long-bone fragments was observed (Sampson 1968, p. 65). This is the only site in Table 1 where burnt bone is the sole indicator of fire use. Carbonized plant material or seeds are reported from 11 sites. Details of charred plant material are not always available (Butzer et al. 1978), but sometimes carbonized seeds (e.g., Sievers 2006) and other plant material (e.g., Albert and Marean 2012; Sievers and Muasya 2011; Wadley et al. 2011) have been analyzed.

Heat-treated or heat-fractured rocks or heat-treated stone tools are reported from nine sites. For example, some lithics at Pinnacle Point 5-6 display an increased reflectance or gloss from being heated (Brown et al. 2009), and points from Rhino Cave are cracked and crazed (Coulson et al. 2011, p. 32). Burnt seashells are reported at six sites; at Klasies River they have been interpreted as an indication of cooking (e.g., Henderson 1992, p. 21). Burnt ostrich eggshell is reported from three sites. At Diepkloof, ostrich eggshell fragments are interpreted as parts of engraved containers, and the burning observed on them is thought to be one of various postdepositional effects (Texier et al. 2010).

It is difficult to distinguish archaeological material burned by natural fires from material burned in intentional fires, but clustering of burnt material can, as described above, be a sign of intentional fires (e.g., Alpers-Afil and Goren-Inbar 2010; Alpers-Afil et al. 2007). Most of the MSA sites report more than one type of burnt material, but subsequent accidental or intentional burning at an archaeological site can affect previously deposited materials (e.g., Sievers and Wadley 2008; Wadley 2009). Thus, carbonized material does not necessarily imply hearths or intentional fires. However, intentional fires are suggested by how burnt material relates to ash layers and fire-related features at several sites, such as the burnt and not burnt bone fragments around the hearth at Florisbad (Kuman and Clarke 1986; Kuman et al. 1999).

Ash layers and fire-related features

Ash layers can imply fire use even when their occurrence is mentioned only as part of stratigraphic observations during excavation, such as at Mwulu's Cave (Tobias 1949, p. 5). Ash layers or lenses are reported for 55 % ($n = 19$) of the sites, and ash

features or deposits are reported from 23 % ($n = 8$) of the sites. Ash features or deposits may represent ash dumps, cleaning events, or badly preserved hearths. At Diepkloof Rock Shelter and Sibudu, some ashy deposits are interpreted as ash dumps (Goldberg et al. 2009; Miller et al. 2013; Texier et al. 2010, p. 6181).

Hearths are reported from 70 % ($n = 24$) of the sites, though they are sometimes mentioned only as part of the stratigraphy or briefly described. For example, in MSA layers at the Cave of Hearths, there are references to “basal ash accumulation” (Mason 1988, p. 278) and “hearth lines” (Mason 1988, p. 330). There is a reference to MSA fireplaces at Apollo 11 (Vogelsang et al. 2010, Table 2), and hearths are described as “carbonized lenses that mark ancient fireplaces” at Ysterfontein (Avery et al. 2008, p. 67).

More details and descriptions of MSA hearths, including the horizontal outline, are provided in other reports. Generally, the MSA hearths are depicted as irregular or circular ash patches of various sizes, sometimes with convex bases. For example, Still Bay hearths at Blombos Cave (Henshilwood et al. 2001b) are basin shaped and up to 0.5 m in diameter. Mumbwa Caves is the only site that has stone-lined hearths, one of which is described as a rough circle, almost 1 m across, of large dolomite, sandstone, phyllite, and quartz rocks, dipping toward the center (Barham 2000, pp. 27–30). At Strathalan Cave B, one large and three smaller hearths were found inside a 1 × 4-m carbonized area with a clear black ash outline (Opperman 1996; Opperman and Heydenrych 1990), which has not been observed at other MSA sites.

Hearths of different sizes and shapes and various combustion features are present at some of the sites. At Sibudu, for example, three main types of in situ combustion features are recognized: small discrete hearths, larger hearths, and superimposed burnt sediments, including carbonized organic material, which might represent maintenance fires for burning bedding (Goldberg et al. 2009; Wadley 2012; Wadley et al. 2011). Combustion features can be difficult to separate from each other. Eleven of the sites that have hearths also have superimposed hearths, showing that repeated fires were lit at the same place, and 13 sites have carbonized or reddened substrata as a result of burning.

Interpretations of fire use in the MSA

The many sites with signs of fire use demonstrate that pyrotechnology was important in the MSA and that a hearth was more than a home base. Several researchers have provided interpretations of fire-related behavior in the MSA, which is described below.

Examples of choice of fuel in the MSA

Modern fire users seem to have strong preferences for particular firewood taxa and/or properties (e.g., Abbot et al. 1997), and the expectation is that this would also be the case in the past. There are studies of firewood choice at MSA sites, mainly through charcoal analyses. In Diepkloof, environmental changes may have resulted in the use of a variety of woody taxa toward the end of the MSA occupation of the

site (Parkington et al. 2005, p. 483). At Sibudu Cave, layers approximately 60,000 years old contain many charcoal fragments of *Erica* spp., which have small branches and burn quickly. There are fewer fragments of *Erica* spp. in layers that are approximately 50,000 years old, while the occurrence of *Acacia* spp. is greater. *Acacia* wood provides a long-lasting fire without noxious fumes by producing many coals. This change in wood collection, however, does not seem to reflect cultural preferences alone and must be interpreted in light of the environmental context of the Sibudu area (Allott 2006, pp. 192–194).

Interpretations of firewood also can be made from other types of analyses such as phytolith studies. At Pinnacle Point, such studies reveal that plants occur more frequently in some hearths than others, suggesting differential use or short-term activities (Albert and Marean 2012). People in the MSA may have looked for wood properties different from those sought after by modern people. At Sibudu Cave, *Podocarpus* spp. (yellowwood) was the dominant taxon used for firewood in Howiesons Poort layers, but there is no reference to its use as firewood in southern Africa today (Allott 2006, p. 191). *Podocarpus* has, however, been identified in charcoal assemblages from the LSA at Elands Bay Cave (Cartwright and Parkington 1997; Cowling et al. 1999), further documenting its use in prehistory.

The use of bone as fuel was mentioned above. Taphonomic studies of burnt bones from Sibudu Cave (Cain 2005, 2006; Clark and Ligouis 2010; Hanson and Cain 2007) suggest a range of temperatures reached by the campfires at the site, but it does not seem that bones were used as primary fuel. It is difficult to comment further on the possible use of bones as fuel in the MSA in southern Africa based on current knowledge.

Cooking techniques, transforming materials, and making tools in the MSA

There are few published observations on MSA cooking techniques. Milo (1998, pp. 116–117) suggests that the parts of animals that are represented by bones at Klasies River, as well as the burning patterns on the bones, are evidence that limbs were roasted while the tarsals were still attached. He further suggested that the upper portions of the legs were sometimes roasted whole on or near the fire and that the mandibles were removed before the head was roasted. Fish and shellfish were also cooked in the MSA (e.g., Avery et al. 2008; von den Driesch 2004; Halkett et al. 2003; Henshilwood et al. 2001b; Klein et al. 2004; Marean et al. 2007). At Blombos Cave, bones from white sea catfish (*Galeichthys feliceps*) were found mainly in trenches outside the cave. This species has a toxic spine, and the bones were probably discarded or cooked outside the cave (Henshilwood et al. 2001b) to avoid the danger of people being pierced by the bones. Henderson (1992, p. 21) suggests that the occurrence of fragments of burnt *Perna perna* shells in a hearth feature at Klasies River indicates the cooking of shellfish. It also has been suggested that coastal resources were less intensively exploited in the MSA compared to the LSA due to smaller population or group size (e.g., Avery et al. 2008; Klein et al. 2004), but further comparisons of the use of fire to process these resources have not been made.

Plants and seeds are other possible food items that may have been cooked in the MSA. Tracing the use and processing of plants is archaeologically challenging. Agents such as birds and rodents can introduce a variety of plants to a site, and it may not always be possible to distinguish these from the anthropogenic use of plants (e.g., Sievers 2006). Even if the origin of plants at a site is anthropogenic, they may not all be food sources. At Sibudu the most commonly occurring seeds and plant remains come from sedges that appear to have been used for bedding (Goldberg et al. 2009; Sievers 2006; Sievers and Muasya 2011; Wadley et al. 2011). As is the case with burnt bone, the presence of carbonized seeds and other fruiting structures might not always be the result of cooking, even when edible plants are represented. Apart from the possibility of eating most plants raw, recent research on the carbonization of seeds and fruits (Sievers and Wadley 2008) implies that carbonized seeds and fruit structures would often have been burned before deposition. Nonetheless, H. Deacon (1995, p. 126) suggested that distinctive black residues in the sediments around the hearths at Klasies River are debris from the processing of plant foods. Domestic hearths used in food preparation also are inferred from their size and association with carbonized matter at Strathalan Cave (Opperman and Heydenrych 1990, p. 96).

The occurrence of heat treatment of silcrete rocks to facilitate stone tool production in the MSA has been suggested. Brown et al. (2009, 2012) found evidence for heat-affected silcretes at the site of Pinnacle Point and also reported higher success rates and easier flaking when they worked with experimentally heat-treated local silcrete. A study on Blombos Cave (Mourre et al. 2010) indicated that silcrete artifacts were heated to facilitate the production of Still Bay points at the site. These studies were based on research that found that there was recrystallization in silcretes after heat treatment and promoted careful control of the fire and gradual temperature increase during heat treatment to avoid thermal shock and the formation of cracks (e.g., Domanski et al. 1994). Schmidt et al. (2012, 2013), however, found no sign of recrystallization in heat-treated silcretes but loss of silanol and the creation of new bridging Si-O-Si bonds. Furthermore, their studies imply that South African silcretes can be heated to higher temperatures and at a faster heating rate than indicated by Brown et al. (2009, 2012). Thus, while some researchers (Brown et al. 2009, 2012; Mourre et al. 2010) consider heat treatment of silcretes in the MSA to be a sign of a sophisticated pyrotechnology, others (Schmidt et al. 2013, p. 3529) suggest an opportunistic practice of heat treatment. Future research might examine these hypotheses further.

Ochre has been found at many MSA sites, and its use and processing methodology have been explored (e.g., Henshilwood et al. 2001b, 2009; Lombard 2007; Wadley 2005; Wadley et al. 2009). Experimentally heated ochre may result in yellow ochre turning red, even at temperatures as low as 250 °C (e.g., Wadley 2005, 2009; Wadley et al. 2009). In experiments, regular campfires have reached maximum temperatures of 400–900 °C on the surface of the fire and 100–430 °C 5 cm below the surface (e.g., Bellomo 1994; Bellomo and Harris 1990; Bentsen 2012; Sievers and Wadley 2008; Wadley 2009). It is possible, then, to use fire as a tool to transform ochre to a desired color for symbolic or other purposes, but unintentional, postdepositional heating of buried ochre or heat treatment to change other attributes

would produce the same result. Red-colored ochre might thus be overrepresented in the archaeological record (Wadley 2009). In a recent study, Watts (2010) argues that dark red might be a preferred color in the MSA and that ochre was deliberately heated at Pinnacle Point to achieve red hues and the darkening of red pigments. He bases this interpretation on the disproportionate occurrence of yellowish pieces amongst the smallest debris at Pinnacle Point; he argues that these pieces most likely would have been transformed to red hues during incidental or postdepositional heating.

There is a strong possibility that fire was used in making adhesives for hafting in the MSA, because heating the adhesive drives off excess moisture and makes the mixture pliable. Slow heating also speeds up the drying process when making adhesives (Wadley 2005). Microresidue studies on material from Sibudu Cave reveal that most Howiesons Poort segments were hafted, that ochre was part of some adhesives, and that both wood and bone could have been used as shafts (Lombard 2007, 2008, p. 35). Indications of hafting are also found on Still Bay points from Blombos Cave (Villa et al. 2009, pp. 450–451). Using fire as a tool for knapping or hafting involves effective control of heat, and this is technically an advanced process (see Wadley 2005). The mixing of compound adhesives and hafting involves multitasking and abstract thought (Wadley et al. 2009) and are examples of fire use that contribute to our understanding of human variability and development.

Symbolic behavior and spatial structuring of MSA sites

As mentioned above, the symbolic meaning of ochre color in the MSA has been discussed (e.g., Wadley 2009; Watts 2002, 2010). MSA shell beads have been interpreted as signs of symbolic behavior and personal ornamentation (d’Errico et al. 2005, 2008). Other artifacts that have been interpreted as symbolic include standardized tools (Wurz 1999), bone tools (e.g., Backwell et al. 2008; Henshilwood et al. 2001a), shell beads (e.g., d’Errico et al. 2005, 2008), and engraved ochre and ostrich eggshell (e.g., d’Errico et al. 2012; Henshilwood et al. 2009; Parkington et al. 2005; Texier et al. 2010). Coulson et al. (2011) have suggested ritual use of fire in the MSA and deliberate burning and destruction of stone points at Rhino Cave, Botswana. Some examples of spatial distribution, fire-related issues, and possible symbolic behavior are described below.

Ash dumps and discard behavior are now being recognized at MSA sites, including Diepkloof Rock Shelter and Sibudu (Goldberg et al. 2009; Miller et al. 2013; Texier et al. 2010). It will always be difficult to establish which dumps are associated with contemporary hearths, but the spatial relationships and dumping behavior at a site should still remain a possible area of study. Such investigations are largely works in progress at MSA sites. While cooking reduces the risk for illness by killing bacteria in food, fire also can have a cleansing effect in other contexts and can be used for “housekeeping” as well as sanitation. At Sibudu Cave, there are indications of the hearth being used as a waste bin to help clean up discarded bones (Cain 2005, p. 882; Clark and Ligouis 2010). Additionally, bedding at the site seems to have been burned to get rid of pests or to change the use of an area. Burning of bedding at Sibudu began about 73,000 years ago and intensified around 58,000

years ago, suggesting a change in settlement and maintenance strategies (Goldberg et al. 2009; Wadley et al. 2011). The burning of bedding also has been recognized through micromorphological analysis at Diepkloof Rock Shelter (Miller et al. 2013). These interpretations offer a perspective on site maintenance behavior that complements research on ash dumps and needs to be further explored. Some studies also have suggested that fire was used for ecological management in the MSA (see Daniau et al. 2010 and references therein), for example, to promote the growth of geophytes that were an important food resource (Deacon 1993, p. 89).

The use of windbreaks and subsequent organization of space has been suggested at Mumbwa Caves (Barham 2000; Barham et al. 2000). The size of hearths in one of the MSA layers at the site is interpreted as a sign of more structured use of space compared to earlier phases. It is further suggested that four family groups and a communal space, or six family units without a communal space could fit into the cave (Barham et al. 2000, p. 144).

The many reported superimposed hearths at MSA sites (Table 1) indicate that some areas of a site were favored for fire use. Placing hearths at the same spot as during earlier occupations may be related to environmental factors and local conditions such as moisture or wind, although previous occupations may not have been visible when the hearths were placed. These superimposed hearths suggest intensive and repeated use of fire that may be related to organization, function, and/or other specific tasks performed at a site.

At Klasies River, the size of hearths has been interpreted as a sign that food preparation took place in small family units rather than within the group as a whole (Henderson 1992), that is, the hearths had a domestic function and represented family organization within the group (H. Deacon 1995, p. 28). Cooking fires, however, need not necessarily represent nuclear families (Wadley 2001, p. 205). At Rose Cottage Cave, the size and distances between hearths have been used as indicators of social differences between people living in the LSA and MSA (Wadley 2006). The placing of combustion features seems to be more structured at Rose Cottage Cave during the LSA, with fewer hearths placed at greater distances from each other. During the MSA, hearths seemed to be placed closer together, and new occupants apparently made new hearths rather than reusing the existing features (Wadley 2001, 2006). This could mean that the hearth had different social connotations, if any, in the MSA compared to the LSA.

The MSA spans a long period, so one might expect to find different patterns of fire use through time. A recent study (Herries and Fisher 2010) of Pinnacle Point 13B indicates that there is a change in the occupation patterns in the cave over time. This study also suggests that it is possible to distinguish different zones, such as sleeping areas and activity areas, based on the mapping of fire-related features in the cave. Another study of the same site, however, indicates differential use of hearths at the same level in the cave (Albert and Marean 2012). Further studies of suggested spatial differences within the MSA, as well as between the LSA and the MSA, should involve looking at spatial data from several sites. An in-depth study of MSA spatial relationships (e.g., Henderson 1992) might suggest different rationales for arrangements of MSA features. At sites such as Sibudu, where the excavation spans several layers and archaeological periods, it also is possible to study changes in

spatial strategies during a larger part of the MSA (Wadley et al. 2011). Another example is Blombos Cave, where space was structured using a barrier of rocks in the Still Bay layers (77,000–72,000 years ago). The later Howiesons Poort layers at other sites (65,000–59,000 years ago) do not have a similar physical structuring of space, but there are indications of individual domestic hearths (Henshilwood and Dubreuil 2011). This suggests diachronic changes in the use of space, but further and more detailed studies are needed to describe this development more thoroughly. Similar studies of organization in the preceding Early Stone Age and the following LSA would contribute to an even larger perspective on the development of organization and fire use in the Stone Age.

Summary

There is still uncertainty about the origins of the human use of fire. The earliest African evidence comes from Swartkrans (e.g., Brain 1993a, b; Brain and Sillen 1988; Pickering et al. 2008) and Koobi Fora (e.g., Bellomo 1994; Clark and Harris 1985). However, the importance of natural fires in Africa has long been used to dispute early fire use in the region (e.g., Bellomo 1993; Oakley 1954; Pickering 2012; Roebroeks and Villa 2011a). Different researchers accept different kind of evidence of fire use, which contributes to the diverse views on its origins. For example, burnt bone and experimental results that compare favorably with archaeological evidence are accepted signs of fire use at Swartkrans (e.g., Brain 1993b; Brain and Sillen 1988; Pickering 2012), and the importance of contextualized sediments is underlined in the study of Wonderwerk Cave (Berna et al. 2012). Other studies emphasize the importance of combustion features and/or several proxies for fire in the same context (Roebroeks and Villa 2011a). The different opinions on casual and harvested fire on the one hand, and habitual and self-sustained fire on the other complicate the picture further (e.g., Alperson-Afil and Goren-Inbar 2010; Alperson-Afil et al. 2007; James 1989; Karkanas et al. 2007; Roebroeks and Villa 2011a, b; Sandgate et al. 2011).

A broad view of the status of research into MSA pyrotechnology shows that many different forms of evidence for fire use have been recognized. Charcoal and burnt materials are the most common evidence, and the majority of the sites (82 %; $n = 28$) have more than one indication of fire. About 70 % ($n = 24$) of the sites have hearths. The MSA hearths vary in shape and size, and some sites have different types of hearths and fire-related features, including possible ash dumps and burnt bedding (e.g., Goldberg et al. 2009; Texier et al. 2010; Wadley et al. 2011). This clearly shows that pyrotechnology was an integral part of the cultural tradition. Nevertheless, the data from Gesher Benot Ya'aqov (Alperson-Afil and Goren-Inbar 2010; Alperson-Afil et al. 2007; Goren-Inbar et al. 2004) show that fire had already been used intensively for hundreds of thousands years before the MSA. However, any differences in use through time should be identified and the meaning of these differences explored.

Fuel properties can affect a fire. Collection of firewood must always be seen in relation to the environment, but charcoal analyses from Sibudu Cave do not indicate

that cultural preferences had priority during the collection of firewood (Allott 2005, 2006). The lack of clear preferences for firewood taxa suggests that burning properties of fuel were either not recognized or were not considered important. Phytolith studies from Pinnacle Point (Albert and Marean 2012), however, reveal that some plants were more important fuels in some hearths than in others, which could point to differential use of the fires. This might mean that fuel taxa were important for some fires or at some sites, but the sample is very small and the differences between Sibudu and Pinnacle Point in this case might be related to differences in research methods and/or preservation, as well as the different vegetation regime. Since burnt bone appears archaeologically long before the MSA (e.g., Berna et al. 2012; Brain 1993b; Brain and Sillen 1988), the burning properties of bone could have been well known during many periods. The use of bone as fuel at later European sites has been explained by the lack of suitable firewood, although the burning properties of bone also might have promoted its use (Théry-Parisot 2001, 2002). Bone might not have been a primary fuel in the MSA, at least not at Sibudu (Cain 2005, 2006; Clark and Ligouis 2010), but burnt bone is found at many of the sites (see Table 1) and the bone may sometimes have been burned deliberately as part of site maintenance. The possibility of burning bone as part of site maintenance in other archaeological periods is a potential future research topic.

Meat, shellfish, fish, and plants may have been roasted on MSA fires (e.g., Avery et al. 2008; H. Deacon 1995; von den Driesch 2004; Henshilwood et al. 2001b; Klein et al. 2004; Marean et al. 2007; Milo 1998). Possible pits for meat roasting have not been reported from any of the sites reviewed here, indicating that this technique was not used in the MSA and supporting the view that pit roasting was not established until later (Thoms 2009). Yet there are indications that rocks were heat treated in the MSA to improve knapping properties, as described above (see Brown et al. 2009; Mourre et al. 2010; cf. Schmidt et al. 2013). Artisans might have known that rocks and other things could be heated underground but chose not to exploit this process for cooking. This raises the question of how to distinguish cooking pits from rock-roasting pits. Brown et al. (2009, Supplementary Online Material, pp. 1–2) reported that their experimental pits were only 2–3 cm deep and were covered with sand. If a similar technique was used in the MSA, the pits could have been so shallow that subsequent activities and/or postdepositional processes have made it very difficult to distinguish the pits during excavation. The sands and ashes scraped out of such a pit could be difficult to distinguish from the regular cleaning of a combustion feature, and features labeled “ash dump” or “ashy deposits” could be the remains of heat treatment, or even cooking. These are questions that future excavations could address and also explore at sites older or newer than the MSA.

The many superimposed hearths from MSA sites (Table 1) indicate that the same organizational rules for placing hearths were effective for tens of thousands of years, although local topographic factors also could affect the placement of hearths. Humans did structure and maintain their space during the MSA (e.g., Barham et al. 2000; Cain 2006; Goldberg et al. 2009; Henshilwood and Dubreuil 2011; Herries and Fisher 2010; Texier et al. 2010; Wadley et al. 2011), similar to Neanderthal groups in Eurasia (e.g., Albert et al. 2012; Bar-Yosef et al. 1992; Schiegl et al. 1996; Speth 2004, 2006; Vallverdú et al. 2012; Vaquero and Pastó 2001; Vaquero et al.

2001). The existence of MSA family groups has been suggested (e.g., H. Deacon 1995; Henderson 1992), and the new data generated by the last decades of excavations are important contributions to the understanding of spatial structuring of pyrotechnology in the MSA. The MSA spans a long period, however, and changes over time might be expected. A more detailed look at the MSA and spatial changes relating to fire use during the past 300,000 years could be compared to earlier and later periods and also to other observable changes within the MSA. It might be possible to examine whether pyrotechnological changes coincided with other technological changes during the MSA and also to examine similar issues for other archaeological periods.

The outline above clearly shows that pyrotechnology was well developed and consistently used in the MSA, and this has implications for our understanding of sites with earlier and later dates, as well as other areas. The habitual character of MSA fire use might imply that extensive knowledge of pyrotechnology existed before the MSA. The heat treating of rocks in pits, for example, might have developed earlier than, and independent of, the heat treating of food in pits, although these activities use similar techniques. In contexts postdating the MSA and/or in other geographical areas, cooking pits might be common, while the heat treatment of rocks might not have been practiced because local rock types did not benefit from such treatment, because of poor knowledge of the technique, or for other reasons. Relationships between pyrotechnology and other technologies might profitably be examined in a variety of contexts to understand costs and benefits of different strategies, as well as the variability of human behavior.

Excavation methods, publication strategies, and preservation issues are among the factors that have influenced what data are available for Table 1. This illustrates a point relevant to sites that are suspected of having evidence of early fire use—indications of pyrotechnology can be hard to find. A productive future approach might thus be to focus on data requirements for recognizing fire at sites and on the methods for retrieving data. What are acceptable proxies for campfires when neither ash nor charcoal is visible to the naked eye? What methodologies can be used effectively for the detection of these proxies? At MSA sites, for example, methods such as micromorphology and experimental studies have contributed new knowledge about postdepositional burning, site formation processes, and activities related to fire (e.g., Brown et al. 2009; Goldberg 2000; Goldberg et al. 2009; Karkanas and Goldberg 2010; Mourre et al. 2010; Sievers and Wadley 2008; Wadley 2009; Wadley et al. 2011). Micromorphology (e.g., Berna et al. 2012; Goldberg et al. 2001) and the mapping of burnt artifacts (e.g., Alpersen-Afil and Goren-Inbar 2010; Alpersen-Afil et al. 2007; Goren-Inbar et al. 2004) have already been achieved results at sites with early fire use and which might be used in discussions of a common platform for the recognition of early fire use. The micromorphological studies identifying fire use at Wonderwerk Cave (Berna et al. 2012) demonstrate that, at least in some cases, a site excavated decades ago can be revisited with the new methodological tools. Indeed, the success of micromorphology for the detection of different types of combustion features suggests that all sites currently being excavated should embrace this methodology, regardless of where the sites are or what period they cover.

The status of knowledge on MSA fire is an important reminder of the benefits of international cooperation and a multidisciplinary approach. The use of a combination of analytical techniques could provide compelling evidence of the use of pyrotechnology, not only at the MSA sites discussed here, but at any site where rocks or organic materials were subjected to transformations through heat. The results would complement the information from other sources, such as the spatial structuring at a site or the type of artifacts found at a site. Detailed information on combustion features and their contents is not only useful in interpretations of intrasite behavior, it can also contribute to our understanding of seasonal movements and the determination of the existence of separate groups with specific cultural or social fire-related behavior. The methodology could contribute, for example, to recognizing differences between sites that share similar cultural expressions (e.g., sites with the same type of pottery but different spatial management).

There also is clearly a place for much more experimental work. The precise effects of wildfires on bone, stone, and sediments, the range of temperatures reached by these natural fires, and the effects of weather, vegetation load, and soil substrate on fire temperatures are all profitable topics for research. They are topics for which the results would be relevant to any archaeological study, regardless of regional and chronological differences. The role of experiments in helping explain archaeological situations cannot be overemphasized. In this article, the burning of bone to examine early fire use at Swartkrans (Brain 1993b; Brain and Sillen 1988) and the heat treatment of silcretes in the MSA (Brown et al. 2009; Mourre et al. 2010) are but two examples of the productive use of experiments. One of the strengths of experimental studies is that they can be conducted in both the field and the laboratory, and these two aspects complement each other. Experiments in the laboratory have the advantage of being able to control variables so that the effects of heating on bone, stone, or sediment are unequivocal. There also is room for actualistic experiments because these often highlight the uncontrollable attributes of natural products that people in the past would have had to deal with.

The problems and issues discussed in relation to MSA pyrotechnology find common ground in almost any archaeological site where people used fire as a tool. The archaeological evidence of fire can support interpretations of the pyrotechnological techniques used, the activities related to fire, site maintenance, social structures, and other aspects of prehistoric life. Methodologies developed for recognizing facets of pyrotechnology in the deep past can be harnessed across continents and through the ages.

Acknowledgments This article is the end result of a long process. I am forever grateful to my supervisor, Prof. Lyn Wadley, for all her comments and feedback on the various versions of the manuscript. My Ph.D. research has been supported by grants from the Palaeontological Scientific Trust (PAST) and its Scatterlings of Africa programme, and Eivind Sannes' legat for studerende ungdom fra Fauske kommune in Norway. I thank Dr. Jamie Clark, Tammy Hodgskiss, Helen Kempson, Dr. Christopher Miller, Christine Sievers, Paloma de la Peña, Aurore Val, and a few anonymous reviewers for all the productive feedback on the manuscript. I also am very grateful to the editors and editorial staff at the *Journal of Archaeological Research* for valuable and constructive feedback on both content and technical issues. Any errors and oversights are fully my own and do not necessarily represent the views of others.

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3 INTRODUCTION TO SIBUDU

Sibudu is a rock shelter, situated on a cliff 20 m above the uThongathi River (Figures 1.1 and 3.1), 40 km north of Durban and 15 km inland from the Indian Ocean (see Figure 2.1). The shelter faces south-west, and a few natural rock steps lead from the river to the floor of the shelter. Aron Mazel from the Natal Museum dug a small trial trench at Sibudu in 1983. His research focus was, however, the Iron Age, and he stopped excavating after realising that Sibudu had MSA layers (Wadley & Jacobs, 2006). Subsequent excavations were conducted by Prof. Lyn Wadley and her team from the University of the Witwatersrand from 1998 to 2011 (Figure 3.2), and the deepest part of this excavation covers 6 m² and is ca. 3 m deep. In this thesis I analyse material excavated by the Wadley team, mainly between 2008 and 2010, and the following introduction is based on material from the MSA layers documented in these excavations. Continuing excavations at Sibudu are currently being led by Prof. Nicholas Conard from the University of Tübingen, Germany.



Figure 3.1 The uThongathi River below Sibudu. Sibudu can be accessed from the south-west by crossing the river and climbing up the cliff to the right in these pictures. The river under normal conditions to the left (photo taken 15.11.2009) and in flood to the right (19.11.2009).

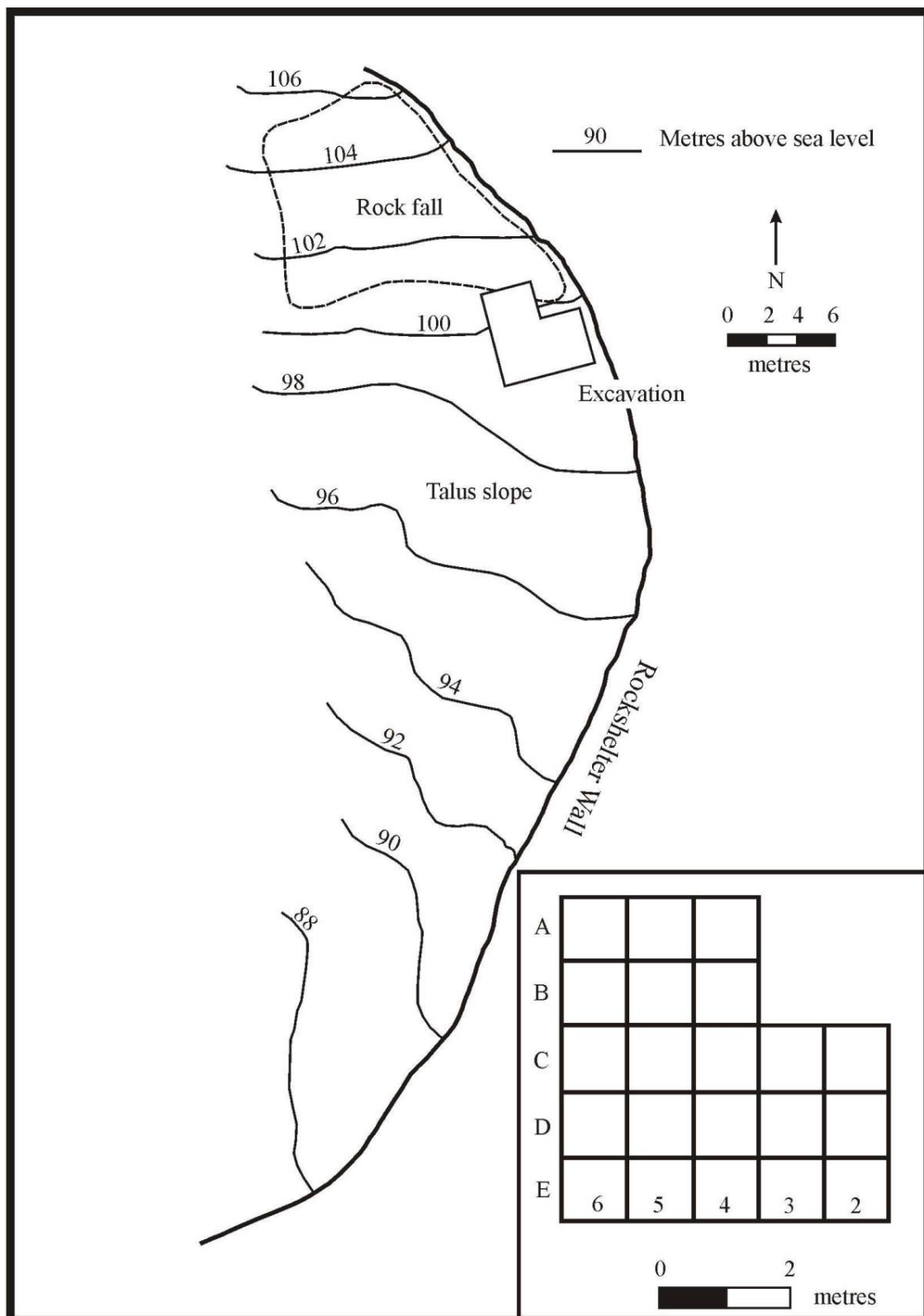


Figure 3.2 Plan of Sibudu showing the location of the excavations (Wadley & Jacobs 2006)

3.1 EXCAVATION

Sibudu was excavated using standard techniques, but a short introduction to the field methodology at Sibudu is given here. Twenty one meter squares were excavated to a depth of approximately one meter below the surface and, within this grid, six of the squares were excavated as a deep sounding that was excavated to about three meters below the surface (Figure 3.3). The site was divided into meter squares, named with a capital letter running from north to south (e.g., A, B, C, etc.) and Arabic numerals running from east to west (e.g., 1, 2, 3, etc.) (see Figure 3.2). Squares were excavated in 50 x 50 cm quadrants, and these were named using lower case letters, 'a' being the north-eastern, 'b' the south-eastern, 'c' the north-western and 'd' the south western quadrant of each square. The site was excavated by stratigraphical layers, generally named by colour determined by the Munsell Colour Chart. Thus, for example, layer Pinkish Gray Sand refers to a pinkish gray layer, abbreviated to PGS. Combustion features, most of them perceived as hearths, were excavated within the quadrants by strata and named consecutively within each stratigraphic unit (Wadley & Jacobs, 2006). This means, for example, that H2 in PGS2 C4b signifies the part of Hearth 2 excavated in the layer named Pinkish Gray Sand 2, in quadrant b of square C4.

The horizontal plane of each layer within each square was drawn to scale during excavation. The top and base of each layer and features within layers were always drawn, and different parts of a layer (e.g., middle) and objects within it (e.g., worked stone or shell beads) were drawn where appropriate. Above the ground surface, on the shelter wall, a permanent datum line is marked at 1.3 m (Wadley & Jacobs, 2006), and a theodolite was used to measure the depth of each layer and each feature as the excavation progressed. Depth readings for each corner of each square, the middle of the square and other parts of the square where appropriate (e.g., top of a hearth) were added to every drawing. These drawings were combined by layer to horizontal site plans by Prof. Lyn Wadley, and the maps used in this thesis were scanned and digitised using ArcMap software by me. Objects such as combustion features and rocks are drawn as polygons, and objects such as lithics marked on the site plans are drawn and recorded as points in ArcMap.

The volume of the excavated deposit was recorded in litres and a sediment sample from each layer was collected before the sediment was sieved. Only 2 mm sieves were used until 2003, after which stacked sieves of 2 mm and 1 mm were used. The volume in each sieve was recorded. The contents of the 1 mm sieve were subjected to archaeobotanical analysis (e.g., Sievers, 2013a) and the contents of the 2 mm sieve were sorted by material type (e.g., bone, charcoal, shell and stone) before being sent for specialist analyses.



Figure 3.3 Detail of stratigraphy at Sibudu and collection of micromorphological sample. Left: detail of layers at Sibudu 17.08.2011. Right: Dr. C. Miller collecting samples 18.02.2009.

Samples for other purposes from selected layers and contexts were also collected during the excavations. These include samples for dating and samples for micromorphological and organic petrological analyses. The dating samples were collected by Zenobia Jacobs and the other samples were collected at different times and from different parts of the excavation by Lyn Wadley, or Paul Goldberg, Boston University, USA, and Solveig Schiegl and Christopher Miller, University of Tübingen, Germany. The micromorphological samples were either cut from the excavated surface, or cut from the vertical sediment profiles and wrapped tightly with paper and packaging tape or plaster (gypsum) bandages (see Figure 3.3). The samples were dried and impregnated with unpromoted polyester resin, styrene and MEKP, redried, sliced and subsampled for thin sectioning and further analyses (see Goldberg et al., 2009; Wadley et al., 2011).

3.2 STRATIGRAPHY AND DATING

As mentioned above, the deepest part of the Wadley excavation in the deep sounding is 3 m below ground level and covers 6 m². Little or no water-borne transport of deposits is evident and the cultural material and *in situ* features at Sibudu are evidence of the almost entirely anthropogenic origin of the deposits (Pickering, 2006). The uppermost MSA sequence consists of several thin (centimeter scale) colourful strata (see Figure 3.3) that represent multiple superimposed and inter-fingering combustion features. In the east wall of square B4 (Figure 3.4), these layers are found down to ca. 3.4 m below datum (1.1 m below ground surface). This part of the sequence also contains much gypsum (see Schiegl & Conard, 2006). The lower sequence consists of grey deposits that include discrete combustion features with gypsum, suggesting a relationship between large burning events and gypsum (Schiegl & Conard, 2006). At Pinnacle Point Cave 13B, it has been suggested that some of the gypsum formation has been caused by decayed guano (Karkanas & Goldberg, 2010), but it is difficult to estimate guano deposition at Sibudu in the past and to determine if this could account for all the gypsum (Schiegl & Conard, 2006, p. 161).

Sibudu has been dated by single-grain optically stimulated luminescence (OSL) on sedimentary quartz grains (Jacobs et al., 2008a, 2008b). These dates imply several pulses of occupation and hiatuses between ~78 - ~38 ka (see Table 3.1). Environmental issues may have contributed to the hiatuses in occupation. During periods with much water in the river, for example, it may have been difficult to cross the river and get access to the site (see Figure 3.1). Sibudu may also at times have been situated within the habitat of the malaria carrying mosquito species *Anopheles* and this health risk may have discouraged people from staying at the site (Wadley, 2012b).

The lowest layers (BS to LBG) contain material older than 71 ka, and this group of layers with its oldest age at ~77 ka is presently named pre-Still Bay. Layers RGS2 and RGS contain the Still Bay lithic industry and layers PGS to GR contain the Howiesons Poort lithic industry. The uppermost layers are divided in three informally named

Table 3.1 Summary of research results from Sibudu, including OSL ages and environmental information. See references in text.

Layer	OSL age (ka)	Lithic industry	Fauna	Flora	Combustion features	Examples of fire-related behaviour
Co	38.0 ± 2.6	Final MSA	Savannah fauna.	Dry, deciduous	Some discrete, but	↑ ↑ ↑ Burning of bedding from ~73 ka. Intensified site maintenance Making adhesives for hafting tools? Disposal of bone in fires
Bu	39.1 ± 2.5		Zebra, large and	savannah	mostly superimposed	
LBMOD	49.9 ± 2.5	Late MSA	medium-sized bovids	Forest and savannah	and inter-fingering	
MOD	49.1 ± 2.1					
OMOD	46.6 ± 2.3					
OMOD-BL	47.6 ± 1.9					
RSp	46.0 ± 1.9					
RD	49.4 ± 2.3					
BSp	57.6 ± 2.1	Post-	Zebra and large and very	Dry, cool savannah		
SS	59.6 ± 2.3	Howiesons	large bovids	and some forest		
P	59.0 ± 2.2	Poort				↑ ↑ ↑ Burning of bedding from ~73 ka. Intensified site maintenance Making adhesives for hafting tools? Disposal of bone in fires
Ch2	58.3 ± 2.0					
Y1	58.6 ± 2.1					
B/Gmix	58.2 ± 2.4					
GR2	61.7 ± 1.5	Howiesons	Wide variety of species	Evergreen, moist	Discrete, small and	
GS2	63.8 ± 2.5	Poort	Small bovids (blue	forest	large	
PGS	64.7 ± 1.9		duiker abundant)			
			Suids (particularly bushpig)			
			Marine shell and land snail common			
RGS	70.5 ± 2.0	Still Bay	Not yet available	Moist forest, some savannah	Discrete, small	
LBG	72.5 ± 2.0	Pre-Still Bay	Not yet available	Not yet available		
LBG2	73.2 ± 2.3					
BS	77.2 ± 2.1					

groups: the post-Howiesons Poort layers (YA2 to RGS), the late MSA layers (YSp to PB) and the final MSA layers (Mou to Co). The terms "Sibudu technocomplex" and "Sibudan" have been suggested for lithic industries in these layers (Conard et al., 2012; Lombard et al., 2012), but are not necessarily agreed upon and the broader informal designations will thus be used here. In this thesis I shall mainly examine fire-related behaviour in the Howiesons Poort (HP) and post-Howiesons Poort (post-HP) layers. The previously mentioned change from grey deposits to the upper colourful sequence coincides with a change in the cultural material from HP to post-HP at ~58 ka.

3.3 ENVIRONMENTAL AND CULTURAL CONTEXTS

The thorough excavations and extensive research on material from Sibudu have provided detailed information on the environmental and cultural context of the site (Table 3.1). Analyses of charcoal and plant remains from the site (e.g., Allott, 2004, 2005, 2006; Sievers, 2006, 2013a) show the fluctuations in vegetation around the shelter (Table 3.1). The woody taxa identified from charcoal in the HP layers, such as *Podocarpus*, *Buxus* spp., *Curtisia dentata* and *Sapium/Spirostachys*, imply an evergreen forest around the shelter, and the taxa identified in post-HP layers, such as *Erica* spp., *Rapanea melanophleas*, *Morella pilulifera*, *Bridelia* sp., *Acacia* spp. and *Ximenia* sp., imply patches of evergreen forest and less densely wooded savannah and a dryer environment (Allott, 2005, 2006). Analyses of fruits and seeds combined with the charcoal identifications imply that there were more deciduous taxa by the shelter in the post-HP than in the HP (Sievers, 2006). Bruch and colleagues (2012) recently combined environmental data from Sibudu using a GIS-based Coexistence Approach to describe the climatic range that would allow the maximum number of identified taxa to coexist (provided that the fossil taxa have climatic restrictions similar to their nearest living relatives). Their results imply less vegetation density and slightly colder winters during the HP than today and even colder and drier conditions with less vegetation density during the post-HP.

Almost any plant taxa can be used as fuel, but modern fire-users can have distinct opinions about taxa considered as suitable for firewood (e.g., Abbot et al., 1997; Archer, 1990; Munalula & Meincken, 2009; Tabuti et al., 2003; Tietema et al., 1991). People at Sibudu do not seem to have selected firewood based on burning properties alone, but more woody taxa favoured as fuel by modern fire-users are represented in the post-HP assemblage than during the HP (Allott, 2005, 2006). Other types of plants may have been used as fuel or tinder at the site (e.g., Sievers & Muasya, 2011), but some of the burnt plant material was not primarily brought to the shelter as fuel. Plants were also brought to the shelter as bedding (surface preparation), and the oldest known example is from the pre-Still Bay layers at ~77 ka (Wadley et al., 2011). The earliest known bedding examples at Sibudu were not burnt, but bedding from ~73 ka were disposed in fires and this site maintenance practice intensified from ~58 ka (Goldberg et al., 2009; Sievers, 2013a; Wadley et al., 2011).

Most of the bone fragments found at Sibudu are highly fragmented, and up to 95% of the bone in some of the layers are burnt (Cain, 2005; Clark & Ligouis, 2010). Bone fragments seem to have been disposed of in fires, not to have been used intentionally as fuel, and both green and dry bone have been burnt in fires (Cain, 2005, 2006; Clark, 2009; Clark & Ligouis, 2010; Hanson & Cain, 2007). The fragmentation makes zooarchaeological analyses difficult, yet not impossible. The fauna identified from the HP layers at Sibudu show that people hunted and brought a wide variety of species to the site (Table 3.1), although there is an abundance of small bovids identified from these layers, while the post-HP sample consists of relatively more larger animals such as zebra and large and very large bovids (Clark & Kandel, 2013; Clark & Plug, 2008; Clark, 2009). The HP faunal assemblage, which includes small carnivores and the dangerous bushpig, provides circumstantial evidence for the use of snares (Wadley, 2010a). Nevertheless, use-traces on stone tools suggest the use of bow and arrow during the HP (Lombard & Phillipson, 2010). Microscopic traces of adhesives on stone tools also suggest that they were hafted (e.g., Lombard, 2005, 2007), and fire may have been used to produce the adhesives and dry the hafted tools (Wadley, 2005a).

3.4 SELECTED COMBUSTION FEATURES

The excellent preservation at Sibudu allowed recognition of different types of *in situ* combustion features (see also Table 1.1). Fortunately, combustion features at Sibudu have not been altered significantly or destroyed by biological activity such as root formation or diagenetic alteration such as calcification, which, for example, is the case in some parts of Pinnacle Point Cave 13B (Karkanas & Goldberg, 2010). Primarily deposited combustion features, named 'hearths' at Sibudu, often have distinct hearth strata: a white top stratum, a base stratum with much charcoal and rubified sediments under the feature (e.g., Schiegl et al., 1996). The bone fragments in each stratum tend to have the same colours as the sediments due to the physical changes in bone at certain temperatures. This means that the bone in the white stratum, for example, tend to be calcined and white because it has been exposed to high temperatures and bone in the black stratum have been exposed to lower temperatures and is thus carbonised and black (e.g., Stiner et al., 1995; see also Cain, 2005 on Sibudu). *In situ* and primarily deposited combustion features of burned bedding from maintenance fires have similar hearth strata, but also consists of finely laminated and fibrous charcoal (organic matter) (Goldberg et al., 2009) that sometimes can only be recognised through micromorphology. Furthermore, secondarily deposited combustion features have been recognised at Sibudu. These are generally uniformly grey in colour, do not have hearth strata and consist of mixed material such as charcoal and bone fragments of various sizes oriented at various angles (see Goldberg et al., 2009). Below follows a description of selected combustion features from the HP and post-HP layers.

3.4.1 PRIMARILY DEPOSITED COMBUSTION FEATURES

It was possible to distinguish two, sometimes three, strata in primarily deposited combustion features at Sibudu, and I will describe four features as examples here. I have chosen these examples because I excavated both the HP features myself and helped excavating the post-HP features, which means that I have extensive notes about these features. Two of the selected primarily deposited combustion features were found in the HP layer Pinkish Grey Sand 2 (PGS2). Both Hearth 1 (H1) and Hearth 2 (H2) in PGS2

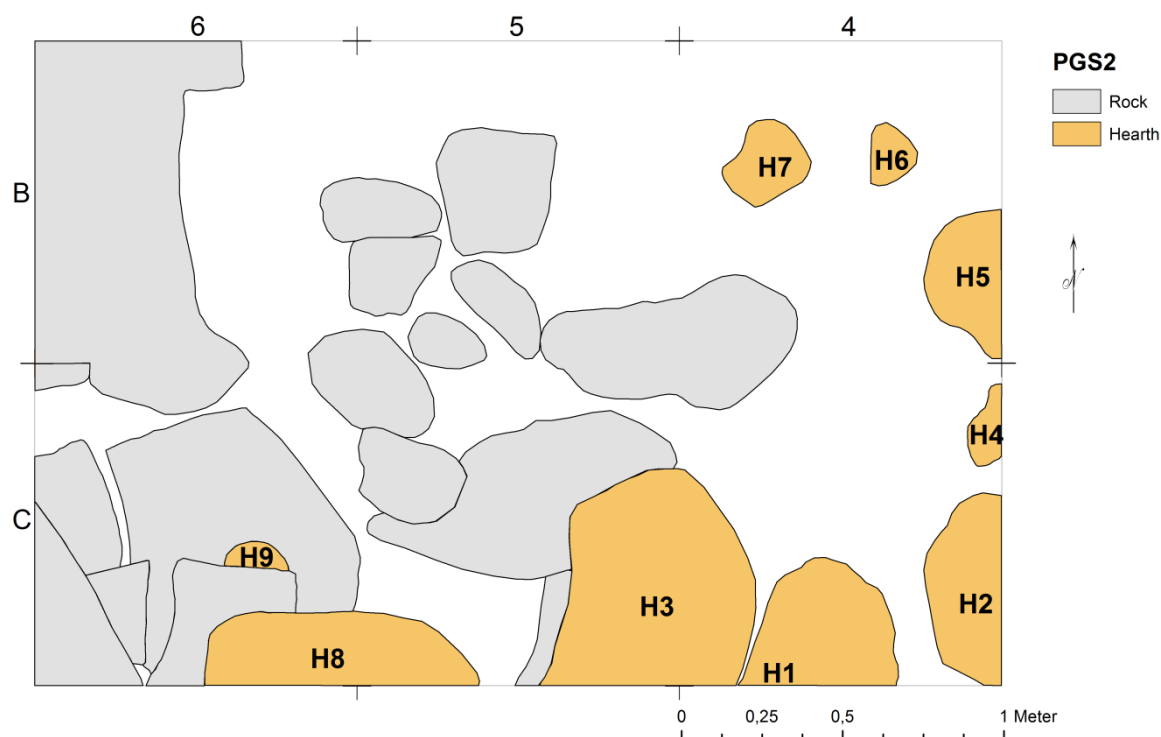


Figure 3.5 Overview of combustion features in layer PGS2.

were found in square C4 (Figures 3.5 and 3.6), extended out of the excavation trench and were excavated in November 2009. These features were perceived as clear and discrete hearths in the field. They were spatially constrained and contained classic hearth strata: a distinct white top, a black (H1; Munsell colour reading 5 YR 2.5/1) or very dark grey (H2; Munsell colour reading 7.5 YR 3/1) middle and a very dark grey (H1; Munsell colour reading 7.5 YR 3/1) or very darkish brown (H2; Munsell colour reading 10 YR 3/2) base stratum.

The other two selected primarily deposited combustion features were found in post-HP layers and were excavated in November 2008. Both H in B/Gmix (Figures 3.7 and 3.8) and H1 in BYA2(i) (Figures 3.9 and 3.10) were large combustion features with a diameter of more than one meter and extended beyond the excavation trench, although the latter feature covered a much larger area than the former. Two strata were

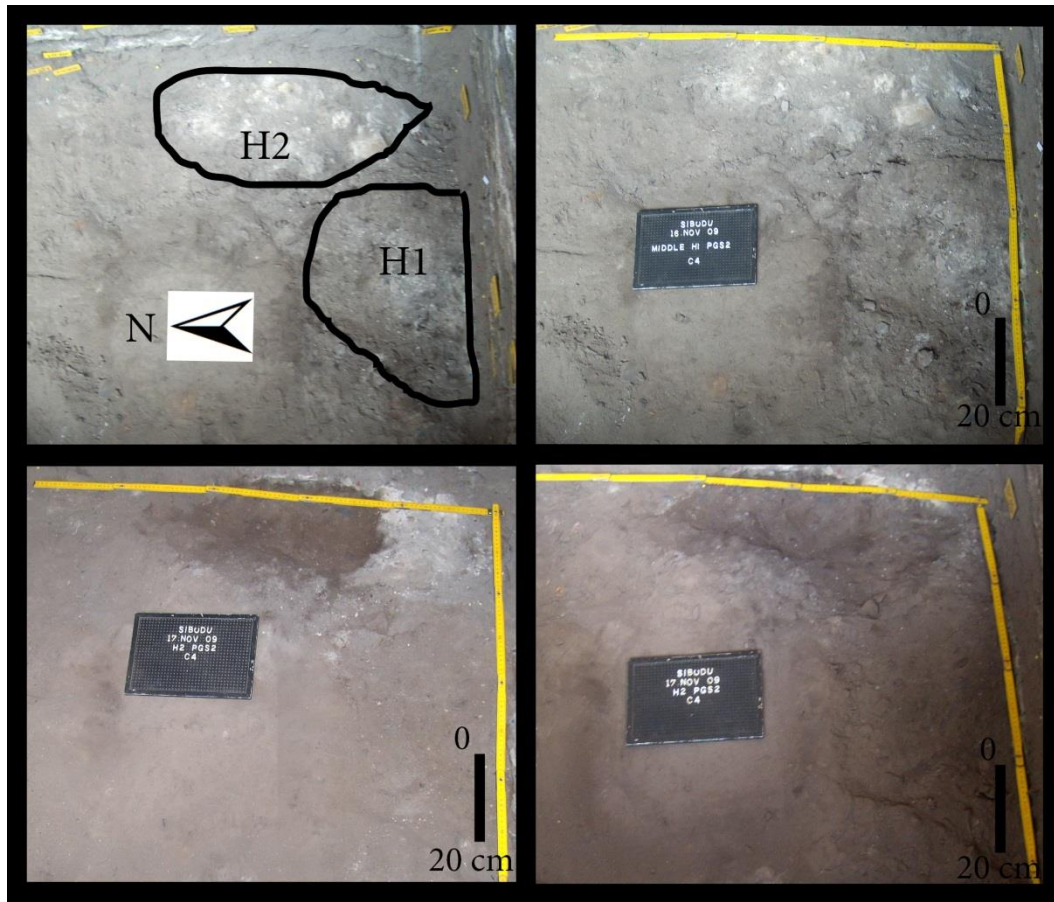


Figure 3.6 Excavation of H1 and H2 in PGS2. Top left: The extent of the hearths as seen in the field. Top right: The white top of H1 in PGS2 is removed. Bottom left: H1 in PGS2 and parts of the white top of H2 in PGS2 is removed. Bottom right: Excavation of the black base of H2 in PGS2.

documented in H in B/Gmix: a white top and a black base. Subsequent micromorphological analysis by Dr. Christopher Miller at the University of Tübingen, Germany, demonstrated that post-depositional processes have altered this feature significantly, but that it probably was a maintenance fire for burning bedding (see Chapter 9). Three strata were documented in H1 in BYA2(i): a white top (Munsell colour 2.5 YR 8/1), a dark reddish-brown middle (Munsell colour 5 YR 2.5/2) and a black base (Munsell colour 10 YR 2/1) (see Wadley et al., 2011, SOM). The micromorphological analysis of this feature shows that it is a maintenance fire, used for burning bedding (Chapter 9; Wadley et al., 2011).

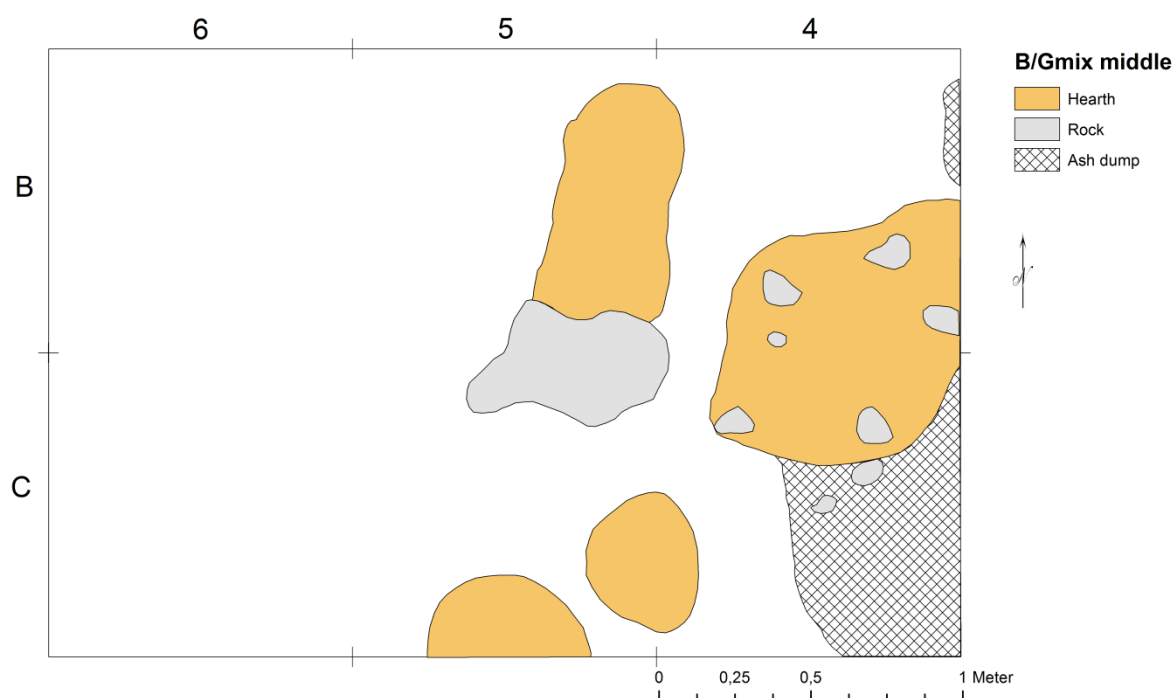


Figure 3.7 Overview of the middle of layer B/Gmix with combustion features.

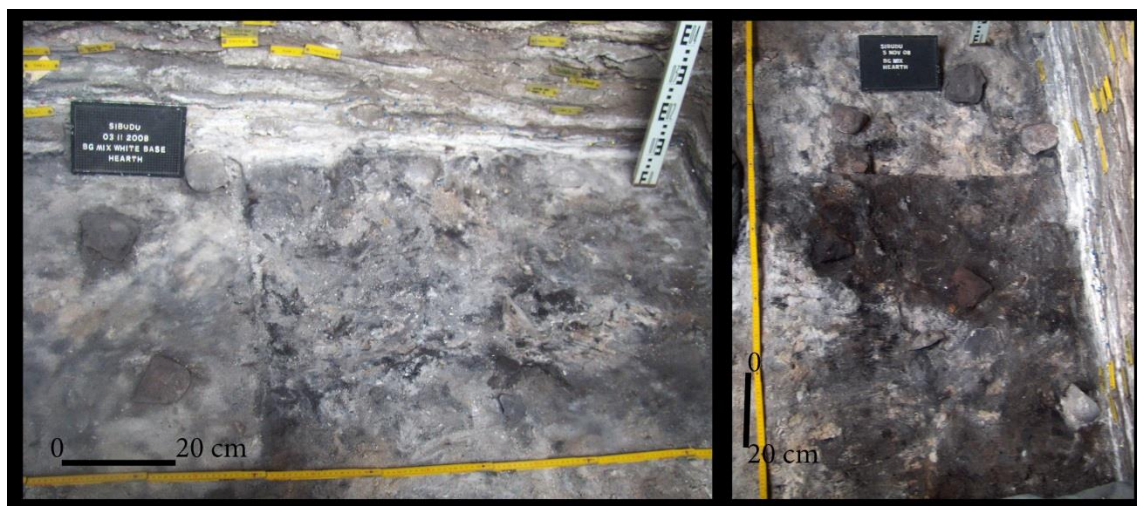


Figure 3.8 Excavation of H in B/Gmix. The picture to the left is taken during the excavation of the white top of the combustion features and while facing the east wall of the excavation. The picture to the right is taken while facing the north wall of the excavation after the white top has been partly removed. The pictures show the part of squares B4 and C4 that was covered by combustion features (see also Figure 3.7).

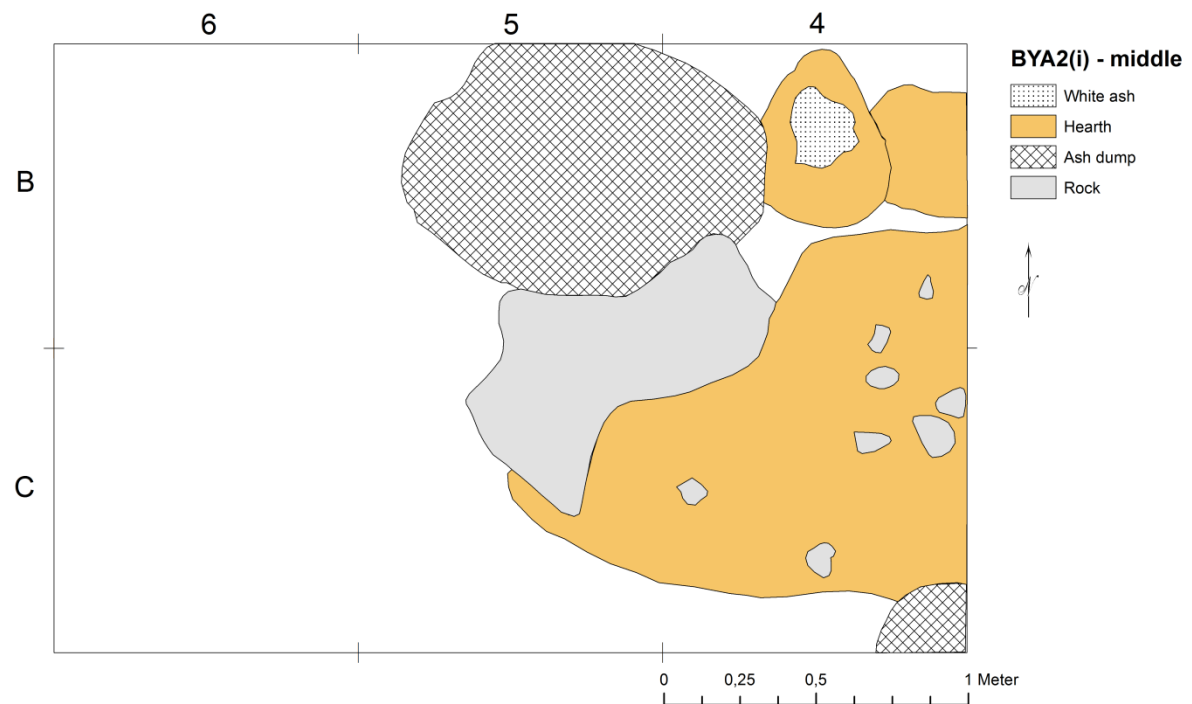


Figure 3. 9 Overview of the middle of layer BYA2(i) with combustion features.

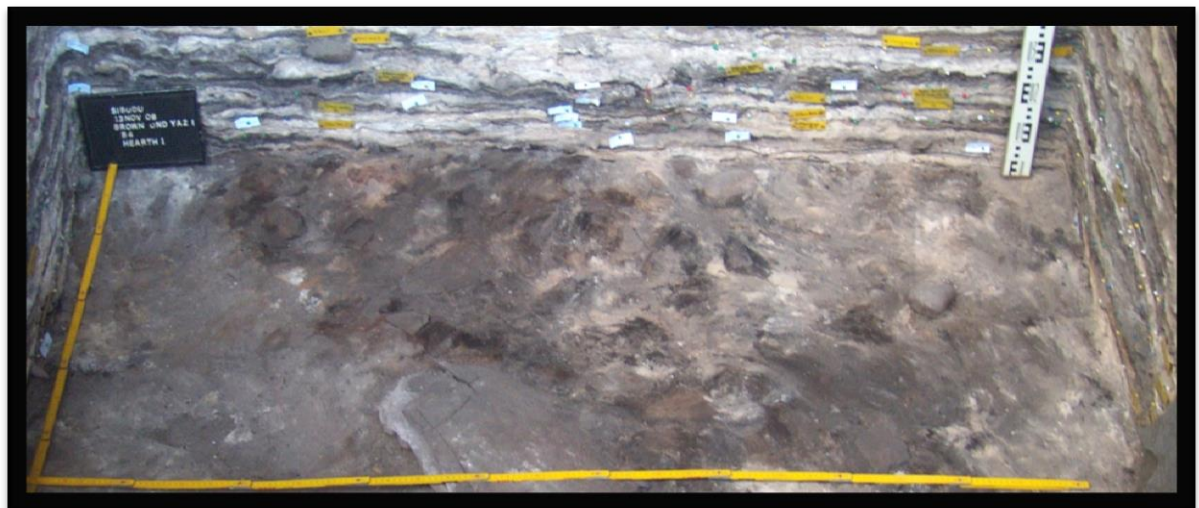


Figure 3.10 Excavation of BYA2(i).The picture is taken while facing the east wall of the excavation.

3.4.2 SECONDARILY DEPOSITED COMBUSTION FEATURES

Three ash dumps illustrate the secondarily deposited combustion features here. All three were found in the post-HP layers; two of them in layer Brown/Grey mix (B/Gmix) and one in layer Brown under Yellow Ash 2(i) (BYA2(i)) (see Figures 3.7 and 3.9). These three dumps were excavated in November 2008 and they were found in square C4. Ten litres of sediment were removed from Ash dump from H1 in BYA2(i). Ash dump 1 in B/Gmix and Ash dump 2 in B/Gmix were smaller and contained nine litres of sediment in total. These features were recognised as ash dumps during excavation partly due to their uniform grey colour when compared to other combustion features in the same layer. For example, the ash dumps in B/Gmix had Munsell Soil Chart Colour 10R 7/1 Light grey. The objects (e.g., bone fragments and charcoal) in these combustion features were not arranged in a laminar way, but were lying at various angles, which is consistent with documented ash dumps (Goldberg et al., 2009; Miller et al., 2010).

3.5 CONCLUDING REMARKS

The hearth strata, colour and laminar arrangements of material are easily recognisable properties of primarily deposited combustion features that can help distinguish them from secondarily deposited features. The excellent preservation and the excavation techniques used at Sibudu allow for field observation of different features, but colourful strata are not preserved at all sites. The bone, charcoal and stone from the selected combustion features at Sibudu will be part of the spatial analysis and the detailed analysis of the combustion features in Chapters 9 and 10. However, in the next four chapters I shall examine fire-related behaviour and the formation of combustion features through experimental studies.

4 INTRODUCTION TO THE FIRE EXPERIMENTS

The term 'experimental archaeology' is sometimes used to describe experiential or educational projects, which aim to reconstruct, reproduce and/or re-enact prehistoric processes, actions and/or objects. This is unfortunate because it gives the impression that scientific components such as testing of hypotheses and controlling variables are not important in archaeological experiments (as discussed in e.g., Cunningham et al., 2008; Lammers-Keijzers, 2005; Mathieu, 2002; Outram, 2008; Reynolds, 1999). Such an impression undermines the important contributions that experimental studies following scientific procedures have made and continue to make, for example to the understanding of prehistoric production of food and tools and formation processes important to the archaeological record (see e.g., Coles, 1973; Crabtree & Butler, 1964; Crabtree & Davis, 1968; Gur-Arieh et al., 2012; Mallol et al., 2013a; Miller et al., 2010; Newcomer, 1971; Nielsen, 1991; Shea et al., 2001; Shipman et al., 1984). The fire experiments I conducted as part of my PhD project are 'actualistic' as described by Outram (2008, pp. 2 – 3), which means that I test hypothetical campfires exposed to environmental conditions (outside of the lab) while following scientific principles. Below, I provide an introduction to fire experiments before outlining the aims and method for my experiments.

4.1 PREVIOUS FIRE EXPERIMENTS

Many researchers have conducted experiments to examine various aspects of fire use, such as the production and use of pottery (e.g., Charters et al., 1997; Courty & Roux, 1995; Evershed et al., 2008; Russell & Dahlin, 2007; Schiffer et al., 1994), but only aspects relevant to the MSA are included in this brief introduction. Mathieu (2002, pp. 2 – 6) suggests a typology of experimental archaeological research that divides projects into replication of objects, behaviours, processes and systems. These four types often

overlap (see Mathieu, 2002, p. 6), and this is also true for fire experiments. For example, in experimental burning of bedding, Miller and Sievers (2012) replicate both behaviours (e.g., intentional vs. unintentional burning of bedding) and formation processes. I will not follow the typology suggested by Mathieu (2002) when describing experimental fires because overlap between categories would lead to unnecessary repetitions, but focus on the formation and strata of combustion features and fire-related behaviour. By 'fire-related behaviour', I refer to the use of fire for different activities such as cooking and tool production, but also to site maintenance behaviours such as the raking out of hearths and the creation of ash dumps. Furthermore, I do not include ethnoarchaeology in 'experimental archaeology', which is suggested by Mathieu (2002). Most of the experiments in this overview are actualistic, but I also include laboratory experiments where appropriate.

4.1.1 THE FORMATION AND STRATA OF COMBUSTION FEATURES

As defined in Chapter 1, a primarily deposited combustion feature often consists of a light (white) top ash stratum, a black stratum with much charcoal and rubified (reddened) substrate (e.g., Schiegl et al., 1996). Bellomo (1993, 1994; Bellomo & Harris, 1990) examined the difference between natural and anthropogenic fires in his experiments based on suspected fire-related features at the site FxJi20 East near Koobi Fora in Kenya. One of his conclusions was that campfires produce basin-shaped combustion features, but natural fires do not, and that anthropogenic fires can produce enough heat to cause reddening of the soil underneath the fire (Bellomo, 1993). Yet Canti and Linford (2000) find in their experiments that not all anthropogenic fires generate rubified subsoil. Wattez (1988, 1992) conducted experiments that demonstrate that a typical white ash stratum is produced by strong heat and that moderate temperatures produce ash in shades of yellow or brown, and she also found that fires of high intensities reduce all the charcoal to ash. Furthermore, Mallol and colleagues (2013a) demonstrate experimentally that the black stratum in flat combustion features can represent the carbonised surface of the soil underneath the fire, and that charcoal fragments are embedded in the white ash layer in experimental combustion features and do not form a separate black stratum rich in charcoal.

There could be many reasons for the discrepancy between the typical archaeological hearth (e.g., Schiegl et al., 1996) and the experimental results described above. Canti and Linford (2000) suggest that low temperatures and/or reducing organic matter may prevent iron oxide transformations, which again would prevent reddening of the soil. Wattez (1988, 1992) finds that the strata and colours of combustion features are related to temperatures and the intensity of burning, while Mallol et al. (2013a) suggest that post-depositional processes or specific pyrotechnological practices can contribute to the appearance of hearth strata. These are all plausible hypotheses that could be examined further in future experiments.

Raking out ashes, dumping ashes and trampling are other processes that could affect combustion features and that were addressed experimentally by Miller and colleagues (2010). They constructed six experimental fires burning dried wood and bones and reworked five of the six resulting combustion features by trampling, sweeping out ashes, dumping ashes and combinations of these activities before sampling the combustion features for micromorphological analysis. The analysis demonstrated that the general structure of the combustion feature, in this case a stratum of charcoal on top of rubified subsoil, was intact after trampling, whereas swept and dumped deposits did not retain the original strata and items in swept and dumped deposits were lying at different angles (Miller et al., 2010).

The formation and strata of combustion features in the MSA have been examined through the above mentioned experiments of Miller and Sievers (2012). They focused on the formation of maintenance hearths for burning bedding and demonstrated that burning sedges produces layers of laminated phytoliths (Millers & Sievers, 2012; see also Sievers, 2013a), and these laminations resemble layers observed in micromorphological samples from Sibudu (e.g., Goldberg et al., 2009; Wadley et al., 2011). Stratigraphy and formation of MSA combustion features have not been the focus of other experimental studies, but are addressed in my experiments (Chapters 7-8).

4.1.2 FIRE-RELATED BEHAVIOUR

The use of fire and fire-related behaviour can be inferred by studying the effects of fire on bone because the colour of burned bone reflects the temperatures the bone was exposed to. High temperatures such as those in open flames make bone calcined and white, while lower temperatures such as those at the base of the fire or under the fire transform bone to black or other dark hues (e.g., Brain, 1993b; Nicholson, 1993; Shipman et al., 1984; Stiner et al., 1995). These colours match the colours of strata in a typical hearth, and this means that white and highly burned bone fragments are usually found in the white ash stratum and black bones usually in the black stratum (see e.g., Cain, 2005; Stiner et al., 1995). Therefore, bones of different colours mixed in a hearth stratum suggest that post-depositional processes such as trampling and/or site maintenance and the creation of ash dumps have affected the stratum. However, heat from new fires on top of bones buried in deposits from previous occupations can affect the bones and cause colour changes in bones that were not burned when originally deposited (e.g., Stiner et al., 1995). Nevertheless, experiments by Asmussen (2009) show that the uniformity of burning, burning patterns and burning frequency by taxa can be used to distinguish incidental from intentional fires. Similarly, experiments by Cain and Hanson (2007) suggest that histological analysis can help identify the pre-burning condition of bone, which is useful for identifying burning of fresh or dried bone and potentially also post-depositional burning. Burning of fresh bone may be an indication of cooking, but burning damages on bone (e.g., Shipman et al., 1984; Stiner et al., 1995) and post-depositional burning (e.g., Asmussen, 2009) makes it difficult to recognise cooking from bones burned for disposal purposes. To my knowledge, no researchers have published experiments to examine specific cooking techniques in the MSA and their archaeological implications.

Could bone be used as fuel? This question has been examined through fire experiments because bone appears to have been used as fuel during the European Palaeolithic (e.g., Beresford-Jones et al., 2010; Théry-Parisot, 2002). Théry-Parisot (2001, 2002) shows in her experiments that burning bones produces more light than burning wood and that heat is transferred well through radiation and convection, but not as well through

conduction, when burning bones. This means that the use of bones as fuel can sometimes be a deliberate choice based on functional requirements (e.g., Théry-Parisot, 2002). After comparing the colours, textures and burning patterns of bone from Sibudu with results from experimental studies, Cain (2005, 2006) concludes that bones were thrown into the fires as a means of disposal and not intentionally used as fuel at the site.

Rocks can fracture, change colour and undergo other changes when exposed to heat (e.g., Backhouse et al., 2005; Domanski et al., 1994; House & Smith, 1975; Lintz, 1989; Mercieca, 2000; Purdy & Brooks, 1971; Schmidt et al., 2012). These changes are important for the identification of cooking with heated rocks (e.g., Ellwood et al., 2013; Thoms, 2009), but the people in the MSA do not appear to have used hot rocks when cooking (see e.g., Chapter 2). Nevertheless, silcrete rocks at the site complex Pinnacle Point in the Western Cape were analysed using archaeomagnetism, thermoluminescence and maximum gloss, and the team of researchers concluded that the rocks were affected by heat (Brown et al., 2009). Silcrete rocks can become easier to flake when exposed to certain temperatures and controlled heating (e.g., Domanski & Webb, 1992) and experiments based on archaeological observations at Pinnacle Point (Brown, 2011; Brown et al., 2009, 2012) and Blombos Cave (Mourre et al., 2010) suggested that slow heat treatment of silcrete in sand covered pits was used to facilitate tool production. However, Schmidt et al. (2013) found in their experiments that South African silcretes can endure high temperatures and suggested that the rocks may have been heated next to campfires and that heat treatment of silcrete may have been an opportunistic practice. Oestmo (2013) examined experimentally heated quartzitic sandstone from the Western Cape using digital imaging technology and concluded that rocks may have been heated post-depositionally by campfires or intentionally heat treated, so the issue of heat treatment and tool production is still debated (see also Chapter 5). But heat could also have been used for other tasks during tool production. Wadley (2005a) showed, for example, that the heat from a campfire can help dry adhesives when hafting tools, thus shortening the time needed to produce the tools.

Fire-related behaviour can lead to post-depositional changes in bone and stone, as mentioned above. Some experiments were conducted to examine how heat can affect other types of material post-depositionally. Wadley (2009) shows that pieces of ochre can change colour from yellow to red when buried under a campfire, and this means that there may not be a preference for red ochre in the MSA (cf. e.g., Watts, 2002, 2010). Furthermore, the heat of a fire can carbonise and thus preserve seeds and plant material buried in the sediments under the fire (Sievers, 2013a; Sievers & Wadley, 2008). These post-depositional consequences of fire are important to remember when discussing fire, and I will comment on this topic when discussing my experiments.

4.2 AIMS FOR MY EXPERIMENTS

The aims for my experiments were based on the aims for this project, presented in Chapter 1, and involved the following research questions (see also Table 4.1):

- 1) The use of fire
 - a) How much effort is needed to control the temperatures of a fire? By "effort", I mean planning and gathering of fuel (such as selecting wood mass) and maintenance skills (such as adding logs or raking out ashes from a hearth before starting a new fire) as well as the labour and attention needed during fire use.
 - b) Are there differences in the predictability of subsurface and surface temperatures in the same fire?
- 2) The formation of hearths
 - a) Which strata can be observed in hearths? Is the formation of hearth strata affected by different topsoil horizon, multiple fires in the same hearth or the fuel load?
 - b) How is the formation of hearths affected by the use of the fire? I will examine whether fuel load, wood taxon, topsoil horizon or multiple fires in the same hearth affect hearth size and depth.

Table 4.1 Overview of hypotheses and variables tested in the fire experiments.

Research aim	Hypotheses	Variables tested
The use of fire: Controlling the temperature and the predictability of temperatures (see Chapters 5 and 6)	Fires burning a similar fuel mass of the same wood taxon on a similar topsoil horizon will produce maximum surface temperatures within a range of 100°C	Wood mass, topsoil horizon, wood taxon,
	Fires burning a similar fuel mass on a similar topsoil horizon will produce fires of similar duration (i.e., reach maximum surface temperature within a short period)	Wood mass, topsoil horizon, wood taxon
	Subsurface temperatures generally develop alongside (similar temperature curve to) the surface temperatures of a fire	Fuel mass, topsoil horizon, wood taxon
	Regularly adding logs to a fire helps maintaining constant heat	Number of logs
	The number of logs affects the maximum surface temperature of a fire burning a similar fuel mass of the same wood taxon on a similar topsoil horizon	Number of logs
	A larger fuel mass produce a higher surface temperature than a smaller fuel mass	Wood mass
	Repeated fires in the same hearth affects maximum surface temperature in a fire	Topsoil horizon (ash)

Table 4.1 (continued). Part 2 of 2.

Research aim	Hypotheses	Variables tested
Hearth formation: Hearth strata and the effect of using the fire (see Chapters 7 and 8)	The fuel load of a fire affects hearth size	Wood mass, hearth area
	The fuel load in a fire affects hearth depth (ash thickness)	Wood mass, hearth depth
	The number of fires in a hearth affects hearth size	Number of fires, hearth area
	The number of fires in a hearth affects hearth depth	Number of fires, hearth depth
	Fires of long duration produces deeper hearths than fires of short duration	Wood mass, hearth depth
	Ash dumps do not consist of distinct strata	Hearth strata
	The fuel mass of a fire affects the number of hearth strata	Wood mass, hearth strata
	The number of fires in a hearth affects the number of hearth strata	Number of fires, hearth strata
	The texture of the topsoil horizon affects hearth area	Topsoil horizon, hearth area
	Some wood taxa produce more ash than others	Wood taxon, ash depth

4.3 METHOD

The method in my experiments is based on the method of Sievers and Wadley (2008; see also Sievers, 2013a; Wadley, 2005a, 2009), but experiences during my first experiments and suggestions from Sievers, Wadley and other researchers influenced my decision to make some adjustments to the method. Both the experimental papers included in this thesis (Chapters 5 and 7) contain brief descriptions of the method, but a full description of the method is provided here as a reference and background. See also Table 4.2 for an overview of the experiments and Figure 4.1 for the setup of experiments.

4.3.1 THE NUMBERING OF THE EXPERIMENTS

Two cycles of experiments are included in this thesis. The first cycle consists of experiments conducted at various times between 2009 - 2011 and various places (Ballito, Johannesburg and the Waterberg), and these experiments are named with the letter F and a number, e.g., F1, F2 and F3. All the experiments in the second cycle were conducted within two weeks in 2011 at the same property in Johannesburg, and these experiments are named with the letter E and a number, e.g., E1, E2 and E3. A 'primary fire', meaning a fire made directly on the topsoil horizon, was part of all the experiments in both cycles. Some experiments also included a 'secondary fire', meaning a fire started on top of the cold ashes from one previous fire, and some also included a 'tertiary fire', meaning a fire started on top of the cold ashes from two previous fires. To distinguish between events in experiments with multiple fires, the primary fire is called .1 (e.g., E1.1), the secondary fire is called .2 (e.g., E1.2) and the tertiary fire is called .3 (e.g., E1.3). All fires were conducted outside and in open air in order to replicate the sort of situation applicable to the MSA, and no roof or similar structure covered the experimental area for any of the experiments.

Table 4.2 Overview of all experiments and experimental results. Part 1 of 4.

Exp #	Fire	Wood mass (kg)	# logs	Bone mass (g)	Max. surface temp. (°C)	Max. surface temp. reached	Max. subsurface temp (°C)	Max. subsurface temp reached	Diameter (cm)	Hearth area (cm²)	Tot. layers	Tot. ash depth (cm)	Tot. hearth depth (cm)	Wood taxon	Topsoil horizon
F1	1	5.1	13	0	-	-	-	-	42.0	1385.4	-	ca. 1.0	ca. 5.0	<i>Casuarina equisetifolia</i>	Fine/medium sand (Ballito)
F2	1	5.25	13	0	132	0 h 15 min	189	3 h 15 min	41.0	1320.3	2	2.5	7.0		
	2	5.15	12	0	484	1 h 15 min	270	4 h 45 min							
F3	1	4.8	11	0	591	14h 35 min	396	14h 35 min	46.0	1661.9	3	2.5	9.0	<i>Dichrostachys cinerea</i>	Coarse sand (Johannesburg)
	2	4.8	11	0	569	10h 05 min	259	9 h 05 min							
	3	5.0	11	0	597	10h 05 min	234	9 h 35 min							
F4	1	5.0	5	510	490	7 h	209 (7 cm)	7 h 30 min	46.0	1661.9	3	>0.25	3.0	<i>Eucalyptus globulus</i>	Coarse sand (Waterberg)
	2	5.0	5	500	716	2 h	292 (7 cm)	5 h 45 min							
	3	5.1	5	510	795	4 h	325 (7 cm)	5 h 15 min							
F5	1	14.1	9	1550	567	5 h	439 (7 cm)	5 h	45.0	1590.4	3	>0.25	5.0	<i>Acacia erioloba</i>	Fine sand (Sibudu)
F6	1	5.1	12	0	529	13h 15 min	292 (5 cm) 256 (7 cm)	12h 15 min 10h 45 min	38.0	1134.1	2	5.0	12.0		

Table 4.2 (continued). Part 2 of 4.

Exp #	Fire	Wood mass (kg)	# logs	Bone mass (g)	Max. surface temp. (°C)	Max. surface temp reached	Max. subsurface temp (°C)	Max. subsurface temp reached	Diameter (cm)	Hearth area (cm ²)	Tot. layers	Tot. ash depth (cm)	Tot. hearth depth (cm)	Wood taxon	Topsoil horizon
F6	2	5.0	11	0	589	1 h 45 min	284 (5 cm)	8 h 30 min	38.0	1134.1	2	5.0	12.0	<i>Acacia erioloba</i>	Fine sand (Sibudu)
F7	1	5.0	13	0	577	1 h 45 min	248	3 h	37.0	1075.2	3	1.0	5.0	<i>Eucalyptus globulus</i>	Fine/medium sand (Ballito)
F8	1	5.0	13	0	677	1 h	200	3 h 30 min	37.0	1075.2	2	0.5	4.0		Sibudu sievings
F9	1	5.0	14	0	529	1 h 45 min	293	3 h 15 min	37.0	1075.2	3	1.5	5.0	<i>Casuarina equisetifolia</i>	Fine/medium sand (Ballito)
	2	5.1	14	0	645	2 h 30 min	277	3 h 15 min							
F10	1	5.0	14	0	549	1 h 45 min	430	2 h	35.0	962.1	2	1.5	6.0		Sibudu sievings
	2	5.1	14	0	709	2 h	261	5 h 15 min							
E1	1	5	7	0	739	4 h	215	4 h 15 min	49.0	1885.7	4	4.0	8.0	<i>Dichrostachys cinerea</i>	Fine/medium sand (Johannesburg)
	2	5		0	658	2 h 45 min	225	4 h 45 min							
	3	5	6	0	830	2 h 45 min	275	3 h 15 min							
E2	1	5	7	0	594	2 h 45 m	224	3 h 30 min	49.0	1885.7	3	3.0	8.0		

Table 4.2 (continued). Part 3 of 4.

Exp #	Fire	Wood mass (kg)	# logs	Bone mass (g)	Max. surface temp. (°C)	Max. surface temp reached	Max. subsurface temp (°C)	Max. subsurface temp reached	Diameter (cm)	Hearth area (cm ²)	Tot. layers	Tot. ash depth (cm)	Tot. hearth depth (cm)	Wood taxon	Topsoil horizon
E2	2	5		0	686	2 h 15 min	242	3 h 30 min	49.0	1885.7	3	3.0	8.0	<i>Dichrostachys cinerea</i>	Fine/medium sand (Johannesburg)
	3	5	6	0	613	3 h	251	4 h 15 min							
E3	1	5	5	0	760	2 h 15 min	243	3 h 45 min	45.0	1590.4	3	2.0	7.0		
	2	5	6	0	601	2 h 30 min	255	3 h 30 min							
	3	5	5	0	772	1 h 15 min	237	3 h							
E4	1	5	5	0	599	5 h	234	5 h 45 min	45.0	1590.4	3	4.0	9.0		
	2	5	6	0	685	2 h 30 min	254	6 h							
	3	5	7	0	589	1h30min	296	8 h							
E5	1	5	7	0	577	2 h 30 min	240	4 h	41.0	1320.3	3	3.0	9.0		
	2	5	5	0	807	1 h 15 min	221	4 h 30 min							
E6	1	5	5	0	466	3 h 45 min	178	6 h 15 min	41.0	1320.3	3	3.0	9.0		
	2	5	7	0	848	1 h 15 min	307	3 h							

Table 4.2 (continued). Part 4 of 4.

Exp #	Fire	Wood mass (kg)	# logs	Bone mass (g)	Max. surface temp. (°C)	Max. surface temp reached	Max. subsurface temp (°C)	Max. subsurface temp reached	Diameter (cm)	Hearth area (cm ²)	Tot. layers	Tot. ash depth (cm)	Tot. hearth depth (cm)	Wood taxon	Topsoil horizon
E7	1	15	16	0	730	5 h	361	5 h 15 min	45.0	1590.4	4	4.0	13.0	<i>Dichrostachys cinerea</i>	Fine/medium sand (Johannesburg)
E8	1	15	15	0	690	2 h 15 min	354	9 h	47.0	1734.9	4	4.0	13.0		
E9	1	15	19	0	562	4 h 15 min	354	5 h 15 min	50.0	1963.5	5	4.0	14.0		
E10	1	15	13	0	571	4 h 15 min	286	5 h 30 min	47.0	1734.9	4	3.0	9.0		



Figure 4.1 Illustrations of experiments. From left to right: The start of E2.1, E2.1 after c. 2 hours, setup of fire E1.2 and experimental hearth E2 after 3 fires.

4.3.2 THE TOPSOIL HORIZONS

The topsoil horizon could be expected to affect the fires. Moist soil can increase the thermal conductivity of the sediments, but restrict temperatures below the fire to about 95°C or lower due to the evaporation of water (see e.g., Campbell et al., 1994, 1995; Frandsen & Ryan, 1986). None of my experiments were, however, conducted on moist soil. Furthermore, some experiments imply that the texture of the sediments have little influence on their thermal conductivity (e.g., Campbell et al., 1994; Canti & Linford, 2000), and I will discuss the topsoil horizon as a contributing factor to surface temperatures.

All the experiments in the second cycle (E1 – E10) were conducted in the same place and on the same topsoil horizon; a fine-grained and hard-packed sediment. Experiments in the first cycle (F1 – F10) were conducted at different places, and thus on different topsoil horizons. F1, F2, F7 and F9 were conducted in Ballito on the local topsoil. F6, F8 and F10 were also conducted in Ballito, but on discarded sieved sediments from Sibudu that included < 1 mm fragments of charcoal, seeds and other items small enough to fall through the mesh used at the excavation. F3 was conducted in Johannesburg, but not on the same property as the experiments in the second cycle, and on the local topsoil. Experiments F4 and F5 were conducted in the Waterberg on local river sand.

I took soil samples from the topsoil horizons of the experiments in Ballito and Johannesburg and Lyn Wadley provided a soil sample of the topsoil horizon for the experiments in the Waterberg. I sieved these soil samples through stacks of sieves at the soil laboratory at the University of the Witwatersrand to examine grain sizes, and the results are given in Table 4.2. Classification of soil types followed international standards based on grain size (see e.g., Goldberg & Macphail, 2007) and I grouped the primary fires by the texture of the topsoil horizon following the column "Soil" in Table 4.2 for statistical analyses and the secondary and tertiary fires were grouped together because they were all started on a topsoil horizon of ash.

Table 4.3 Grain sizes for topsoil horizons used in experiments.

Experiments	Place	Grain size for topsoil horizon	Soil
F1, F2, F7, F9	Ballito (local soil)	53 – 710 μm	Fine/medium sand
F6, F8, F10	Ballito/Sibudu sievings	<38 – 500 μm	Fine sand
F3	Johannesburg (local soil)	300 μm – >1 mm	Coarse sand
F4, F5	Waterberg (river sand)	250 μm – >1 mm	Coarse sand
E1 – E10	Johannesburg (local soil)	53 – 710 μm	Fine/medium sand

4.3.3 ENVIRONMENTAL CONDITIONS

Ballito, Johannesburg and Waterberg belong to different veld types (Acocks, 1988) and are also at different altitudes. The air pressure is different at different altitudes, and fire safety studies of burning characteristics of wood imply that the ignition temperatures of wood are similar at different altitudes and that flame height and fuel burning rate is higher at higher altitudes (Yafei et al., 2010; Zhang et al., 2012). These results suggest that a fire could produce more light and burn quicker in Johannesburg than in Ballito, and I shall comment on this shortly.

The weather is another variable that cannot be controlled during experiments, and weather conditions may affect combustion. Gusts of wind may, for example, provide extra oxygen to a fire and rain may cool down or even terminate a fire. Table 4.4 contains data on humidity, mean temperature and precipitation collected by weather stations nearby the locations for the experiments on the dates of the experiments. I collected these data from the weather archive at www.tutiempo.net.

Table 4.4 Weather data from www.tutiempo.net.

Exp.	Location for experiment	Date	Temperature at start of experiment (°C) (first reading from surface probe)	Weather station location		Mean humidity (%)	Mean temperature (°C)	Precipitation amount (mm)
F1	Ballito	15.02.09	-	Durban	Louis	79	21.6	0
F2.1		20.02.09	28	Botha		82	25.1	2.03
F2.2		21.02.09	33			77	27.4	0
F3.1	Johannesburg	15.04.09	18	Johannesburg		64	15.8	0
F3.2	(Northcliff)	16.04.09	55	Botanical Gardens		48	15.8	0
F3.3		17.04.09	36			58	15.4	0
F4.1	Waterberg	15.05.10	30	Warmbaths		67	18.9	0
F4.2		15.05.10	27			67	18.9	0
F4.3		16.05.10	27			75	16.7	0
F5		17.05.10	17			No data		
F6.1	Ballito	10.10.10	24	Durban	Louis	81	23.7	0
F6.2		11.10.10	78	Botha		73	22.6	0
F7		21.03.11	25			No data		
F8								
F9.1		22.03.11	26			74	24.8	0
F10.1								
F9.2		23.03.11	50			76	26.5	0
F10.2								
E1.1	Johannesburg	29.08.11	10	Grand Central		59	13.8	0
E2.1	(Midrand)							

Table 4.4 (continued). Part 2 of 2

Exp.	Location for experiment	Date	Temperature at start of experiment (°C) (first reading from surface probe)	Weather station location	Mean humidity (%)	Mean temperature (°C)	Precipitation amount (mm)
E1.2	Johannesburg (Midrand)	30.08.11	16	Grand Central	38	17.3	0
E2.2							
E1.3		31.08.11	21		26	18.0	0
E2.3							
E3.1		01.09.11	14		20	19.4	0
E4.1							
E3.2		02.09.11	19		15	18.6	0
E4.2							
E3.3		04.09.11	16		19	15.5	0
E4.3							
E5.1	Johannesburg (Midrand)	07.09.11	16	Grand Central	20	19.6	0
E6.1							
E5.2		08.09.11	17		31	18.4	0
E6.2							
E7		05.09.11	14		14	18.9	0
E8							
E9		06.09.11	14		18	18.9	0
E10							

The weather conditions were stable for experiment F1, F2, F3, F4, F5 and F6, with regards to environmental conditions. Nevertheless, I started to conduct experimental fires in pairs at the same time to reduce the effect that the weather on different days potentially could have on the experiments (Figure 4.2). The experiments F7/F8, F9/F10, E1/E2, E3/E4, E5/E6, E7/E8 and E9/E10 were conducted simultaneously in pairs. The distance between the fires (centre-centre) in each pair was at least 2 m to avoid the heat of one fire affecting the result of the other.



Figure 4.2 Fire experiments conducted in pairs. Left: E4.2 in the foreground, E3.2 in the middle, E2 about to be excavated in the background. Right: E6.1 in the foreground, E5.1 in the background.

4.3.4 RECORDING TEMPERATURES

F1 was a pilot experiment to examine the formation of hearths and ash dumps, and temperatures were not recorded during this experiment. The temperatures for all the other experiments were recorded using MajorTech MT 632 thermometers attached to thermocouples (probes). I manually recorded the temperature because the thermometers did not record data automatically, and I recorded temperatures from the time that the fire started until the temperatures of the fire decidedly declined. The temperatures were generally recorded every 15 minutes, but were recorded every 30 minutes after the first hour of F3. However, this does not appear to have affected the temperature curve substantially. After stopping the recording of temperatures at 15 (or 30) minute intervals in each experiment, control recordings were taken after one hour. In some experiments, several control points were taken even later, but these are not included here.

In general, the subsurface temperatures of fires were recorded by placing a probe under the centre of the fire. This was prepared before the fire was started by excavating a pit down to the desired depth, placing the probe in the excavated pit and filling the pit with the sediments excavated. The subsurface probe would not be moved during experiments with multiple fires in the same hearth. This means that ash accumulating on the surface could and was expected to affect the subsurface temperatures in secondary and tertiary fires. A subsurface probe was placed 5 cm below the surface in experiments F2, F3, F6-F10 and E1-E10. Some of these experiments contained extra subsurface probes; a second subsurface probe was placed under a rock 5 cm below the surface during experiment F2 and a second subsurface probe was placed 7 cm below the ground during experiment F6. The subsurface probe was placed 7 cm below the surface during experiments F4 and F5. The surface temperatures were recorded by placing a probe on the topsoil horizon and in the middle of the fire for experiments F2-F10 and E1-E10. However, the surface probe in fire 2.1 ended up next to the fire, and I will be careful when comparing the temperatures of fire 2.1 to other fires. The surface probe would be lifted on top of the ashes and placed between the logs for the next fire in experiments with multiple fires, except for F2.2. During this fire, the first surface probe was left

were it was and a second surface probe was added to the top of the ashes from the primary fire of the experiment.

4.3.5 FIREWOOD

Only one wood taxon was burned in each experiment. I chose to use precut, commercially available logs in my fires to limit the variables in my experiments. In addition, many of the trees used as firewood at Sibudu are protected species today and may not be cut. The use of commercially available wood restricted the taxa I could use for the experiments because not many taxa are sold in the required quantity (see Section 4.5 for more details). *Eucalyptus globulus* (Blue Gum, not an indigenous taxon) was used for experiments F4, F5, F7 and F8. F4 and F5 also included bone fragments from a tibia with the knee attached from a lamb (*Ovis aries aries*) and a femur from a bull (*Bos primigenius*). *Casuarina equisetifolia* (she-oak, not indigenous to South Africa) was burned in experiments F1, F2, F9 and F10, *Acacia erioloba* (Camel thorn, indigenous to South Africa) was used in experiment F6 and *Dichrostachys cinerea* (Sickle bush, indigenous to South Africa) was burned in experiments F3 and E1-E10. The fuel mass and number of logs in each experiment is given in Table 4.2. All the firewood was well dried.

4.3.6 ASH DUMPS

All the contents (ashes and charcoal) of the combustion feature in F1 were scraped to one side to create an ash dump. Half the contents of the combustion features in experiments F4, F5, F6, F7, F8, F9 and F10 were also scraped to the side to create an ash dump as contrast to the layers of the experimental hearths.

4.3.7 EXCAVATION

All the hearths and ash dumps in these experiments were excavated using the same techniques as at Sibudu. I documented the excavations with photos and drawings (Figure 4.2). Measurements of the diameter of the hearths were taken at the widest extent of the white ashes and, for experiments which included ash dumps, always before scraping out ashes for creating dumps.

4.3.8 STATISTICAL ANALYSIS

Statistical analysis of the data from my experiments was conducted using the program GNU PSPP release 0.7.10-g29c145. Some analyses of correlation contained categorical variables, and I then tested Spearman's Rank correlation coefficient and used Table H for critical values in Fletcher and Lock (1991) to determine the statistical significance of the test. I have followed statistical conventions and use r_s for Spearman's Rank correlation. Yet most of my variables are continuous, and I then tested (Pearson's) product moment correlation coefficient r .

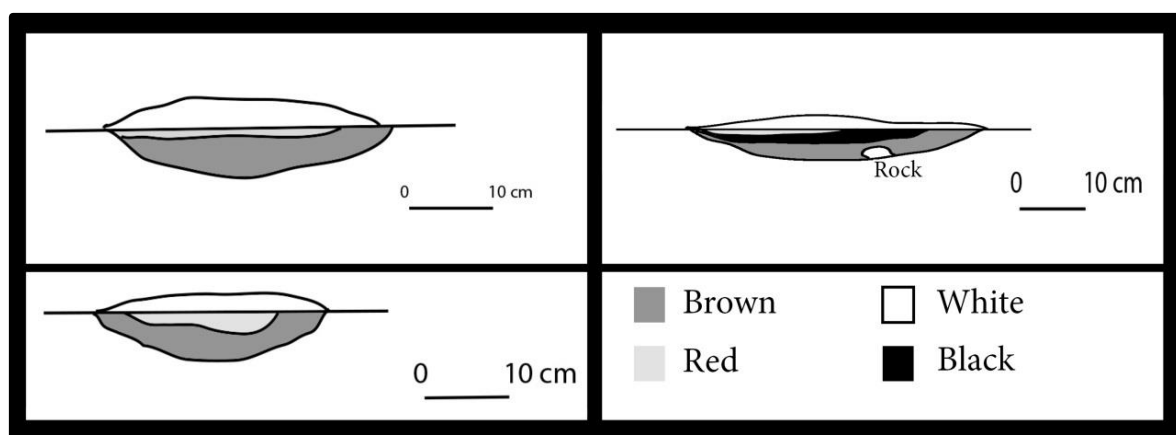


Figure 4.3 Drawings of cross sections from selected experiments. Top left: E2. Base left: E5. Top right: E10. Base right: legend.

4.4 SUMMARY OF RESULTS

The results from these experiments are summarised in Table 4.2. Excluding fire F2.1, where the surface probe may have been next to the fire, the maximum surface temperature in primary fires burning ca. 5 kg wood and no bone (n = 12) ranged from 466°C (E6.1) to 760 (E3.1) with an average of 598.9°C. The maximum surface temperature in primary fires burning 15 kg wood (n = 4) ranged from 562°C (E9) to 730°C (E7) with an average of 638.3°C. The maximum surface temperature in secondary fires burning ca. 5 kg wood (n = 12) ranged from 484°C (F2.2) to 848°C (E6.2) with an average of 666.4°C and the maximum surface temperature in tertiary fires burning ca. 5 kg wood (n = 6) varied from 589°C (E4.3) to 830°C (E1.3) with an average of 699.3°C. Fires burning *Dichrostachys cinerea* resulted in both the highest (848°C in E6.2) and lowest (466°C in E6.1) surface temperature recorded in all the experiments. Fire F3.1 took the longest to develop maximum surface temperature (14 hours 35 minutes). Excluding this fire, the primary fires burning ca. 5 kg of wood conducted in Johannesburg (E1.1, E2.1, E3.1, E4.1, E5.1 and E6.1) took 3.4 hours on average to develop maximum surface temperatures, while the primary fires burning ca. 5 kg wood conducted in Ballito (F2.1, F6.1, F7.1, F8.1, F9.1 and F10.1) took 3.3 hours on average to develop maximum surface temperatures. In other words, the expectation that fires in Johannesburg would burn quicker than fires in Ballito, was not met. I shall discuss results on the temperatures and use of fires in Chapters 5 and 6.

The hearth area of the experimental combustion features ranged from 962.1 cm² (F10) to 1963.5 cm² (E9); meaning that two fires burning 10 kg *Casuarina equisetifolia* on fine sand (Sibudu sievings) produced the smallest hearth area and one fire burning 15 kg *Dichrostachys cinerea* on fine/medium sand produced the largest hearth area. Little ash was produced in experiments F4, F5, F7 and F8, which might be related to the wood taxon (*Eucalyptus globulus*) used for these fires (see Chapters 7 and 8). From 2 to 5 different hearth strata and lenses were documented in the experimental hearths, yet none of the experimental combustion features contained a well-defined black and charcoal rich stratum under a well-defined white ash top stratum. Some fires produced a thin black lens directly below the white ash or under a rubified layer in the hearth, but this

black layer did not contain large charcoal fragments. The ash dumps contained mixed layers and not the clear stratigraphy of the *in situ* combustion features. The Munsell colour of the hearth strata in the experimental hearts and the ash dumps are given in Table 5.2. I shall discuss results on the hearth strata and the formation of combustion features in Chapters 7 and 8.

4.5 CONCLUDING REMARKS

Through planning, conducting and analysing the first cycle of experiments, I learned valuable lessons on the many different variables that can affect a fire and the formation of combustion features and the difficulty in controlling them. I used these lessons to improve my method for the second cycle of experiments. One example of the variables that can affect a fire concerns the firewood taxon used. The staffs at many places that sell firewood in South Africa (such as gas stations or supermarkets) do not know the taxon or origin of the wood for sale. Some places had managers that were willing to contact their supplier for me, or give me contact information so that I could contact the company myself, but many places did not. Furthermore, even the supplier did not always know which wood taxon or batch of wood they supplied to a certain outlet. Suppliers might not have the same taxon or taxa in stock at all times because some wood taxa are more popular than others or only available to the wood supplier for limited periods or in small batches, depending on the areas harvested (Jeremy Wood, wood supplier, personal communication, Ballito 2011). Experiments F1, F2, F5, F6, F7, F8, F9 and F10 were conducted in Ballito during field trips, which meant that I had to use the taxa available during the weeks I stayed in Ballito. During the second cycle of experiments, the fires were conducted consecutively and during two weeks. I could buy wood for these fires from one supplier and get a large batch of one wood taxon that had grown in the same area and had been harvested, transported and stored in similar conditions, which limited variables connected to the firewood used. I demonstrate, however, in the next chapter that it is difficult to predict the temperatures of a fire even when only one wood taxon is used as firewood.

5 CONTROLLING THE HEAT: AN EXPERIMENTAL APPROACH TO MSA PYROTECHNOLOGY

The paper presented in this chapter contains experimental results on the use of fire. Only fires in the second cycle of experiments are included in this chapter, and the remaining experiments are included in Chapter 6. The paper in this chapter was published in the South African Archaeological Bulletin in 2013, volume 68, pages 137 – 145.

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Research Article

CONTROLLING THE HEAT: AN EXPERIMENTAL APPROACH TO MIDDLE STONE AGE PYROTECHNOLOGY

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ABSTRACT

Pyrotechnology, or the use and control of fire, was important during the Middle Stone Age (MSA). Fire would have been used for tasks such as cooking, hafting and possibly heat treatment of silcrete, and it might have been necessary to control the temperatures of the fire to achieve the desired result in these tasks. In this paper I report results from ten actualistic fire experiments conducted to illustrate the effort involved in controlling fire temperatures, such as the planning, labour, maintenance skills, fuel resources and attention to the process. The experiments were conducted in open air, and variables such as wood taxon, wood mass and topsoil horizon were controlled. Dichrostachys cinerea wood was used in all the ten fires. Six of the fires each burned totals of five kg of wood and no logs were added during these fires. Four fires each burned totals of 15 kg of wood and logs were gradually added to these fires at intervals of 30 minutes. The temperatures of the fires were recorded using Major Tech MT 632 thermometers attached to thermocouples recording surface and subsurface temperatures during the fires. The peak surface temperatures varied greatly, whereas the subsurface temperatures were more predictable. These experiments suggest that some effort, such as attention to the development and maintenance of the fire, and gathering plentiful fuel resources, is necessary when a specific range of temperatures is needed for an activity.

Key words: fire use, fire experiments, fire maintenance, Middle Stone Age.

INTRODUCTION

Pyrotechnology, or the controlled and habitual use of fire, was an essential part of daily life in prehistory. The initial control and use of fire is much debated (e.g. Brain & Sillen 1988; James 1989; Gowlett 2006; Alpersen-Afil & Goren-Inbar 2010; Roebroeks & Villa 2011; Berna *et al.* 2012), but researchers have focused less on the subsequent development of this technology (Brown *et al.* 2009) to include increasingly sophisticated uses of fire. The African Middle Stone Age (MSA) provides a window into this development through an extensive, and growing, collection of data on fire-related behaviour and combustion features (e.g. Mason 1988; Goldberg 2000; Cain 2005; Allott 2006; Brown *et al.* 2009, 2012; Goldberg *et al.* 2009; Karkanas & Goldberg 2010; Wadley 2010, 2012; Wadley *et al.* 2011; Miller *et al.* 2013; Bentsen, in press). Modern humans living in the MSA displayed a variety of behavioural patterns similar to our own (e.g. McBrearty & Brooks 2000; Henshilwood, d'Errico *et al.* 2001, 2002; Wadley 2001; Wadley *et al.* 2009; Shea 2011); clearly controlled fire, and regularly used fire for several tasks (e.g. Bentsen, in press and references therein). A more holistic understanding of pyrotechnology in the MSA would, furthermore, provide a basis for comparisons with contemporary Neanderthals and modern humans in other regions, as well as insight into the fluctuations in the development of this technology and how it relates to developments and changes in lithic and other technologies.

This paper uses the results from ten fire experiments to explore the effort, such as the planning and gathering of fuel resources, labour, maintenance skills, and attention needed to control the temperatures of a fire. The results are discussed in relation to some of the tasks assumed to require fire in the MSA. On the one hand, if every fire burning a similar fuel mass on the same type of topsoil horizon can be predicted to produce, repeatedly, a limited range of temperatures with similar duration, then little labour and few skills are needed to ensure the desired temperatures and to control the fire. On the other hand, if fires generally are unpredictable and produce a wide range of temperatures of varying duration, even when burning similar masses of fuel on the same type of topsoil horizon, much maintenance of the fire and effort seem necessary to ensure the desired result. There is also the issue of how best to maintain a fire and whether the subsurface and surface temperatures of a fire have the same level of predictability. The experiments described below are designed to provide answers for these questions.

Specific temperatures are not necessary to achieve the desired result for some activities. A campfire can, for example, provide light and heat even if the temperature of the fire is not controlled. Using fire for site maintenance, for example to burn waste, is another activity that does not rely on specific temperatures. During the MSA, examples of sanitary purposes include burning bones to dispose of them (Cain 2005, 2006; Clark & Ligouis 2010) and burning old bedding (meaning plant material used to prepare the surface) (Goldberg *et al.* 2009; Wadley *et al.* 2011; Miller & Sievers 2012; Miller *et al.* 2013). Such activities will not be discussed further in this paper.

Furthermore, a fire can induce post-depositional changes in archaeological material buried under a new hearth. New occupations at a site can thus unintentionally affect artefacts from previous occupations. One example is the colour of ochre. 'Ochre' has in archaeological contexts been used to describe a wide range of rock types that produces a coloured streak (e.g. Hodgskiss 2010 and references therein). Watts (2010) suggests that red was a preferred colour in the MSA and that ochre might have been roasted to obtain redder hues 100 000 years ago. However, Wadley (2009) has shown that ochre can change colour when buried 10 cm under a hearth and exposed to relatively low temperatures. Another example of post-depositional transformation is the charring of seeds and fruiting structures buried below a fire. Sievers and Wadley (2008) conducted experiments that demonstrate that seeds buried 5 cm below the centre of a fire appear carbonised even at low temperatures, while seeds on the surface of the fire become completely ashed and seeds buried at the perimeter of the fire did not appear altered at all. These unintentional consequences of fire-related behaviour are important to remember when analysing an archaeological site, but only intentional consequences of fire use will be discussed below.

USING PYROTECHNOLOGY IN THE MSA

Intentional use of fire can be inferred from several activities in the MSA. However, I will focus here on three tasks where control of heat is important: cooking, hafting, and heat treatment of rocks. Cooking was not a novelty in the MSA. For example, Wrangham (2009), Carmody and Wrangham (2009) and Wrangham and Carmody (2010) emphasise the evolutionary significance of cooking and suggest, based on anatomical features, that *Homo erectus* regularly cooked food. On the other hand, some cooking techniques seem only to have developed after the MSA. Based on the lack of archaeological evidence of pits with charcoal, rock-filled hearths, and heaps of fire-cracked rocks, for example, Thoms (2009) suggests that using heated rocks to facilitate cooking of food originated c. 30 000 years ago. In general, food can be slowly cooked at temperatures as low as 55–95°C or roasted or baked for a short time on higher temperatures (Wandsnider 1997). Cooking meat and starches increases the energy gained by these foods (Carmody *et al.* 2011). High temperatures might, however, char the food, thereby destroying energy. The lack of evidence of cooking pits and similar structures at MSA sites (Bentsen, in press and references therein) suggests that people used the heat in, around, or above the fire when cooking. At Klasies River, the burning patterns on bones and the parts of the animals preserved imply that limbs were roasted while the tarsals were attached and that the upper parts of the legs were roasted whole by or on the fire (Milo 1998). However, at Sibudu, flesh might have been removed from bones before roasting (Cain 2005). Different processing and cooking techniques might thus have been used. In addition to meat, marine food, such as shellfish, fish, and seals, was also cooked in the MSA (e.g. Deacon 1995; Henshilwood, Sealy *et al.* 2001; Halkett *et al.* 2003; Klein *et al.* 2004; von den Driesch 2004; Avery *et al.* 2008). Plants seem also to have been cooked or their residues burnt in the vicinity of hearths (e.g. Opperman & Heydenrych 1990; Deacon 1995; Albert & Marean 2012).

Hafting, including the production of adhesives, could also benefit from pyrotechnology. The occurrence of adhesives on stone tools indicating hafting at Sibudu has been the topic of several studies (e.g. Lombard 2005, 2007; Wadley 2005, 2010; Wadley *et al.* 2009). Microscopic analysis implies that ochre was used in the compound adhesives and that the recipe might have been adjusted to accommodate different raw materials (Lombard 2007). Four adhesive recipes were tested in experiments by Wadley (2005), who used fire to heat the mixtures during their production and to dry them when they were hafted on tools. This study concluded that heat was necessary to dry the adhesive and shorten the production time of the hafted tools. The study also showed that the distance to the fire is very important when drying adhesive on a tool, because when a tool is placed too close to the fire boiling and cracking cause weaknesses in the adhesive (Wadley 2005). Macroscopic analysis of stone tools implies the use of simple glue for hafting made from *Podocarpus* gum at Diepkloof Rock Shelter (Rigaud *et al.* 2006). Chemical analyses of the residue on one stone tool did identify *Podocarpus* gum, but heating glue might not have been part of the hafting process at Diepkloof because no evidence of by-products from the fire was found in the sample analysed (Charrié-Duhaut *et al.* 2013).

Lastly, heat treatment of rocks is inferred based on material from MSA sites Pinnacle Point, Blombos Cave and Diepkloof Rock Shelter (Brown *et al.* 2009, 2012; Mourre *et al.* 2010; Brown 2011; Schmidt *et al.* 2013). This paper will not discuss to what extent heat treatment was conducted, or what kinds of physical changes occur during heat treatment of silcrete. It focuses on

the pyrotechnological implications of the two models of MSA heat treatment suggested. The first model, suggested by Brown *et al.* (2009) and also used by Mourre *et al.* (2010), implies slowly heating rocks covered by sand (or underneath the fire) for approximately five hours up to a maximum temperature of 350°C before slowly cooling down. This means that planning and gathering sufficient fuel loads and loads of silcrete would be needed to conduct the heat treatment. The second model implies that South African silcretes can be heated fast above ground, can be left in the heat for a short time (50 minutes at maximum temperature is suggested), and can endure high temperatures, ideally 400–500°C (Schmidt *et al.* 2013; see also Schmidt *et al.* 2012). This method requires little effort, meaning little planning and labour to gather sufficient fuel loads, and few maintenance skills. This second model implies that little attention to fuel or the development of the fire would be needed for heat treatment of silcrete.

VARIABLES AFFECTING COMBUSTION

This section will briefly describe how the temperatures and duration of heat in a fire can be affected by variables involved in the making of the fire. The choice of fuel is one of these variables. Burnt bones may have been used as fuel during the European Palaeolithic (e.g. Théry-Parisot 2002; Beresford-Jones *et al.* 2010), but bones may have been thrown into fires as a disposal strategy in the MSA, and not intended as fuel (Cain 2005, 2006; Clark & Ligouis 2010). The use of dung as fuel can have technological implications, as it produces a predictable and slow-burning fire (Lancelotti & Madella 2012). Many methods for recognising dung in archaeological contexts have been and are being developed, but dung as fuel seems mostly relevant after the domestication of animals (Shahack-Gross 2011; Lancelotti & Madella 2012). This paper will focus on the use of wood as fuel.

Ethnographic studies have shown that modern fire users can have clear preferences for a wood taxon or a range of taxa considered to be suitable as firewood (e.g. Tietema *et al.* 1991; Abbot *et al.* 1997; Tabuti *et al.* 2003), and deliberate choices might also have been made in prehistory. However, it is difficult to distinguish preferences for a single taxon or a few taxa from the charcoal analyses currently available (e.g. Cartwright & Parkington 1997; Allott 2006), although studies of wood-collecting behaviour during the MSA at Sibudu imply that many of the taxa burnt at the site are considered good firewood today (Allott 2005, 2006). Nevertheless, the combustion behaviour of wood is not solely dependent on the taxon burnt.

Variables and properties that are relevant for the combustion of wood include physical properties, such as density (partly dependent on moisture and wood taxon); the size of the burning material (logs), and thermal conductivity (increasing with density, moisture content and temperature) (e.g. Ragland *et al.* 1991; Nurmi 1992). For example, a high moisture content means that much energy is needed to vaporise the water from the wood during the flaming phase of combustion, which decreases combustion efficiency and increases smoke formation (e.g. Core *et al.* 1982; Simoneit *et al.* 2000). Factors such as moisture and size of logs can be distinguished without modern techniques, and were possible selection criteria in the past. The physiological state of wood, i.e. the level of decay of the wood, can affect the combustion and can be easily recognised (Théry-Parisot 2001; Théry-Parisot & Henry 2012). For example, different fungi affect wood. Some cause white rot, which may not lead to significant changes in the combustion of wood, while other fungi cause brown rot, which may increase the combustion heat (Dobrá *et al.* 1986). The growth conditions of the wood used can also affect thermal behaviour (Théry-Parisot & Henry 2012).

The heat below a fire is related to the properties of the topsoil horizon. For example, Campbell *et al.* (1994) have demonstrated that the thermal conductivity of soil increases with temperature in moist soil. Nevertheless, a moist layer of soil will not reach temperatures above about 95°C due to the evaporation of water (Campbell *et al.* 1995: 373). This model is based on laboratory and computer simulations of forest and range fires. As an archaeological combustion feature would have affected a much smaller area, it is possible that a moist layer underneath a hearth might dry out and not cause a lasting temperature threshold beneath the fire. Yet, an actualistic study of subsurface temperatures under a heap of burning wood indicated that wet soil does indeed produce a limited range of temperatures even in contained fires (Frandsen & Ryan 1986). However, soil texture can be regarded as simply a minor, contributory part of thermal conductivity in soils (e.g. Campbell *et al.* 1994; Canti & Linford 2000).

EXPERIMENTAL DESIGN

Previous fire experiments by other researchers have demonstrated that small wood fires can produce a small range of temperatures on different topsoil horizons (e.g. Bellomo & Harris 1990; Bellomo 1993; Canti & Linford 2000; Linford & Canti 2001; Wadley 2005, 2009; Sievers & Wadley 2008; Braadbaart *et al.* 2012; Miller & Sievers 2012; Théry-Parisot & Henry 2012). For example, Théry-Parisot and Henry (2012) report a 100°C difference in maximum surface temperature (i.e. the temperatures measured on the surface of the topsoil horizon) in the fires in their controlled experiments. We have seen above that several variables may affect the temperatures of a fire, but also that a variety of temperatures can be important for different tasks. The ten fire experiments described below were designed to examine the efforts involved in controlling a fire. The experimental design was carefully planned to replicate an MSA scenario, yet at the same time attempting to control the variables affecting the temperatures of the fire. Experiments are named by the letter E and a number, for example, E1, E2, E3.

REPLICATING AN MSA SCENARIO

To replicate the sort of situation applicable to the MSA, all wood fires were conducted in open air. The experiments were conducted on part of a property in Johannesburg, South Africa (25.9668100°S; 28.1519400°N, 1570 metres above sea level), that was sheltered from wind by trees (no roof or similar structure covered the experimental area). The fires were made in the shade, but sunlight would reach the fires about 5 hours into the experiments and stay for c. 2 hours. All experiments were conducted on the same type of topsoil horizon; a fine-grained sandy and hard-packed sediment. Weather conditions were stable during the experiments, with little wind. The air temperature ranged from c. 20–25°C at midday during the experiments and there was no rain during the two weeks of experiments. As the experiments were conducted towards the end of the South African winter, it had not rained for approximately two months before the experiments started. The experiments replicated two possible scenarios: E1, E2, E3, E4, E5 and E6 were small fires that replicated a situation where a campfire was lit and then left eventually to extinguish itself, with no attempts to revive the fire or keep the fire going. Each of these small fires burned 5 kg of wood. Experiments E7, E8, E9 and E10 were larger fires that replicated a situation where a campfire was lit, kept going by adding logs to the fire and then left to extinguish itself. This simulates a situation where a minimal effort was used to maintain the fire. These large fires were started with 5 kg wood, a further c. 2 kg wood were added one

hour later and c. 2 kg wood were then added every 30 minutes until 10 kg of wood had been added to the fire. At that point, the fire was left to burn out and the ashes to go completely cold. To ensure that weather conditions had as little influence as possible on the results, the fires were conducted in pairs. This means that two fires burning the same amount of wood were lit simultaneously. Thus, E1 and E2 were performed simultaneously, as were E3 and E4, E5 and E6, E7 and E8, and E9 and E10. Each pair of experiments was started between 6 and 7 a.m. on the respective day of the fire.

FUEL

Only one wood taxon, *Dichrostachys cinerea* (Sicklebush), was used in the experiments. This indigenous wood taxon is commonly used for barbeques in South Africa today and is thus easy to obtain in large quantities. All the wood used in these experiments was from the same batch from the same supplier. This may mean that the trees grew in the same area and were harvested at the same time. The wood would then have received the same treatment and been stored together under the same circumstances before it was transported to the outlet and put out for sale. This ensured that the size, moisture content, and other properties of the logs were as similar as possible. A bag with c. 8 kg wood from this same supplier was selected for controlling the moisture content of the wood. The moisture content was measured with an MD-4G 4-pin digital wood moisture meter. This instrument has four pins that are driven into each log. The electrical resistance in wood changes in direct proportion to its moisture content, which is the basis for the measurements of the meter. The meter has an accuracy of $\pm 1\%$. The moisture measurements of the wood from the bag ranged from 12–20%, showing that this was well-dried wood. All logs used in these experiments were c. 18 cm long. Many were cut in a triangular shape, each side of the triangle being c. 7–10 cm wide, and some were shaped as a semicircle with the straight edge c. 10 cm wide, and some were round. All logs looked healthy and no rot or decay was observed on them. Logs were arranged in a tepee formation around the tip of the probe in all the fires (Fig. 1), and this tepee formation had a diameter of c. 40 cm for all fires.

RECORDING TEMPERATURES

Temperatures were recorded using two MajorTech MT 632 thermometers, one for each of the fires burning simultaneously. Thus, when referring to maximum/minimum/average temperatures below, I refer to the maximum/minimum/average *recorded* temperatures. Each thermometer was attached to 2 K-type thermocouples (probes). One of the probes was buried 5 cm below the topsoil, under the fire, while the other probe was placed on the surface of the topsoil and in the centre of the fire. Temperatures were recorded just before the fire was lit and subsequently every 15 minutes for at least 10 hours, depending on the development of the fires and the temperatures recorded at this stage. If there were reasons for continuing to record temperatures, such as large temperature differences between the two fires lit simultaneously, or a very slow decline of the temperatures, I continued recording temperatures until the issue was resolved.

RESULTS

Results from the experiments are summarised in Table 1 and Figures 2–6. In general, the peak surface temperatures of the fires varied greatly, even in fires that were lit at the same time and that were burning the same amount of fuel. In the six small fires burning 5 kg of wood each, the peak surface temper-



FIG. 1. Left: Start of fires with logs in tepee formation. Right: E1 and E2 after c. 2.5 hours.

atures ranged from 466°C (E6) to 760°C (E3). The larger fires, burning totals of 15 kg wood each, produced peak surface temperatures ranging from 562°C (E9) to 730°C (E7). The peak subsurface temperatures also varied, but less so than the surface temperatures. The small fires produced subsurface temperatures between 177°C (E6) and 240°C (E5), while the large fires produced peak subsurface temperatures of 286°C (E10) and 361°C (E7).

DISCUSSION

Variables such as topsoil horizon, wood taxon, wood mass, and log size were controlled in these experiments. Nevertheless, the difference in peak surface temperatures is larger than 100°C, a result which was previously reported for similar exper-

iments by Théry-Parisot and Henry (2012). It is possible that other variables might also influence fire temperatures. One such variable is the weather; yet fires started at the same time on the same day, and thus burning in similar weather conditions, also produced different temperatures (Figs 2–6). These temperature variations could be natural and related, for example, to factors such as the wood taxon burned or the amount of resin within each log. Furthermore, the duration of the surface temperatures and the time taken to reach the maximum temperature (Table 1) also varied, even for fires that were lit at the same time. The fire user cannot rely on any fire to produce certain surface temperatures, nor to reach maximum surface temperatures at a given time, even if the fires are burning the same wood taxon and are on the same type of topsoil horizon.

TABLE 1. *Experimental design and results.*

Experiment	Fuel mass (kg)	Total logs on fire	Fire refuelled	Max surface temp. (°C)	Max surface temp. reached	Max subsurface temp. (°C)	Max subsurface temp. reached
E1	5	7	N	739	4h	215	4h 15 min
E2	5	7	N	594	2h 45 min	224	3h 30 min
E3	5	5	N	760	2h 15 min	243	3h 45 min
E4	5	5	N	599	5h	234	5h 45 min
E5	5	7	N	577	2h 30 min	240	4h
E6	5	5	N	466	3h 45 min	177	6h 15 min
E7	15	16	Y	730	5h	361	5h 15 min
E8	15	15	Y	690	2h 15 min	354	4h 30 min
E9	15	19	Y	562	4h 15 min	354	5h 15 min
E10	15	13	Y	571	4h 15 min	286	5h 30 min

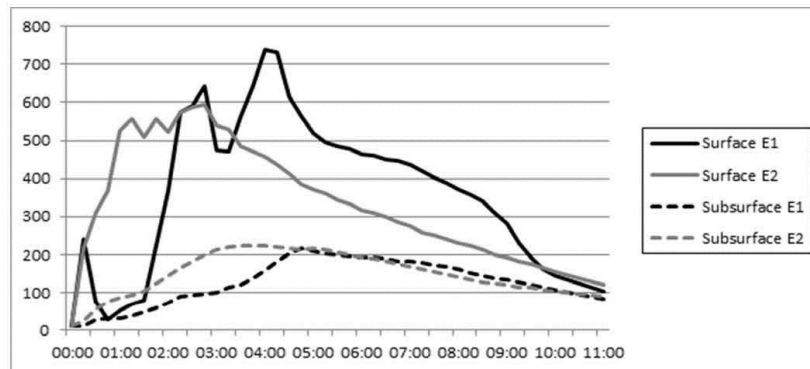


FIG. 2. Surface and subsurface temperatures of E1 and E2.

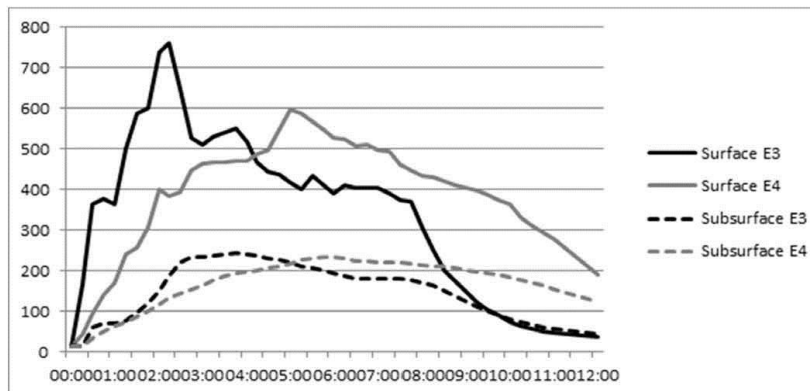


FIG. 3. Surface and subsurface temperatures of E3 and E4.

Instead, the person must be able to judge carefully when the temperature of the fire is right and to control the heat through maintenance techniques, for example, adding or subtracting logs.

In general, the subsurface temperatures in the experiments reported here were more predictable than the surface temperatures. Subsurface temperatures generally developed alongside the surface temperatures, yet both small and large fires produced subsurface temperatures that were lower and within a

narrower range than the surface temperatures. This indicates that burying items at different depths below the ground surface can be a strategy to control the heating of items and maintain constant temperatures. There is some variation in the time taken to reach maximum subsurface temperatures (Table 1), and this may be related to the overall stability and evenness of the surface temperatures rather than the time taken to reach maximum surface temperatures (Figs 2–6). The fire user thus needs to be aware that maintaining stable surface

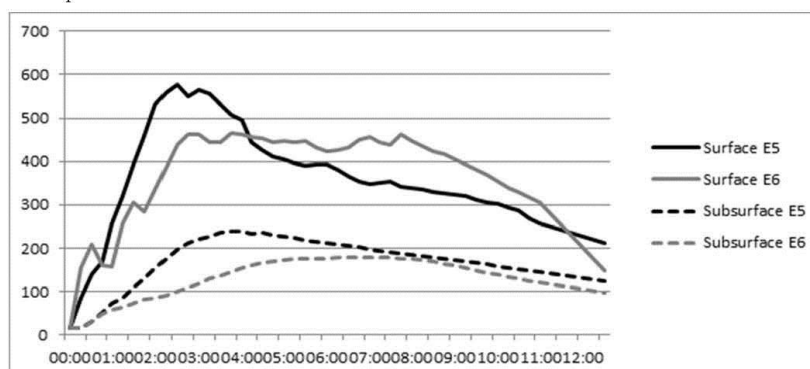


FIG. 4. Surface and subsurface temperatures of E5 and E6.

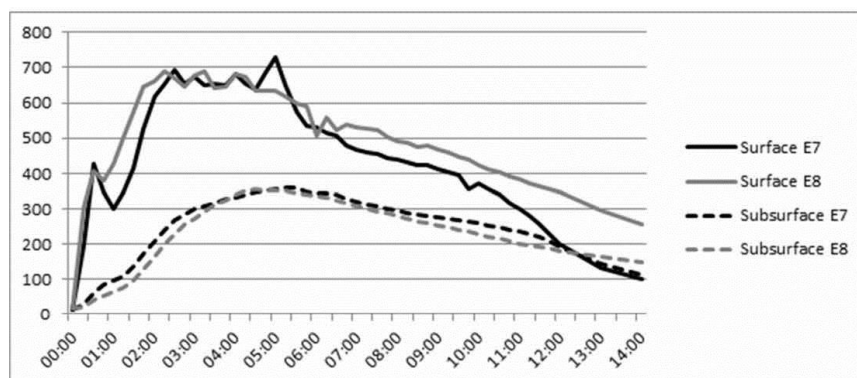


FIG. 5. Surface and subsurface temperatures of E7 and E8.

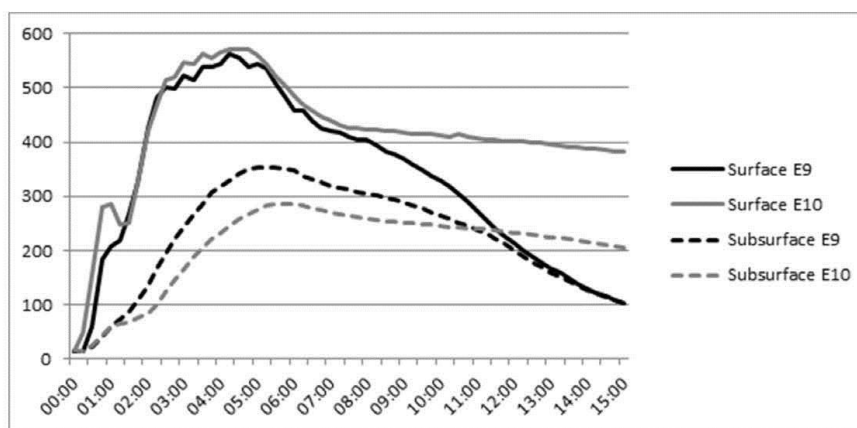


FIG. 6. Surface and subsurface temperatures of E9 and E10.

temperatures is important for controlling subsurface temperatures for a task. Using subsurface temperatures does, then, seem to require an extra set of skills and more effort than merely using the surface temperatures of a fire. Indeed, Wadley (2013) points out that the kind of analogical reasoning needed for subsurface heat treatment is an example of a cognitive trait similar to those in modern humans.

Regularly adding logs to sustain a fire is one possible strategy for maintaining constant heat in a fire. Indeed, the large and sustained fires in these experiments (E7, E8, E9 and E10) produced a narrower range of surface temperatures than the small fires in which fuel was not replenished (Figs 2–6). The large fires tended to produce even temperatures with only minor fluctuations for some duration of time. Nevertheless, the time taken to reach maximum surface temperatures (Table 1) varied among the large fires, showing that adding logs to a fire is not the only method of achieving peak temperatures within a given time. While constant tending of the fire might not be needed for every task using fire, some skills and attention are required. The person controlling the fire must understand the benefits of adding logs to the fire at appropriate intervals.

IMPLICATIONS FOR PYROTECHNOLOGY IN THE MSA

Cooking might be possible using temperatures as low as 55–95°C (Wandsnider 1997), as mentioned earlier. We do not know whether people in the MSA preferred slow roasting in

coals or ashes, fast grilling using flames and hot temperatures, other techniques, or a combination of these. My experiments retained surface temperatures suitable for cooking for many hours after the flames had died (Table 1, Figs 2–6). This implies that the same hearths can be used for cooking as well as other tasks, by staggering the activities to suit the temperatures. Thus it might not be necessary to make fires simply for cooking. Furthermore, if there were warm ashes and embers from previous fires in a camp, these could be used for cooking and new fires would not need to be made. Nevertheless, the person or persons using the fire would require some skills to judge the time needed for cooking and where to place the food to avoid charring, as the temperatures of the fires varied. Similarly, the variation in temperatures also indicates that some care would have to be taken when using the fire to dry adhesives and hafting tools. The fire user would need to be able to judge where and at what distance to place the adhesives or the hafted tools, and some monitoring would be necessary to reach the desired result (see Wadley 2005). My experiments imply that 5 kg firewood is sufficient for cooking and that this fuel mass would provide temperatures suitable for cooking for several hours.

The temperatures in these experiments also have implications for the understanding of the heat treatment methods of silcrete mentioned above. The first method implied slow heat treatment underground to a maximum temperature of 350°C

(Brown *et al.* 2009; Brown 2011). The large fires, i.e. E7, E8, E9 and E10, were closest to this subsurface temperature threshold (Table 1) and all the small fires produced maximum subsurface temperatures more than 100°C below this threshold. This means that a casual, little maintained fire, such as the small fires of these experiments, would not be suitable for heat treatment. Heat treatment using this method requires collection of at least 15 kg firewood, maintaining the fire by adding logs, and paying attention to the development of the surface temperatures. The second heat treatment method implied faster heating on the surface to an ideal temperature of 400–500°C for 50 minutes (Schmidt *et al.* 2013; see also Schmidt *et al.* 2012). All of the fires in my experiments reached maximum surface temperatures within or above this range. This means that even casual fires maintained with little effort potentially could be used for this method of heat treatment. Nevertheless, as the temperatures of the fires vary, fire users would need some skills such as the ability to monitor and evaluate the heat of the fire to avoid too high temperatures, if this method was to be used. Thus, some effort and management skills are needed to conduct both the suggested methods of heat treating silcrete.

My experiments bring up questions that can be examined in future experiments. For example, only one wood taxon was used in these experiments, although charcoal analyses have identified many plant taxa burnt in MSA fires (e.g. Cartwright & Parkington 1997; Allott 2005, 2006). The burning properties of these taxa could be tested in fire experiments. One might also test the predictability of fires burning more than one taxon and fires burning both bone and selected plant taxa. Maintenance of the fire is another area that could be further explored experimentally. Such experiments might explore using larger logs, combinations of branches and logs, moving logs in the fire, and other techniques that may affect the temperatures of a fire. A last example is examining how a fire is affected when used for different activities.

CONCLUSION

In conclusion, some effort such as planning and gathering sufficient fuel, maintenance skills, and attention during the process would be needed in order to control the temperatures of fires and achieve the desired results for some activities using fire in the MSA. Even when controlling many of the variables affecting a fire, such as wood taxon, fuel mass, and topsoil horizon, the heat of a fire is generally difficult to predict and a fire can produce a wide range of temperatures with varying duration. Furthermore, the subsurface temperatures, although generally following the development of the surface temperatures, seem to be more predictable than the surface temperatures. Adding logs to the fire is one way of maintaining it and ensuring more even temperatures for some duration, yet it seems that other techniques must also be used to control the temperatures of a fire.

Laboratory studies are excellent starting points for understanding the possibilities and limitations of an archaeological material. Nevertheless, a more comprehensive understanding of pyrotechnology in the MSA relies on actualistic studies of fire that replicate the situation people would have been facing. The rate of heating in a fireplace, for example, is quite different from the situation that can be replicated in a modern furnace, and this should be taken into account when discussing fire-related behaviour in the MSA. Furthermore, the experiments described in this paper included controlling many variables that might not have been as easy to control during the MSA. For example, MSA fires might have contained several wood and plant taxa as well as bone. This might have affected

the temperatures of the fire; consequently even more effort than indicated in my experiments would have been needed to control the heat of a fire. The people living in the MSA must have been skilled fire users to have achieved the desired result.

ACKNOWLEDGEMENTS

Many thanks to my supervisor, Lyn Wadley, for her patience and numerous comments and feedback on earlier versions of this paper. My PhD has been supported by grants from the Palaeontological Scientific Trust (PAST) and its 'Scatterlings of Africa' programme. I would also like to thank Christine Sievers for many interesting discussions on fire experiments and Helen Kempson and others that have given me feedback on previous versions of this paper. Many thanks also to Marlize Lombard and Andrew Kandel for their valuable and constructive feedback on this paper and Jamie Clark for helping me with the final corrections. Any errors and oversights in this paper are fully my own and do not necessarily represent the views of others.

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6 USING THE FIRE - MORE EXPERIMENTAL RESULTS

The previous chapter presented and discussed some results from experiments E1 – E10 on the predictability of temperatures in a fire in primary fires. As mentioned in Chapter 4, a 'primary fire' is a fire made directly on top of the topsoil horizon. Experiments E1 - E10 also consisted of secondary fires, made on top of the ashes from one previous fire, and tertiary fires, made on top of the ashes from two previous fires. I include primary, secondary and tertiary fires from all my experiments in this chapter, which means that I include both the first and second cycle of experiments. I used GNU PSPP Software Release 0.7.10-g29c145 for the statistical analyses in this chapter. Topsoil horizons in the experiments were classified according to grain size (see Table 4.2) and as described in Chapter 4; ash ($n = 14$), fine/medium sand ($n = 14$), fine sand ($n = 3$) and coarse sand ($n = 3$).

6.1 USING AND CONTROLLING THE FIRE

Cooking, drying adhesives and heat treatment of silcrete have already been mentioned as activities using fire in the MSA (see Chapters 2 and 5), and I will not repeat the descriptions of these activities here. I will not include new activities in this chapter, although I will comment on the potential post-depositional effects of new fires on top of sediments containing previously deposited objects. As stated in Section 4.2, one of the questions I wish to examine is the effort involved in controlling the temperatures of the fires. In this chapter I will specifically look at the factors that affect:

- a) the maximum surface temperature of the fires, because the heat of the fire can be important for some activities;
 - b) the time it took to reach maximum surface temperature, which suggests the preparation time needed before high temperatures could be used in an activity;
- and

- c) the average temperature during the first hour of temperatures $>100^{\circ}\text{C}$, which suggests the heat that can be generated fast for use in activities.

The other research question on fire use in section 4.2 refers to the differences in the predictability of the surface and subsurface temperatures of the same fire. Research on the heat treatment of silcrete has, as mentioned in Chapter 5, suggested the use of below surface roasting in the MSA (e.g., Brown et al. 2009), although other studies have questioned the need to use this method for heat treatment (Schmidt et al., 2013). I wish to stress that I did not test the heating of silcrete or other rock types, or other activities using the subsurface temperatures, I only focused on the above and below ground temperatures produced by a fire. I will discuss these data later, but only the subsurface temperatures at 5 cm because I only have data on the subsurface temperatures at 7 cm from 6 fires.

6.2 THE SURFACE TEMPERATURES

In this section, I will use the results from my fire experiments in a discussion of the variables that can affect the maximum surface temperature of a fire, the time taken to reach maximum surface temperature and the average temperature during the first hour of temperatures $> 100^{\circ}\text{C}$.

6.2.1 MAXIMUM SURFACE TEMPERATURE

We have seen in Chapter 5 that the temperatures of different fires can vary greatly even if the same wood taxon is used for all the fires. Chapter 5 only included fires burning *Dichrostachys cinerea* wood, which was used in most of my experiments, but data from my other experiments also suggest that maximum surface temperature can vary greatly in different fires burning the same taxon. For example, similar weights of *Casuarina equisetifolia* wood was burned on similar topsoil horizons in the secondary fires F2.2

and F9.2, producing maximum surface temperatures of 484°C and 645°C, respectively (Table 4.2 and Figure 6.1). Nevertheless, F10.2 was started at the same time and place and with the same wood taxon from the same supplier as F9.2, and F10.2 produced a similar maximum surface temperature (709°C) to F9.2 (Table 4.2 and Figure 6.1). Thus, I cannot rule out the possibility that factors such as the weather and the storage conditions of the wood supplier (e.g., moisture) contributed to the differences between F2.2 and F9.2 and, consequently, that the maximum surface temperatures of fires burning *Casuarina equisetifolia* under similar circumstances are more predictable than the maximum surface temperatures of fires burning *Dichrostachys cinerea*.

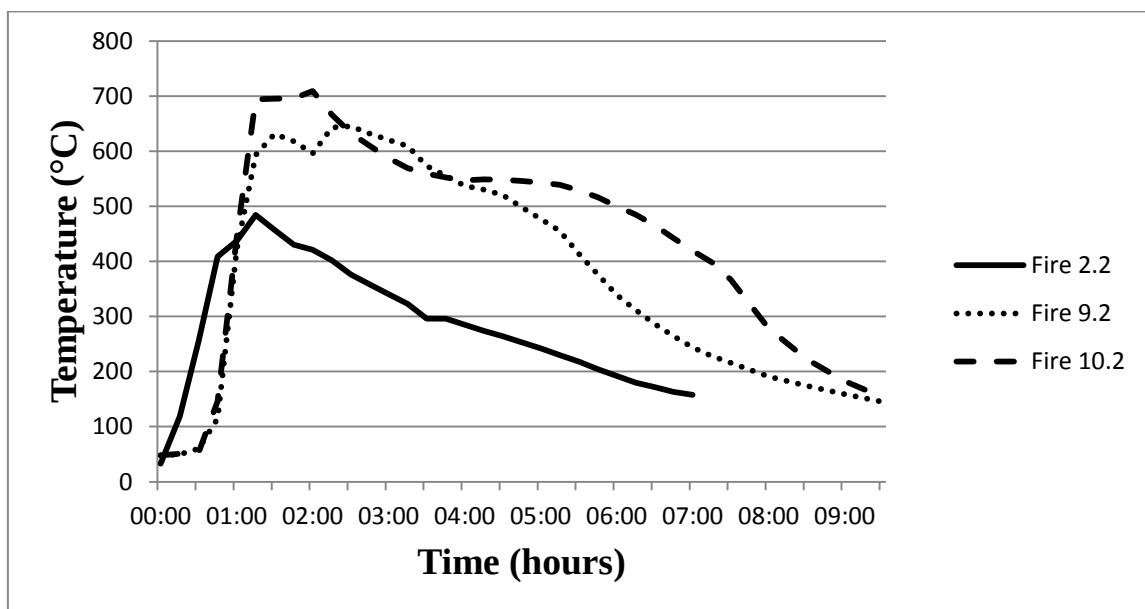


Figure 6.1 Surface temperatures of fires F2.2, F9.2 and F10.2.

The combustible properties of different wood taxa can vary because of their chemical composition and density (e.g., Ragland et al., 1991; Théry-Parisot et al., 2010). A scatterplot of the wood taxa and the maximum surface temperature produced (Figure 6.2) shows that the number of fires burning a wood taxon may account for the temperature range produced because wood taxa burned in many fires produced a larger variation in maximum surface temperature than wood taxa used for few fires. Some researchers (e.g., Théry-Parisot & Henry, 2012; Théry-Parisot et al., 2010) have

suggested that the firewood taxon might be the least important factor affecting a fire, although the differences between the two cycles of experiments I conducted (e.g., different topsoil horizons) and the sample size makes it difficult to draw conclusions on the effect of wood taxon from my experiments.

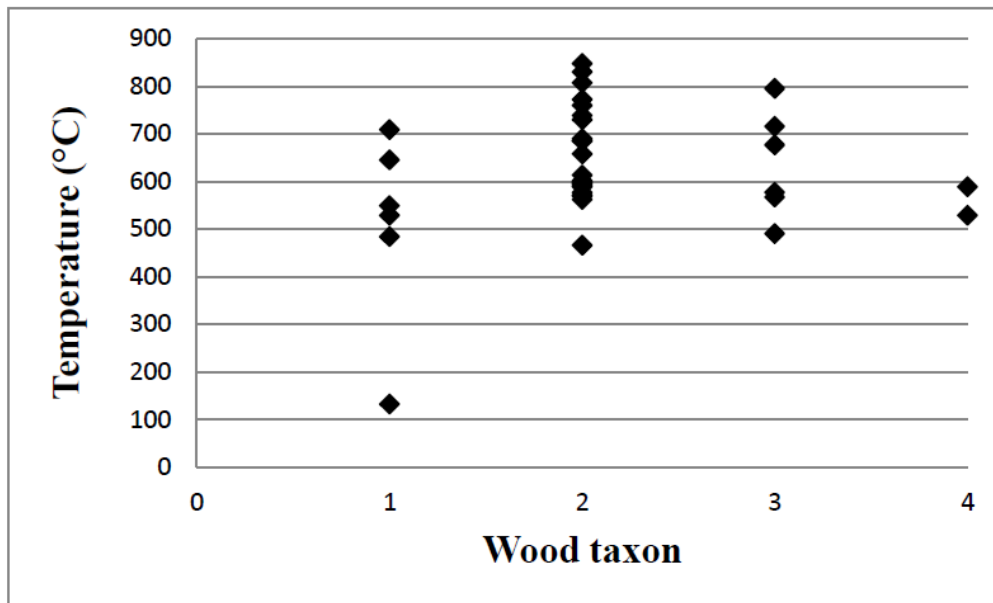


Figure 6.2 Scatterplot of maximum surface temperatures per wood taxon. X-axis: 1 = *Casuarina equisetifolia*, 2 = *Dichrostachys cinerea*, 3 = *Eucalyptus globulus* and 4 = *Acacia erioloba*.

Before I conducted my experiments, I expected that larger masses of fuel would produce higher maximum surface temperatures than smaller masses of fuel. However, as seen in Chapter 5, a small fire burning 5 kg wood can produce higher temperatures than a large fire starting with 5 kg of wood and where 10 kg wood was added at regular intervals to the fire. Figure 6.3 shows the relationship between wood mass and maximum surface temperature in the fires. Adding bone to the initial fuel load, as in F4, resulted in a slightly lower maximum surface temperature for the primary fire F4.1 (490°C) than for F7 (577°C) and F8 (677°C), all fires burning *Eucalyptus globulus* wood (Table 4.2). The experiments of Théry-Parisot (e.g., 2001, 2002) demonstrate that burning bone may affect the properties of a fire, including the method of heat transfer.

The maximum surface temperature of F4.1 is consistent with the results from Chapter 5; a larger fuel load does not automatically produce higher surface temperatures. The statistical analysis also implies that there is no relationship between the wood mass and the maximum surface temperatures, but the result is not statistically significant ($r = -.01$, $p = .97$).



Figure 6.3 Scatterplot showing the relationship between maximum surface temperature and wood mass.

Previous studies have mentioned size of the burning material as a contributing factor for the combustion of wood (see e.g., Nurmi, 1992; Ragland et al., 1991). Figure 6.4 contains a scatterplot of the relationship between the maximum surface temperature and the number of logs in the fires, but I also conducted further statistical analyses. When I include all the fires from all the experiments I conducted in the analysis, there is a significant moderate correlation between the number of logs in a fire and the maximum surface temperature of the fire ($r = -.32$, $p = .05$); fewer logs appear to produce higher temperatures than more logs. If I exclude the fires in experiments F4 and F5 (burning wood and bone) as well as the fires of experiments E7, E8, E9 and E10 and only include the fires burning approximately 5 kg wood, the correlation between the number of logs and maximum surface temperature is stronger and more significant ($r = -.44$, $p = .02$).

Thus, it appears that a few large logs are more appropriate than many small logs with the same total weight if high maximum surface temperature is required.

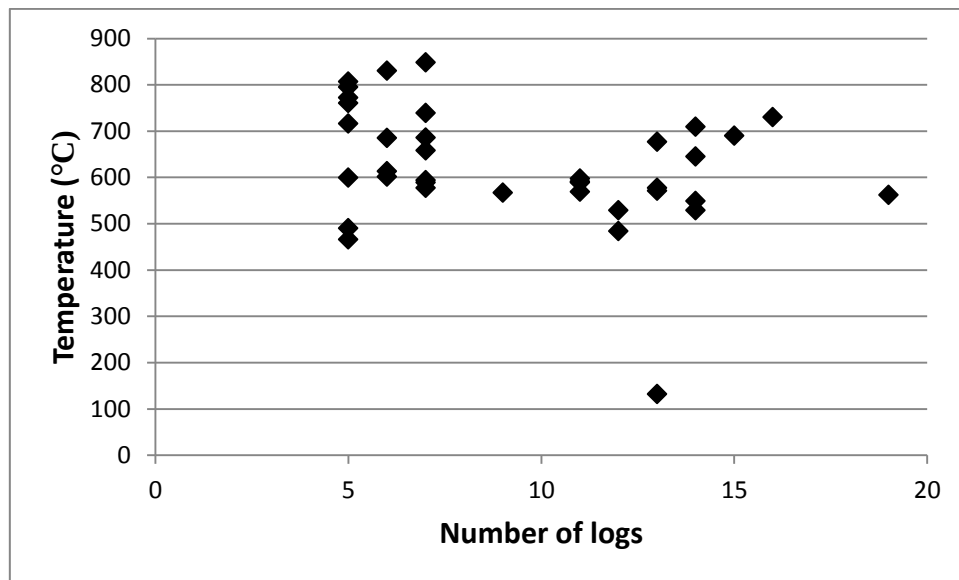


Figure 6.4 Scatterplot showing the relationship between maximum surface temperature and the number of logs in a fire.

The texture of the topsoil horizon is another factor that can affect the combustion of wood, although soil texture might only have a minor effect on the thermal conductivity of soils (e.g., Campbell et al., 1994; Canti & Linford, 2000). A topsoil horizon of ash seems to affect the heat of the fires in all my experiments because the average maximum surface temperature is higher for tertiary fires (699.33°C) than for secondary fires (666.42°C) and primary fires (557.79°C). Figure 6.5 contains a scatterplot of maximum surface temperature and type of fire (primary, secondary, tertiary or large). If I only include the second cycle of experiments, the average maximum surface temperature for primary fires is 622.5°C, secondary fires 714.17°C and tertiary fires 701°C. Statistically, there is a significant relationship ($r_s = .48, p = .01$) between the type of fire (primary, secondary or tertiary) and the maximum average temperature when I include all my experiments, but the relationship is not statistically significant ($r = .32, p > .05$) if I only include fires from the second cycle of experiments. The first cycle of experiments contains more wood taxa than the second, which could mean that

different volumes of ash were produced (see Chapters 7 and 8) and, consequently, that wood taxa contributed to the differences in surface temperatures in secondary and tertiary fires. Nevertheless, it appears that ash as topsoil horizon may have only a small effect on the temperatures of a fire, but this should be examined further.

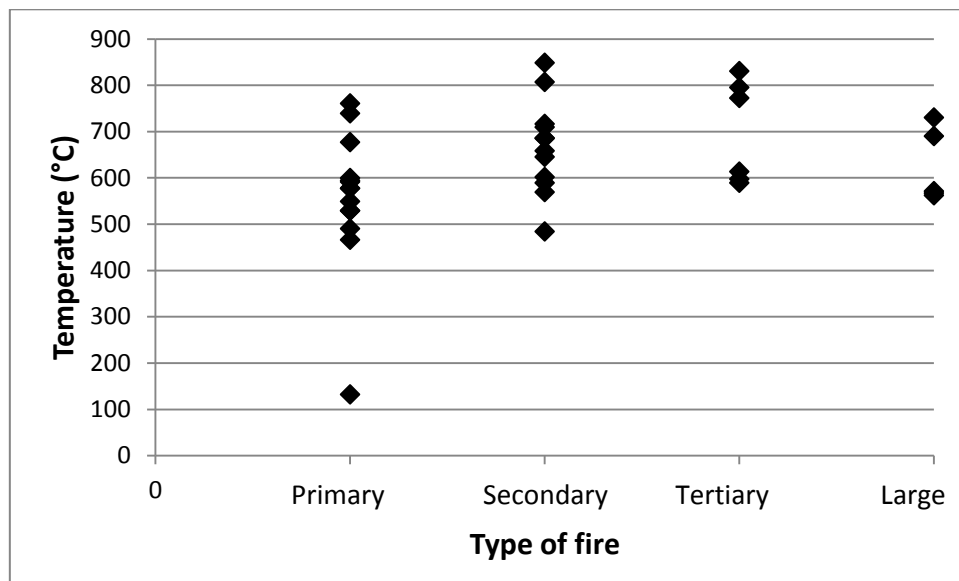


Figure 6.5 Scatterplot showing the relationship between maximum surface temperature and the type of fire.

The statistical analysis also suggests a significant moderate to low relationship between all the different types of topsoil horizon used here (ash, fine sand, fine/medium sand and coarse sand) and the maximum surface temperatures of a fire when I include all the fires from all my experiments in the analysis ($r_s = -.34$, $p > .01$). However, removing all the 18 fires that were started on top of ash from previous fires and only including the remaining primary fires in the analysis gives a result that suggests no relationship between the texture of the topsoil horizon and the maximum surface temperatures ($r_s = -.23$, $p > .05$), although the result is not statistically significant. The scatterplot of types of topsoil horizons and maximum surface temperatures (Figure 6.6) shows that the maximum temperatures of fires on fine/medium sand and ash span a larger range than the maximum surface temperatures of fires on fine sand and coarse sand, and it is possible that sample size is influencing the results here.

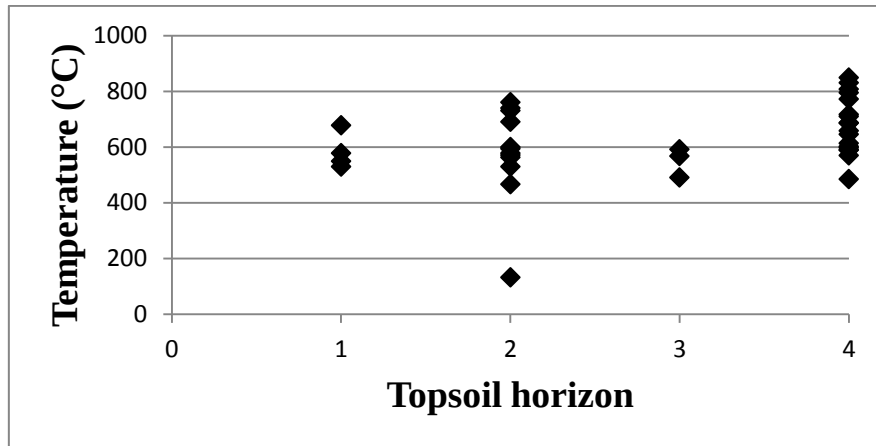


Figure 6.6 Scatterplot of maximum surface temperatures and types of topsoil horizon. X-axis: 1 = Fine sand, 2 = Fine/medium sand, 3 = Coarse sand and 4 = ash.

6.2.2 THE TIME TAKEN TO REACH MAXIMUM SURFACE TEMPERATURE

The primary fires in experiments E1 – E6, all burning 5 kg of the same wood taxon on the same topsoil horizon, took from 2 hours 15 minutes (E3.1) to 5 hours (E4.1) to produce maximum surface temperature (see Figures 5.2, 5.3 and 5.4). In fact, the fires that took the longest and the shortest time to produce maximum surface temperature were conducted at the same time and under the same environmental conditions. The fires E7 – E10, all burning 15 kg of the same wood taxon on the same type of topsoil horizon, also demonstrate a variation in the time taken to produce maximum surface temperature; from 2 hours 15 minutes (E8) to 5 hours (E7) (see Figures 5.5 and 5.6). If I include all the fires from all the experiments, there is an even greater variation in time taken to produce maximum surface temperature; from 15 minutes in F2.1 and 1 hour in F8 to 14 hours 35 minutes in F3.1. Furthermore, there is no strong relationship between wood taxon, wood mass, the number of logs, the texture of the topsoil horizon or the maximum surface temperature on the one hand and the time taken to reach maximum surface temperature on the other, which suggests that it is hard to predict when the fire will reach its maximum surface temperature even when controlling these variables. Nevertheless, all the fires in my experiments were started by the same person using the same basic techniques, and I cannot rule out the possibility that other techniques for

starting the fires would have aided the predictability of the time from the fire started to the maximum surface temperature was reached.

Table 6.1 Average surface temperatures during the first hour of temperatures > 100°C.

Fire	Av. surface temperature during the 1st hour of temp. > 100°C	Fire	Av. surface temperature during the 1st hour of temp. > 100°C
F2.1	80.25	E1.1	99.50
F2.2	305.25	E1.2	410.00
F3.1	423.50	E1.3	353.67
F3.2	310.75	E2.1	355.50
F3.3	438.25	E2.2	444.25
F4.1	143.50	E2.3	239.75
F4.2	524.25	E3.1	317.50
F4.3	519.25	E3.2	342.00
F5	192.25	E3.3	477.00
F6.1	339.00	E4.1	202.25
F6.2	421.50	E4.2	151.00
F7	435.75	E4.3	306.50
F8	572.25	E5.1	220.75
F9.1	352.00	E5.2	403.25
F9.2	440.25	E6.1	169.75
F10.1	437.25	E6.2	744.50
F10.2	495.00	E7	318.75
		E8	379.50
		E9	219.00
		E10	241.75

6.2.3 THE AVERAGE TEMPERATURE DURING THE FIRST HOUR OF TEMPERATURES > 100°C

Fires F2.1 (80.25°C) and E1.1 (99.5°C) produced the lowest average temperature during the first hour of temperatures > 100°C (Table 6.1). Fire 2.1 may be an outlier because the probe was at the side of the fire and E1.1 may be an outlier due to difficulties starting the fire. If we eliminate these outliers, the average temperature during the first hour of temperatures > 100°C for the remaining fires in all experiments ranged from 143.5°C (F4.1) to 744.5°C (E6.2) (Table 6.1). There seems to be a significant strong correlation between the texture of the topsoil horizon and the average temperature during the first hour of temperatures > 100°C ($r_s = -.49, p < .01$) if I include all the fires from all my experiments, but the result is not statistically significant if I only include the primary fires from all my experiments ($r_s = -.43, p > .05$).

We have seen above that there appears to be a relationship between the number of logs and the maximum surface temperature of a fire. When analysing the number of logs used for the fire and the average temperature during the first hour of temperatures > 100°C, the result is not statistically significant, but suggests no relationship between the variables ($r = .05, p = .75$). Furthermore, variables such as wood taxon, wood mass and the time taken to reach maximum surface temperature do not seem to have a strong relationship with the average temperature during the first hour of temperatures > 100°C. However, there is a statistically significant strong relationship between the maximum surface temperature of a fire and the average temperature during the first hour of temperatures > 100°C ($r = .55, p = .00$). Perhaps a fire that reaches high temperatures shortly after being started results in a high maximum surface temperature; however, this relationship should be investigated further.

6.3 THE SUBSURFACE TEMPERATURES

Maximum subsurface temperatures 5 cm below the fires from 178°C (E6.1) to 415°C (F10.1) were recorded in my experiments (Table 4.2 and Figure 6.7). Because ash was

left in the hearth before starting the secondary and tertiary fires and the subsurface probe not moved between primary, secondary and tertiary fires, the ash was expected to affect the heat penetration (see e.g., Canti & Linford, 2000) and the primary fires were expected to produce the highest subsurface temperatures. Nevertheless, the subsurface temperatures for primary fires were lower than for one or two of the subsequent fires in all the experiments that included multiple fires (see Table 4.2). The relationship between the subsurface temperatures and the type of fire (primary, secondary or tertiary) was neither strong enough to be meaningful or statistically significant ($r_s = .19$, $p > .05$), suggesting that the ash did not affect the subsurface temperatures of the fires. This result does not support Canti and Linford (2000, p. 393), who suggest that fires can produce an insulating layer of ash and affect subsurface temperatures. Perhaps my result is different because I only made short fires, whereas some of the fires in the experiments conducted by Canti and Linford (2000) were quite large and lasted for up to 4 days. Furthermore, there does not appear to be a strong correlation between the texture of the topsoil horizon and the subsurface temperatures ($r = .05$, $p > .05$) when including all types of topsoil horizon and all fires from all my experiments. This result is consistent with the result for the surface temperatures, as discussed above.

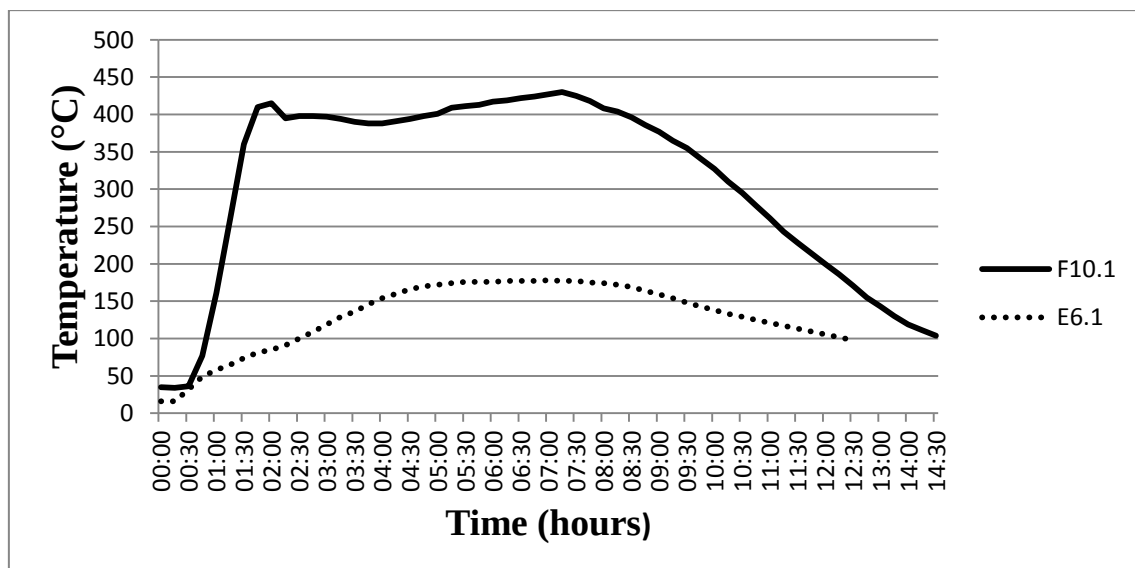


Figure 6.7 Examples of subsurface temperatures: F10.1 and E6.1

The large fires in my experiments were expected to produce higher subsurface temperatures than the fires burning ca. 5 kg wood. If we include only the primary fires burning ca. 5 kg wood and the larger fires burning 15 kg wood, the average maximum subsurface temperature in large fires was 338.75°C and in primary fires 246.33°C, which supports my expectations. The correlation between maximum subsurface temperatures and wood mass is strong, but not statistically significant ($r = .46$, $p = .06$) if we include only large and primary fires from all experiments. Including all fires that burn wood in the statistical analysis of maximum subsurface temperatures and wood mass returns a significant and strong correlation ($r = .47$, $p = .01$) between these two variables. However, the mean maximum subsurface temperature of all fires burning 5 kg wood is 259.1°C, and it appears that the higher temperatures of secondary and primary fires affects the relationship between maximum subsurface temperatures and wood mass positively.

We have seen above that the number of logs can affect maximum surface temperature, and the number of logs appears to also have a strong positive relationship with the maximum subsurface temperatures ($r = .54$, $p = .00$). Yet the maximum surface temperature do not have a statistically significant or strong correlation to maximum subsurface temperatures ($r = .11$, $p = .53$) if we include all the fires from all my experiments. If omitting the secondary and tertiary fires, there is still no strong and statistically significant relationship between maximum surface temperature and maximum subsurface temperatures ($r = .24$, $p = .35$). It is counterintuitive that maximum subsurface temperatures are not related to maximum surface temperature, although both these variables appear to be correlated with the number of logs used in the fire. We have also seen in Chapter 5 that when omitting the first cycle of experiments, the subsurface temperatures appear to follow the general development of the surface temperatures of fires. This issue should clearly be examined more thoroughly in future experiments.

My experimental fires produced subsurface temperatures that could affect objects buried under the fire. Sievers and Wadley (2008) report, for example, that temperatures of 152 °C maintained for long periods can carbonise seeds buried directly under a fire, and Wadley (2005a) report that subsurface temperatures down to 250 °C can transform the colour of ochre (from yellow to red hues). Most of my experiments reached even higher subsurface temperatures (see Table 4.2). Furthermore, Asmussen (2009) shows that post-depositional heat can alter bones and overprint the signals of burning or alterations caused by heat at the time of deposition. The potential post-depositional effects of new fires are thus important to keep in mind at a site such as Sibudu, with repeated occupation involving new fires.

6.4 SUMMARY AND IMPLICATIONS

In this chapter, I have expanded some of the conclusions from Chapter 5 and introduced some new aspects about fire use by combining information from all my experiments and conducting statistical analysis of the data. The results with implications for the effort involved in using fire can be summarised as follows:

- 1) Selecting one wood taxon for firewood does not make it easy to predict maximum surface temperature of the fire because the same wood taxon can produce a wide range of surface temperatures.
- 2) Using a large fuel load may not produce higher maximum surface temperatures than a small one.
- 3) Selecting few, large logs can give a fire with higher maximum surface temperature than selecting many, small logs if the total fuel load is the same for both fires.
- 4) Cleaning ashes from a hearth before starting a new fire can affect the maximum temperature of the hearth because the maximum surface temperature is higher for tertiary fires than for primary and secondary fires. However, the texture of

the topsoil horizon appears to have little effect on the maximum surface temperature of a fire.

- 5) The time taken for a fire to produce maximum surface temperature is difficult to predict and it appears that controlling the type of topsoil horizon, wood mass, wood taxon and the number of logs in the fire will not have an effect on the time taken to produce maximum surface temperature.
- 6) Controlling the number of logs used in a fire, wood taxon and wood mass may not aid the predictability of temperatures produced during the first hour of fire temperatures $>100^{\circ}\text{C}$.
- 7) Controlling the number of logs and possibly the wood mass can help predict the maximum subsurface temperatures. There is no strong relationship between the maximum temperatures at the surface and the subsurface.

Based on these observations, it appears that it is difficult to predict and use a fire. Nevertheless, all the fires in my experiments produced temperatures that could be used for cooking (Wandsnider, 1997; see also Chapter 5) for several hours. Furthermore, more than 5 kg firewood appears necessary for heat treatment as described by Brown and colleagues (2009; see also Chapter 5).

6.5 CONCLUDING REMARKS

The fires in my experiments were not used for activities, for example cooking, because this would introduce yet another variable to the experiments. Yet the people that occupied Sibudu during the MSA would conduct several activities next to the fire and activities using fire, which can be implied, for example, from the production of stone tools at Sibudu (see e.g., Wadley, 2005b; Wadley & Jacobs, 2006) and from the burned bones at the site (see e.g., Cain, 2005; Clark & Ligouis, 2010). Charcoal analyses also suggest that several plant taxa were burned in each fire (e.g., Allott, 2005, 2006; see also Chapter 9), and my experiments (burning a single wood taxon in each fire) cannot rule out the possibility that burning different plants, including several wood taxa, in one

fire, can affect the temperatures of the fire. The people using fire at Sibudu during the MSA thus had to work with and control more variables than the ones in my experiments if specific temperatures were desired. It is possible that maintenance techniques suggested in my experiments, such as adding logs to the fire, are even more important when there are more variables to control in a fire. The use of fire in different activities and the effect of different maintenance techniques form possible topics for future experiments. In the following chapters, however, I shall focus on the formation of combustion features and their archaeological implications.

7 HEARTH AREA, FUEL LOAD AND THE FORMATION OF COMBUSTION FEATURES

I present a paper on experimental fires and archaeological site formation processes in this chapter. The paper was published in *Quaternary International* (2012), volume 270, pages 95 – 102. There is, however, an error in the last column in Table 2: F6 was conducted on top of Sibudu sievings (see Table 4.2).

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journal homepage: www.elsevier.com/locate/quaint

Size matters: Preliminary results from an experimental approach to interpret Middle Stone Age hearths

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ARTICLE INFO

Article history:
Available online 10 September 2011

ABSTRACT

This paper reports on ten fire experiments and their significance for interpreting hearths from the Middle Stone Age site, Sibudu, KwaZulu-Natal, South Africa. The experiments were conducted on four different substrata and four wood taxa were used in the experiments. Four of the experiments consisted of a single fire, while the other experiments consisted of multiple fires on top of each other. The experimental fires produced hearth areas of ~ 962.1 – ~ 1661.9 cm² and hearth depths of 3–12 cm. Hearth size and depth do not correlate. Hearth area seems to correlate with the fuel load used in a hearth, and it is argued that this can be used in interpretations of fire use at an archaeological site. Nine hearths from the same layer at Sibudu are used as examples, and it is argued that variation in hearth area indicates variation in hearth use. Some hearths at Sibudu were possibly only used once, whereas others represent long-term use and/or repeated reloading of the same hearth.

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1. Introduction

This paper reports on experimental fires and their significance for interpreting hearths from the Middle Stone Age (MSA) site Sibudu in KwaZulu-Natal Province, South Africa (Fig. 1). Various fire-related features have been excavated at Sibudu (e.g. Wadley and Jacobs, 2006; Wadley, 2006, 2010, in press; Goldberg et al., 2009), and these display a range of attributes. Experimental fires were conducted to investigate the possibility that some of their attributes could be used to explain archaeologically recovered hearths. One of the hypotheses for testing was that the fuel load in a hearth affects its size and depth. Characteristics of experimental hearths such as area and depth of experimental hearths were therefore recorded in the study. Selected hearths from a single layer from Sibudu were then compared to the experimental hearths.

2. Hearths and fire-related features

The use of fire can result in various features at an archaeological site. Combustion features, such as hearths or special purpose fires, are created through burning events in the area where the fire was lit. Other fire-related features, such as ash dumps, are created through cleaning events. During such events, ash and other waste materials are removed from the combustion features and deposited

in isolated dumps and/or areas with multiple dumps. Fire can be used for several activities. Mallol et al. (2007) report, for example, that the Hadza of Tanzania can have special household fires for cooking, as well as fires inside the huts to keep warm while sleeping and fires to cook tubers or meat away from the camp. Features such as special purpose fires and ash dumps can be difficult to define by field observation alone, but have been distinguished through micromorphological studies (e.g. Courty et al., 1989; Schiegl et al., 2003; Goldberg et al., 2009). Clear definitions of such features are important to distinguish between the different types, interpret fire-related behavior and compare and discuss features from different sites. This study only reports on hearths, but the results can be used in later comparisons of hearths and other fire-related features.

Definitions and characteristics of recovered artifacts and features are an important part of archaeological research. There is, however, no clear archaeological definition of hearths, and this is possibly related to the variability in hearths that can be observed in contemporary contexts all over the world (Alpers-Afil and Goren-Inbar, 2010, p. 21). The definition of a hearth through field observation is also not straightforward. Well-preserved hearths usually have an upper light-colored ash layer, a charcoal-rich and dark middle layer, and a rubefied base (e.g. Schiegl et al., 1996), but experimental studies have shown that significant reddening may not occur at the base of hearths in all types of substrata (Canti and Linford, 2000). It can be difficult to associate observed burning with clear hearths, and it is in some contexts more appropriate to discuss

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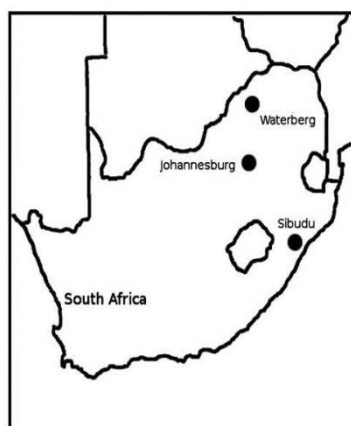


Fig. 1. Map of South Africa, showing the location of Sibudu, Johannesburg and Waterberg.

"burnt layers" rather than "hearths" (Courty et al., 1989, p. 110). Multiple phases of use can, moreover, result in stratigraphy where the different phases cannot be seen with the naked eye (e.g. Rigaud et al., 1995), and in some contexts observable characteristics like charcoal, ash and discoloration of sediments cannot be observed at all. In such cases, the term "phantom hearths" has been suggested, with the recognition of hearths being based on spatial clustering of burned material (Alpersen-Afil et al., 2007; Alpersen-Afil and Goren-Inbar, 2010). Fortunately this is not a problem at Sibudu, where fire-related features are clearly discernible.

A hearth, as understood in this study, is the result of intentional burning. Accidental burning and fires caused by natural agents, such as lightning strikes, can occur at archaeological sites, but will leave different archaeological signatures than intentional burning events. For example, intentional burning events tend to be more contained than grass fires and other naturally caused burning events, and a campfire can leave a distinctive basin or lens shape in cross-section profile (e.g. Bellomo and Harris, 1990; Bellomo, 1993;

Schiegl et al., 1996; Mallol et al., 2007). Moreover, the hearth is the result of deliberate burning at a specific place. Whereas stone linings and other structural elements have been reported for some periods and regions (e.g. Leroi-Gourhan and Brézillion, 1972; Karkanas et al., 2004), reported hearths from MSA sites are generally described as irregular or circular ash patches, without stone linings, and sometimes with convex bases (e.g. Butzer et al., 1978, p. 327; Opperman and Heydenrych, 1990; Henderson, 1992; Deacon, 1995; Marean et al., 2000, 2010; Henshilwood et al., 2001; Klein et al., 2004; Wadley and Jacobs, 2006; Wadley, 2006, 2010, in press). The size and depth of these hearths vary, and these are the attributes to be examined in this study.

3. Sibudu

The earliest MSA occupation at Sibudu was dated to about 77 ka, while the most recent MSA occupation is dated to 38.6 ± 1.9 ka (Jacobs et al., 2008a, 2008b). The site consists of multiple MSA layers and lenses, and many of these consist of ashes and/or are related to the use of fire (e.g. Wadley and Jacobs, 2006; Wadley, 2006, 2010, in press; Goldberg et al., 2009). The layers and lenses themselves can be a centimeter or less thick, but the Wadley excavations at Sibudu reached about 3 m depth in 6 m². Standard excavation techniques were followed when excavating the site (Wadley and Jacobs, 2006) and a short description is given here so that the names of selected features are clear to the reader (see also Fig. 2).

Sibudu was divided into meter squares, that were named with a capital letter running from north to south (e.g. A, B, C etc.) and numbers running from east to west (e.g. 1, 2, 3 etc.). Consequently, square A1 is east of square A2, and square B2 is south of square A2. The squares were excavated in 50 × 50 cm quadrants. Quadrants were named using lower-case letters, so that "a" refers to the north-eastern quadrant of a square, "b" to the south-eastern quadrant, "c" to the north-western quadrant and "d" to the south-western quadrant. Thus, A2c signifies the quadrant bordering on B2a. The site was excavated by stratigraphical layers, and these layers were generally named by color determined by using the Munsell Color chart. Layer Pinkish Gray Sand (PGS), for example, refers to a pinkish gray layer. Hearths were excavated within the quadrants by hearth strata, and named by stratigraphic layer and a number (e.g. H1, H2) (Wadley and Jacobs, 2006; Wadley, in press).

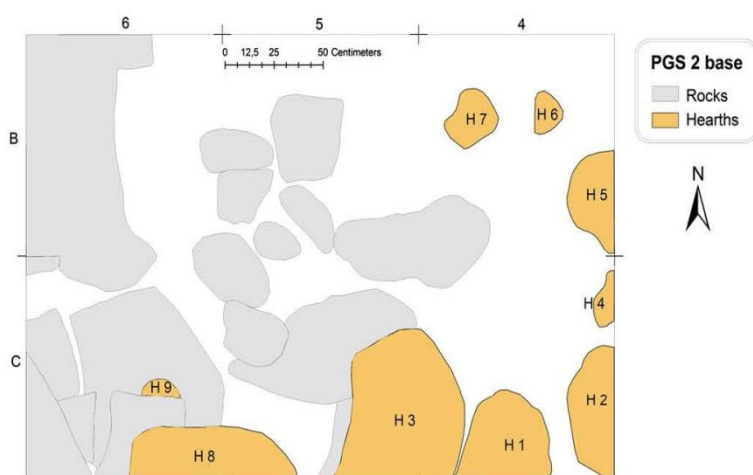


Fig. 2. Map of layer PGS2 base, Sibudu. Site plan drawing by Lyn Wadley and GIS representation by Silje Evjen Bentsen.

The numerous excavated hearths at Sibudu are generally circular or sub-circular features of different sizes. Some have a diameter of less than 50 cm, while others are up to 2 m across. There are features with concave bases, but also features with more or less flat bases. A few hearths have been placed on flat rocks that could have fallen from the shelter roof, but most hearths have no foundation and are laid directly on the sediment (Wadley and Jacobs, 2006; Wadley, 2006, 2010, in press). Nine hearths, H1, H2, H3, H4, H5, H6, H7, H8, and H9, from layer PGS2 serve here as examples of the hearths that have been excavated at Sibudu (Table 1; Fig. 2). All these hearths have an irregular or slightly sub-circular shape, and their approximate areas have thus been calculated as if they were rectangular. Layer PGS2 belongs within the Howiesons Poort Industry and has an age of approximately 64.7 ± 1.9 ka (Jacobs et al., 2008b). H6 and H7 are small discrete features found in square B4, and H9 (square C6) is also a small hearth, situated next to a rock and possibly partly under it. The other hearths in PGS2 extended outside of the excavation grid, so their original size has been estimated as double that of their excavated area. H4 in PGS2 is quite small, while the rest of the hearths selected are larger than the ones already mentioned.

4. Method

A series of 10 fire experiments was conducted to examine size and depth of the hearths (Table 2). This is part of a larger study of MSA pyrotechnology, with particular emphasis on the variables involved in controlling and using fire as well as the properties of fire-related features. Each fire experiment is labeled with numbers (e.g. F1, F2, F3 etc.). Some experiments consisted of multiple fires on top of each other (Table 2), for example, F2 consisted of two sequential fires. Each fire in each experiment is also numbered, so that F2.1 refers to the first fire of F2 and F2.2 to the second fire of F2. The first fire in each experiment was lit on a cleared topsoil horizon or on a pit filled with Sibudu sediments. Subsequent fires within each experiment were lit on top of the cool ashes from the previous fires in that same experiment. Thus, F2.2 was lit on top of the ashes from F2.1, without removing of previous ashes or other preparation of the hearth surface. Different fuels were used in the experiments (Table 2). Most fires burned wood only, but F4 and F5 also burned fragments of a tibia with the knee attached from a lamb (*Ovis aries aries*) and a femur from a bull (*Bos primigenius*). The bone fragments were put into the fire to examine if this had any bearing on the temperatures of the fires. The single fire of F5 was conducted using three times as much fuel as any of the fires in the other experiments, which all burned a similar weight mass in each fire (Table 2). Wood was always arranged in a tepee-like structure before the fire was lit.

Table 1
Hearths from layer PGS2, Sibudu.

Square	Hearth	Size top hearth surface (cm)	Approximate area of hearth (cm ²)	Estimated original area (cm ²)
C4	H1	39 × 48	1872	3744
C4	H2	24 × 67	1608	3216
C4 & C5	H3	58 × 66	3828	7656
C4	H4	10 × 22	220	440
B4	H5	23 × 45	1035	2070
B4	H6	15 × 19	285	285
B4	H7	26 × 28	728	728
C5 & C6	H8	23 × 85	1955	3910
C6	H9	9 × 19	171	342

Table 2
Experimental fire fuel type, fuel mass and topsoil horizon.

Experiment No.	Fire No.	Fuel load	Fuel type	Topsoil horizon
F1	1	5.1 kg; 13 logs	<i>Casuarina equisetifolia</i>	Fine sand (Ballito)
F2	1	5.3 kg; 13 logs	<i>Casuarina equisetifolia</i>	Fine sand (Ballito)
	2	5.2 kg; 12 logs		
F3	1	4.8 kg; 11 logs	<i>Dichrostachys cinerea subsp. africana</i>	Coarse sand
	2	4.8 kg; 11 logs		
	3	5.0 kg; 11 logs		
F4	1	5.0 kg; 5 logs, 510 g bone	<i>Eucalyptus globulus</i> and bone fragments	Fine sand (Waterberg)
	2	5.0 kg; 5 logs, 500 g bone		
	3	5.1 kg; 5 logs, 510 g bone		
F5	1	14.1 kg; 9 logs 1550 g bone		
F6	1	5.1 kg; 12 logs	<i>Acacia erioloba</i>	Fine sand (Ballito)
	2	5 kg; 11 logs		
F7	1	5 kg; 13 logs	<i>Eucalyptus globulus</i>	Sibudu sievings (fine sand)
F8	1	5 kg; 13 logs		
F9	1	5 kg; 14 logs	<i>Casuarina equisetifolia</i>	Fine sand (Ballito)
	2	5.1 kg; 14 logs		
F10	1	5 kg; 14 logs		Sibudu sievings (fine sand)
	2	5.1 kg; 14 logs		

4.1. Hypotheses

These experiments test the following hypotheses and expectations:

- Fuel load affects hearth size and depth.* A large load of fuel should create a larger and deeper hearth than a smaller fuel load.
- Hearths produced by multiple fires will be deeper and larger than hearths produced by single fires.* This is linked to the first hypothesis, as hearths with multiple fires would normally have a larger fuel load than hearths from single fires. The relationship between hearth size and fuel load is important because it might help to interpret fire use and whether the hearth was used for a long or short period. Trampling could alter the original size and shape of a hearth (e.g. Miller et al., 2010), but trampling experiments were not performed here. Consequently, these experiments approximate hearths that were left *in situ*. Trampling is an issue that could be explored in future experiments.

Table 3
Experimental fire measurements: Hearths diameter, surface area and depth.

Experiment no.	Diameter (cm)	Approximate surface area (cm ²)	Total depth hearth (cm)	Depth ashes (cm)
F1	42.0	1385.4	ca. 5.0	ca. 1.0
F2	41.0	1320.3	7.0	2.5
F3	46.0	1661.9	9.0	2.5
F4	46.0	1661.9	3.0	>0.25
F5	45.0	1590.4	5.0	>0.25
F6	38.0	1134.1	12.0	5.0
F7	37.0	1075.2	5.0	1.0
F8	37.0	1075.2	4.0	0.5
F9	37.0	1075.2	5.0	1.5
F10	35.0	962.1	6.0	1.5

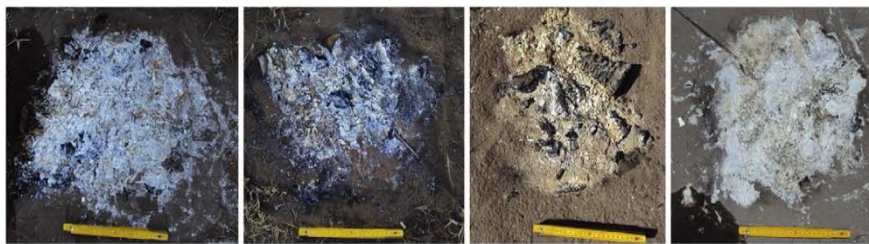


Fig. 3. Top of experimental hearths. From left to right: F6, F7, F8 and F10.

c) Fires of long duration will be deeper than fires of short duration. This hypothesis links to the previous ones, because a fire with a large fuel load would be expected to burn longer, producing more ash and charcoal.

4.2. Preparation of topsoil horizon to create bases for hearths

Experiments F1, F2, F6, F7, F8, F9 and F10 were conducted at the same place in Ballito, near Sibudu, KwaZulu-Natal Province (Fig. 1), though not all at the same time. Experiments F1, F2, F7 and F9 were lit on the local topsoil horizon of fine sand. Experiments F6, F8 and F10 were conducted on top of 10 cm deep sieved and discarded Sibudu sediments that filled shallow pits dug ca. 60 × 60 × 10 cm. F7 and F8 were conducted simultaneously, and F9 and F10 were also conducted simultaneously. F3 was conducted in Johannesburg on a topsoil horizon of coarse sand, while F4 and F5 were conducted in the Waterberg on fine sand. Temperatures for the experimental fires were recorded using Major Tech MT 632 digital thermometers with thermocouples (probes) attached. These results are not included here.

4.3. Excavation of hearths and recording of their characteristics

Hearths were excavated after the last fire of each experiment was extinguished and the ashes were cold, using the same measuring techniques as at Sibudu. The following procedures are important to the results reported in this paper (Table 3):

- The measurement of the diameter and radius of each cool hearth was taken at the widest point of the ash extent. The top of each feature was then drawn and photographed (Fig. 3).
- The experimental hearths were circular with slightly irregular perimeters (Fig. 3). Their areas were calculated as though they were true circles and the area figures are thus approximations.
- The total depth of the hearths was recorded by measuring the depth from the top of the ashes to the base of the color alteration in the substratum (Fig. 4). The thickness of the ashes was also measured. Note that both these measurements were taken after half the feature had been excavated, and that the measurements thus were taken in the middle of the hearth.

5. Results

Duration of the fires varied in the different experiments. F8 reached its surface peak temperature the fastest, after 1 h, while F3.1 took the longest time to reach its peak surface temperature and only reached it after 14 h 35 min. On average, it took ca. 5 h for each fire to reach its peak surface temperature. There were clear differences between primary fires lit on a clean surface and secondary and tertiary fires lit on top of ashes from previous fires. The secondary and tertiary fires were in general shorter than the first, and also produced higher surface temperatures than the first fires

(Figs. 5 and 6). F5 (Fig. 7), burning three times as much fuel as any other single fire in these experiments, did not produce higher temperatures or a fire that lasted three times as long as other fires.

The hearths produced in these experiments were circular (Fig. 3). The area of the hearths ranged from 962.1 to 1661.9 cm² (Table 3), with an average hearth area of 1294.2 cm². The two largest hearth areas of the experiments were produced by F3 and F4, which both included three fires. The smallest hearth area was produced by F10, which included two fires. The total depth of the hearths ranged from 3 to 12 cm, with an average depth of 6.1 cm. F6, which included two fires, produced the deepest hearth, while F4, which included three fires, produced the shallowest hearth. The thickness of the white ash layer ranged from >0.25–5 cm, with an average depth of ~1.6 cm. The thickest layer of ash was produced in F6, while the shallowest layer of ash was produced in F4 and F5. Note that F5 only included one fire.

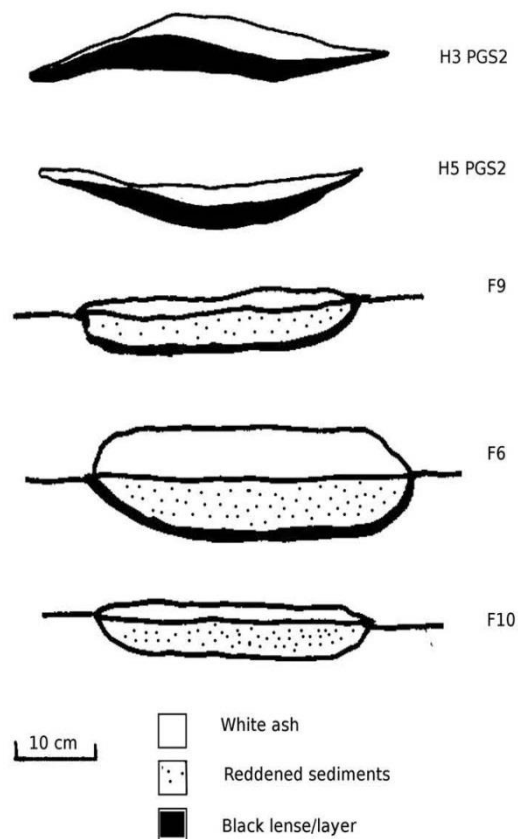
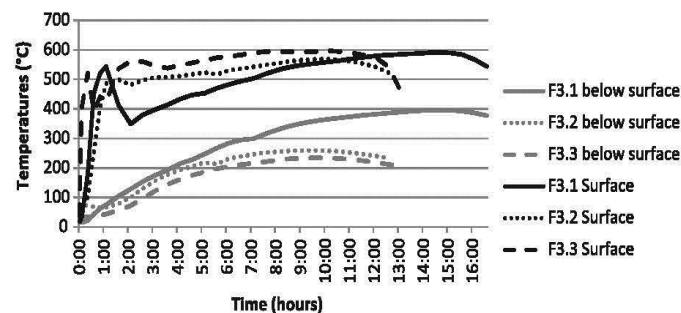


Fig. 4. Cross sections of selected archaeological and experimental hearths.

Fig. 5. Temperatures of F3, burning *Dichrostachys cinerea*.

6. Discussion

The hearth areas produced in these experiments seem quite standardized, but hearth area and hearth depth do not always correlate positively. For example, F5 had the third largest area, but it was one of the shallowest hearths; F3 was one of the largest and deepest hearths, while F10 had the smallest area, but was relatively deep (Table 3). The regular shape of the experimental hearths could be a result of the arrangement of the logs in the fires and the way the fires were reloaded. An irregular shape could have been the result if logs had been thrown or pushed into the fire rather than being neatly arranged in a circle as in the experiments described here. Variables such as fuel load, the number of successive fires in each hearth, the fuel burned and the topsoil horizon will be discussed in relation to hearth area and depth and the hypotheses stated above to reach general predictions about hearths from these experiments. Results and predictions will then be discussed in relation to the sample of hearths from Sibudu.

6.1. Number of fires and fuel load

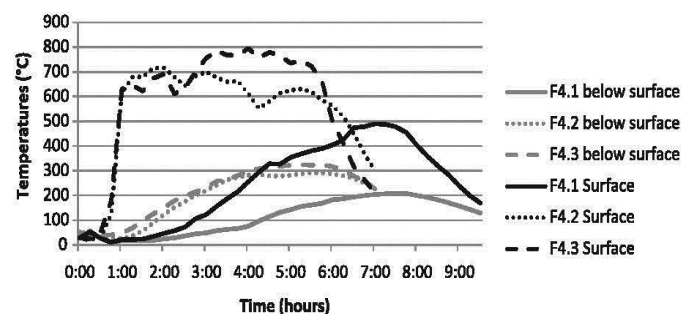
Two of the experiments (F3 and F4) included three fires on top of each other, and these experiments produced the largest hearth areas. The third largest hearth area was produced by F5, which constituted a single fire. The smallest hearth area was produced by F10, which included two fires. It does not immediately seem as though the number of fires and the hearth area correlate in these experiments. However, the number of fires in most of the experiments seem linked to the total fuel load in the experiment. Fig. 8 illustrates the relationship between total fuel load and hearth area; hearth area in this figure is shown in dm^2 ($1 \text{ dm}^2 = 100 \text{ cm}^2$) for a more readable figure. The three largest hearth areas were produced by total fuel loads of 14.6 kg or more. However, hearth

area and fuel load do not correlate with fires using smaller loads, between ~5 to 10 kg of wood.

Repeatedly reheating the substratum with new fires in the hearth could be expected to create a deep discoloring of sediments, but the number of fires in these experimental hearths does not correlate with the depth of the hearths. This result is thus different from the one pertaining to hearth area. F4, including three fires, produced the shallowest hearth, and the deepest hearth (F6) only included two fires. Nor is total fuel loading an important factor to the depth of these hearths. F4, with the largest total fuel load, produced a hearth depth of 5 cm; F6 had a medium fuel load of 10.05 kg and is the deepest hearth. Hearths that were 5 and 4 cm deep had the smallest fuel load (5 kg in F7 and F8). The white ash layer in the hearths is not always thicker in experiments with multiple fires compared to single fires. F4, with 3 fires, and F5, with a single fire burning the most fuel of all the experimental fires, both produced the thinnest layers of white ash in the experiments. Thus, fuel load and number of successive fires does not seem to influence hearth depth in these experiments. This might instead be linked to the wood taxon burned.

6.2. Fuel burned and topsoil horizon

Different types of fuel were burned on different types of topsoil horizon. F2 and F9 burned similar fuel loads of *Casuarina equisetifolia* on fine sand, and produced hearth areas of 1320.3 and 1075.2 cm^2 , respectively. This indicates that a wood taxon can produce slightly different amounts of ash even when used in fires on the same topsoil horizon. Future experiments should examine whether variables such as temperature or weather seem to affect the amount of ash produced. F7 and F8 burned similar fuel mass of the same wood taxon on different substrata and produced the same hearth areas. F4 and F5 burned both wood and bone, and produced

Fig. 6. Temperatures of F4, burning *Eucalyptus globulus* and bone fragments.

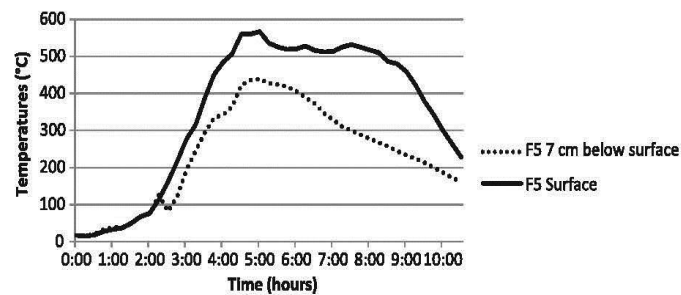


Fig. 7. Temperatures of F5, burning *Eucalyptus globulus* and bone fragments.

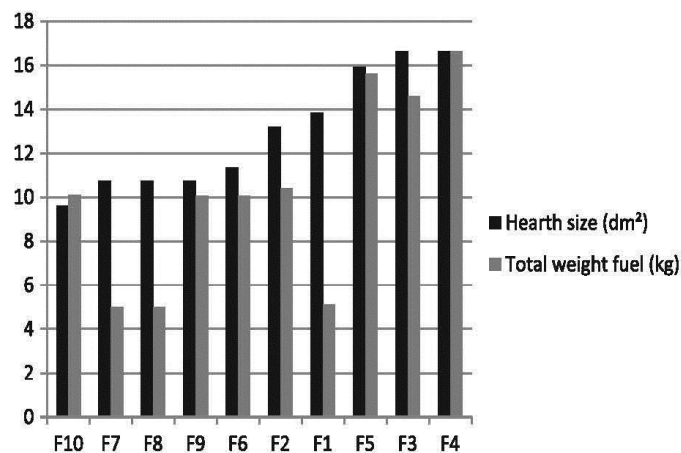


Fig. 8. Weight of fuel compared to hearth area in each experiment. Hearth area given in dm² (1 dm² = 100 cm²) for a more readable figure.

two of the three largest hearths in these experiments. However, F3 produced a larger hearth area than F5, and the former hearth burned wood only. It does not seem from the results of these experiments, then, that fuel type or wood taxon determines hearth area.

There appears to be no correlation between hearth depth and topsoil horizon. Fires lit on the same topsoil horizon, such as F1, F2, F7 and F9, produced hearths that varied in depth from 5 to 7 cm. Different wood taxa appear to affect ash and hearth depths, but more experiments are needed to confirm the preliminary results here. *Eucalyptus* wood resulted in shallow hearths with ash depths of between 0.25 and 1.0 cm thick. F4 ash was only 0.25 cm thick even though three fires were lit on top of each other. Even the addition of bone to *Eucalyptus* wood in F4 and F5 made no difference to the depth of the hearths or the amount of ash produced. However, F4 and F5 had amongst the largest hearth areas, so the ash appeared to spread widely. F3 and F6 burned *Dichrostachys* and *Acacia*, respectively, and both fires produced much ash and deep hearths. F1, F2, F9 and F10, all burning *Casuarina*, produced hearths of similar depths. Note, however, that the white ash layer varied from ca. 1–2.5 cm in these hearths, indicating that the same wood taxon does not produce exactly the same amount of ash every time. The thickest white ash layers of these four experiments were produced in multiple fires. It does not seem from the results of these experiments that fuel type or substrata affect hearth area, but wood taxa appear to affect hearth depth and the amount of ash produced. However, the experiment sample size is small, and the effects of different wood taxa will have to be examined in greater detail in future experiments.

6.3. Fire use

When comparing these results to the sample of PGS2 hearths from Sibudu, it is possible to make some interpretations about fire use at the site. H6 and H7 in PGS2 (Table 1) were small compared to the experimental hearths. The excavated and the estimated original sizes of H4 and H9 in PGS2 were also smaller than any of the experimental hearths. From the experimental results it is possible to predict that less than 5 kg of wood was burned in each fire in H4, H6, H7 and H9. This implies that these small fires were used for a short time only. These hearths were possibly only used once as special purpose fires. This hypothesis will need to be tested through analysis of the artifacts in and around these hearths.

The excavated part of H5 in PGS2 has a similar size to the experimental hearths with fuel loads of ca. 5–10 kg, so this fire may also have been of short duration. The excavated part of H1 in PGS2 is in the hearth area range of the larger experimental hearths where more than 10 kg of wood was burned, while the recorded part of H2 and H8 in PGS2 was larger than any of the experimental hearths (Table 1). This would probably mean that ca. 15 kg of fuel or more was burned in these two fires. However, the complete features are not excavated, and H1, H2, H3 and H5 were at least twice as large as any of the experimental hearths. Data from the experiments cannot inform on differences in fuel load in these fires. The experiments do imply that much more than 15 kg of wood was burned in H3. This could be done in one massive burning event, where much wood was burned at once, or in a large and long lasting burning event, where the same fire was kept going for a while. It could also mean repeated use of the same hearth for subsequent fires.

7. Conclusions

Ten experiments were conducted, involving 18 fires, four wood types, and three topsoil horizon types. It was expected that fuel load would correlate positively with hearth area and depth, and that multiple fires would produce larger, deeper hearths than single fires. It was also expected that longer-burning fires would produce deeper ash than shorter-burning fires. Some experiments were restricted to single fires, whereas other experiments included multiple fires on top of each other. The experiments show some natural, seemingly serendipitous, variation amongst hearth attributes, something that is also observed in other contemporary contexts (e.g. Alpersen-Afil and Goren-Inbar, 2010, p. 21). They also show that hearth area can be important to the understanding of fire use and the length of time that a hearth was used, because hearth area correlates positively with fuel load. This can ultimately be used to interpret the use of hearths and fire at an archaeological site.

Fuel loads of ca. 5–10 kg produced hearth areas of 962.1–1385.4 cm². Fuel loads of ca. 15 kg produced slightly larger hearth areas, but they were less than 1700 cm². Hearth area and hearth depth seemed to be independent of the number of fires in a hearth and variations in topsoil horizons. Contrary to expectations, multiple fires did not produce larger hearth areas than single fires. This result is probably because wood for secondary and tertiary experimental fires was laid on exactly the same place as wood from the first fires. If logs were pushed into an existing fire from the side, it is more likely that there would be hearth 'creep', resulting in irregular hearth shapes and sizes. The shapes of some of the PGS2 hearths at Sibudu suggest that hearths spread into irregular shapes because of the way that fuel was repeatedly added.

There may be a relationship between the amounts of ash produced and the wood taxa used. Taxa such as *Acacia* that produce much ash did seem to result in deep hearths. *Eucalyptus* fires produced little ash and relatively shallow hearths. However, this correlation needs to be tested in future experiments. Interestingly, unlike hearth area, hearth depth may be independent of fuel load and the number of fires in a hearth. Hearth depth, then, might not be as useful a characteristic for interpreting fire-related behavior as hearth area. Clearly more experiments are needed to explore this suggestion.

The difference between the sizes and shapes of archaeological hearths in PGS2 suggests variations in their use at Sibudu. Some hearths seem to have been used for a short time, maybe only once, whereas other hearths were used repeatedly and/or over a longer period. One possibility is that Sibudu was used for both short and long stays and that the hearths are not necessarily contemporaneous. However, these experiments can neither resolve this issue, nor indicate what tasks the hearths were used for. More experiments, combined with thorough studies of the material in and around the archaeologically recovered hearths, are needed to understand better the variations in fire use at Sibudu.

Acknowledgments

My sincere thanks to my supervisor Prof. Lyn Wadley for all her invaluable help and support. Many thanks also to the Sibudu team, especially Christine Sievers, Helen Kempson, Dr. Jamie Clark and Tammy Hodgskiss, for helping me with the experiments, asking the difficult questions and helping me develop and improve ideas and perspectives. I thank Dr. Geeske Langejans and Dr. Gerrit Dusseldorp for inviting me to present this paper at the Panafrican and Society for Africanist Archaeologists Conference in Dakar, 2010. Jerome Reynard helped me identify bone materials used in

F4 and F5, and three anonymous reviewers helped me by suggesting the changes to an earlier version of this paper. My research is funded by a grant from the Palaeontological Scientific Trust (PAST) and its Scatterlings of Africa programme, and I am very grateful for their support. Last, but not least, I need to thank the Badenhorst family for letting me conduct fire experiments in their garden.

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8 FORMATION PROCESSES - MORE EXPERIMENTAL RESULTS

Chapter 7 presented results on the formation of combustion features based on my first cycle of experiments. In this chapter, I will use data from all the 20 experiments I have conducted to discuss the research questions about formation processes that I outlined in Chapter 5.

8.1 THE STRATA IN COMBUSTION FEATURES

The ash dumps produced in my experimental fires contained no distinct strata, which is consistent with archaeologically observed ash dumps (e.g., Goldberg et al., 2009). The hearths produced in my experimental fires contained two to five strata. Experiments F4 and F5 produced a distinguishable charcoal stratum, but no proper white ash layer. The little ash produced in these experiments were found as grey and white (see Table 8.1 for Munsell colour readings) patches on top of and in between the charcoal. Some experimental hearths, e.g., E1-E10, had a distinct black middle stratum without charcoal fragments because all the charcoal fragments were mixed with the ashes, but other experimental hearths such as F2 and F6 did not have similar strata. The lack of a clear charcoal stratum supports the results of Mallol and colleagues (2013a) who found that charcoal was mixed with the white ash layer in their experimental hearths. However, this distinguishes the experimental hearths from many archaeological combustion features, including field observations from Sibudu (see e.g., Wadley, 2012a; Wadley & Jacobs, 2006). Post-depositional processes or pyrotechnological practices have been suggested as reasons for the discrepancy between experimental hearths and archaeological combustion features (Mallol et al., 2013a) and I shall return to the difference between archaeological hearts and experimental combustion features in Chapter 10. Furthermore, all of my experimental fires reproduced a stratum of reddened or reddish brown soil (see Table 8.1 and Figure 8.1), which is in contradiction to the

Table 8.1 Munsell colour readings from the strata in the experimental hearths. Part 1 of 3.

Exp #	Topsoil horizon	Top hearth stratum	Second hearth stratum	Third hearth stratum	Fourth hearth stratum	Fifth stratum	hearth	Ash dump
F1	7.5 YR 4/3	Gley 8/	2.5 YR 6/8	7.5 R 2.5/1				7.5 YR 5/2
	Brown	White	Light red	Reddish black				Brown
F2	7.5 YR 4/3	Gley 1 8/N	2.5 YR 6/8					
	Brown	White	Light red					
F3	5 YR 4/3	2.5 Y N8/0	2.5 YR 5/6	10 YR 2/1				
	Reddish brown	White	Red	Black				
F4	5 YR 4/6	10 YR 7/1	2.5 YR 5/8	7.5 YR 2.5/1				5 YR 5/6
	Yellowish red	Light gray	Red	Black				Yellowish red
		7.5 YR 3/2						
		Dark brown						
F5	5 YR 4/6	7.5 YR 7/2	5 YR 5/6	7.5 YR 2.5/1				2.5 YR 4/6
	Yellowish red	Pinkish grey	Yellowish red	Black				Red
F6	10 YR 5/2	2.5 YR 8/1	7.5 YR 8/3					7.5 YR 8/3
	Grayish Brown	White	Pink					Pink
								7.5 YR 5/2
								Brown
F7	10 YR 5/3	10 YR 8/1	2.5 YR 6/8	7.5 YR 3/1				7.5 YR 4/3
	Brown	White	Light red	Very dark gray				Brown
		1 7/5GY						
		Light green gray						

Table 8.1 Munsell colour readings from the strata in the experimental hearths. Part 2 of 3.

Exp #	Topsoil horizon	Top hearth stratum	Second hearth stratum	Third hearth stratum	Fourth hearth stratum	Fifth stratum	hearth	Ash dump
F8	10 YR 5/2	5 Y 8/1	5 YR 8/3					7,5 YR 8/2
	Grayish brown	White	Pink					Pinkish white
F9	10 YR 5/3	2.5 YR 8/1	5 YR 6/8	7.5 YR 3/2				7.5 YR 4/2
	Brown	White	Reddish yellow	Dark brown				Brown
F10	10 YR 5/2	5 Y 8/1	7.5 YR 8/3					10 YR 6/2
	Grayish brown	White	Pink					Light brownish gray
E1	10 YR 6/3	2.5 Y 8/0	5 YR 7/8	5 YR 3/4	5 YR 2/1			
	Pale brown	White	Reddish yellow	Dark reddish brown	Black			
E2	10 YR 6/3	5 Y 8/1	5 YR 7/8	7.5 YR 4/2				
	Pale brown	White	Reddish yellow	Dark brown				
E3	10 YR 6/3	2.5 Y 8/0	5 YR 6/6	7.5 YR 4/2				
	Pale brown	White	Reddish yellow	Dark brown				
E4	10 YR 6/3	2.5 Y 8/0	5 YR 7/8	5 YR 4/2				
	Pale brown	White	Reddish yellow	Dark reddish gray				
E5	10 YR 6/3	5 Y 8/1	5 YR 7/8	7.5 YR 3/2				
	Pale brown	White	Reddish yellow	Dark brown				
E6	10 YR 6/3	5 Y 8/1	5 YR 7/8	10 YR 4/3				
	Pale brown	White	Reddish yellow	Brown/dark brown				
E7	10 YR 6/3	5 Y 8/1	5 YR 7/8	7.5 YR 2/0	10 YR 3/3			
	Pale brown	White	Reddish yellow	Black	Dark brown			

Table 8.1 Munsell colour readings from the strata in the experimental hearths. Part 3 of 3.

Exp #	Topsoil horizon	Top hearth stratum	Second hearth stratum	Third hearth stratum	Fourth hearth stratum	Fifth stratum	hearth	Ash dump
E8	10 YR 6/3 Pale brown	5 Y 8/1 White	5 YR 7/8 Reddish yellow	2.5 Y 2/0 Black	10 YR 3/2 Very darkish brown			
E9	10 YR 6/3 Pale Brown	5 Y 8/1 White	10 YR 7/3 Very pale brown	5 YR 7/8 Reddish yellow	5 YR 2/1 Black	10 YR 4/3 Brown/dark brown		
E10	10 YR 6/3 Pale brown	5 Y 8/1 White	10 YR 6/3 Pale brown	5 YR 7/8 Reddish yellow	2.5 YR 2/0 Black			

Figure 8.1 Examples of reddened topsoil horizons after experimental fires. Left: The white top of F10 removed, leaving a pinkish topsoil horizon. Middle: Half of the white ash removed from F2. Right: Half of the white ash removed from E10.



experiments of Canti and Linford (2000). The organic content and iron oxides of the topsoil horizons and moisture content are suggested by Canti and Linford (2000) as reasons for no reddening, and it is plausible that the conditions during my experiments were more favourable for reddening of the soil.

In previous studies, researchers have concluded that multiple fires in a hearth within a short time span do not lead to more hearth strata than a single fire in a hearth (e.g., Mallol et al., 2013b). This is supported by my results because I could not distinguish separate burning events in the experimental hearths during excavation. I also examined the number of strata in the experimental hearths and variables such as the number of fires in the hearth, the wood mass and the topsoil horizon, because any relationship between these variables and the hearth strata would be of help when interpreting fire use at a site. Most of the fires burning 5 kg wood produced combustion features with 2 – 3 strata and most of the fires burning 15 kg wood produced 4 – 5 hearth strata (Table 8.1). There is a weak correlation between the number of strata and the number of fires in the hearth, but the relationship is not statistically significant ($r = -.23$, $p = .35$). The number of strata in the experimental hearths has a strong positive relationship to the wood mass, but the result is not statistically significant ($r = .45$, $p = .06$). Nevertheless, this result suggests that a large fuel load would contribute to more strata in the hearth.

Higher temperatures as a result of fuel load could be thought to contribute to the formation of the features. We have, however, seen in Chapters 5 and 6 that a larger fuel load might not necessarily produce a higher maximum surface temperature than a smaller fuel load, although the larger fires produced a higher average maximum surface temperature than the smaller fires. Most of the larger fires in my experiments were made on the same type of topsoil horizon. There does not appear to be a relationship between the topsoil horizon and the number of hearth strata in my experiments, but the result is not statistically significant ($r_s = .13$, $p > .05$). However, it is possible that the relationship between the number of strata and wood mass is connected to the fact that 80% of the large fires were made on the same type of topsoil horizon and that including

more large fires on different types of topsoil horizons might have contributed to resolving this issue.

8.2 FUEL LOAD, HEARTH SIZE AND DEPTH

We saw in Chapter 8 that hearth area appears to be related to fuel load. I calculated the hearth area for all the experimental hearths as if they were perfect circles (Table 4.2), as described in Chapter 8 for the first cycle of experiments. The statistical analysis of the hearths from all my experiments shows a statistically significant, strong positive correlation between hearth area and wood mass ($r = .81$, $p = .00$). Even after including all my experiments, the hearths can be divided into two groups; Fires burning 5 – 10 kg wood produced hearth areas that were 962.1 – 1385.4 cm² and fires burning 14 – 15 kg wood produced hearth areas that were 1590.4 – 1963.5 cm². While it appears that fuel load can be estimated from the size of combustion features, it is important to remember that the shape of the fireplace can affect combustion (e.g., Théry-Parisot & Henry, 2012) and possibly also the shape of the combustion feature produced by the fire. Because I arranged the wood in tepee formation before starting all the fires, it cannot be ruled out that this arrangement affected the size as well as the shape of the combustion features produced in these experiments.

There is a statistically significant positive correlation between the texture of the topsoil horizon and the hearth area ($r_s = .50$, $p > .01$) that I find difficult to explain. It is possible that, for example, the temperatures of fires on different types of topsoil horizon contributed to the production of different amounts of ash. The relationship between hearth area and hearth depth is also strong and statistically significant ($r = .46$, $p = .04$), and one possible explanation is that fires that produce deep ash also produce a wide spread of ash. A different interpretation would be that properties of some topsoil horizons made it easier to distinguish subtle changes in both horizontal and vertical changes of colours and texture, but there does not appear to be a relationship between the topsoil horizon and hearth depth ($r_s = -.05$, $p > .05$).

One conclusion in Chapter 8 was that some wood taxa produces less ash than others, which is consistent with results from other studies (e.g., Tietema et al., 1991). Table 4.2 shows that *Eucalyptus globulus* produced very little ash (<0.25 cm) in experiments F4 and F5 and little ash in experiments F7 and F8 (0.5 – 1 cm) compared to the other wood taxa used in the other experiments (1 – 4 cm ash), suggesting that some wood taxa do in fact produce very little ash compared to others (Figure 8.2). Furthermore, the ash depth in all my experimental hearths does not have a strong relationship to the number of fires in the hearth ($r = .13$, $p = .59$). Yet the fires burning *Eucalyptus globulus* are outliers also when it comes to wood mass burned and ash depth. This suggests that ash depth generally can be used for estimating the fuel mass in a fire, but not for fires burning *Eucalyptus globulus*. Other wood taxa could also have similar properties to *Eucalyptus globulus*. More experiments comparing ash depth from fires burning different wood taxa should be conducted to examine this further.

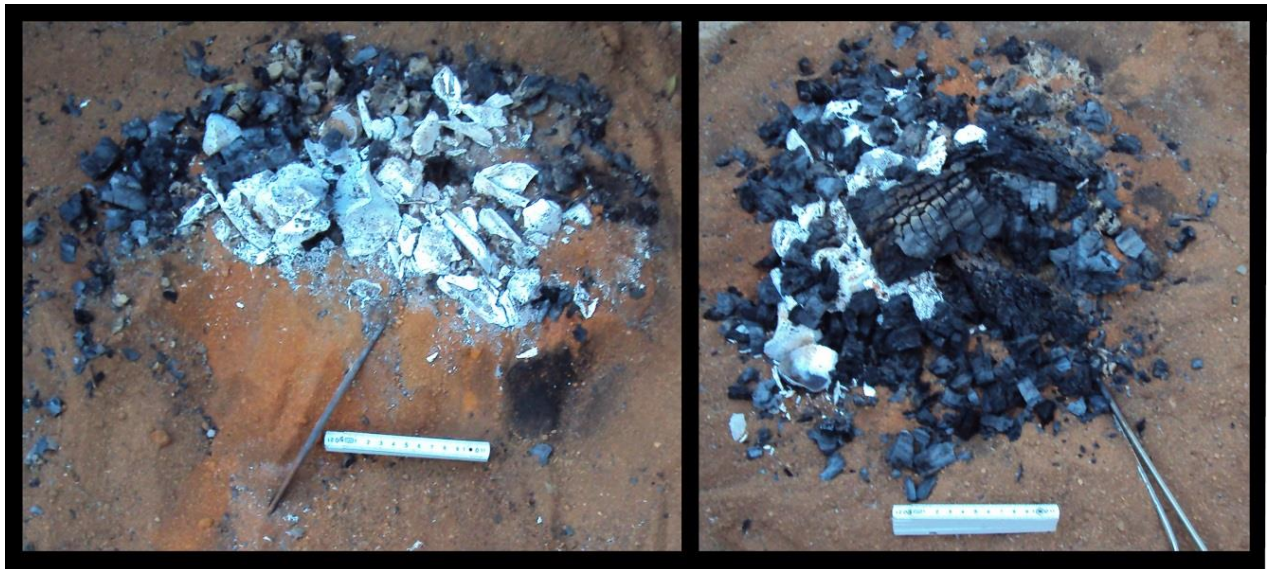


Figure 8.2 Experimental hearths F4 and F5. Left: E4 after half the hearth has been scraped away as ash dump. Right: F5 before excavation.

8.3 SUMMARY AND IMPLICATIONS

In this chapter, I have discussed some of the conclusions from Chapter 8 and introduced some new aspects about the formation of combustion features by combining information from all my experiments and conducting statistical analysis of the data. The results with implications for the formation of combustion features can be summarised as follows:

- 1) An experimental hearth consists of laminar strata, but an ash dump created by raking out ashes does not contain distinguishable laminar stratigraphy.
- 2) Out of the 20 hearths produced in my experiments, 18 did not include a distinguishable black stratum of charcoal although ten included a black hearth stratum with little charcoal. This is partly consistent with other experimental studies (Mallol et al., 2013a), but contrary to archaeological observations, including those at Sibudu (e.g., Wadley, 2012a; Wadley & Jacobs, 2006).
- 3) All the experimental fires produced rubified soil under the fire.
- 4) The number of fires in a hearth does not appear to affect the number of hearth strata and multiple fires could not be distinguished during excavation.
- 5) Many hearth strata appear to be produced by fires with large fuel loads.
- 6) Hearth area is correlated to fuel load (in fires where the wood is arranged in a tepee formation).
- 7) The type (grain size) of the topsoil horizon appears to have an effect on the hearth area.
- 8) Ash depth appears to be related to fuel load, but not for all wood taxa.

8.4 CONCLUDING REMARKS

In this chapter, I have used data from all my 20 experiments to discuss the formation of combustion features, following the research questions outlined in Chapter 5. I have focused on hearth strata, which are important parts of the features. The last four chapters have discussed experimental results on combustion features. In the next chapter, I shall focus on the archaeological sample. The contents and spatial distribution of combustion features are important to the understanding of fire use at a particular site. I combine spatial data and the contents of the features with results from micromorphology, organic petrology and anthracology in Chapter 9 for a more holistic understanding of MSA fire use at Sibudu.

9 COMBUSTION FEATURES AND FIRE-RELATED BEHAVIOUR AT SIBUDU: RESULTS FROM A MULTIDISCIPLINARY STUDY

This chapter contains a collaborative paper that is almost ready for submission. Here I use it as a chapter and I have edited it for this purpose, but it will shortly be submitted to the *PaleoAnthropology Journal*. The following researchers are involved in this work:

From the University of the Witwatersrand:

I, Silje Evjenth Bentsen, conducted the spatial analysis and wrote and edited the draft of the paper. Prof. Lyn Wadley conducted the botanical analysis and helped me write and edit the draft of the paper for submission.

From the University of Tübingen, Germany:

Dr. Christopher Miller conducted the micromorphological analyses for the paper and is currently editing the sections on micromorphology for publication. Dr. Bertrand Ligouis conducted the organic petrological analyses for the paper and is currently editing the sections on organic petrology for publication.

From University College London, United Kingdom:

Dr. Lucy Allott conducted the charcoal analyses as contract work specifically for this project, and she has not contributed interpretations or helped to write the paper.

9.1 INTRODUCTION

The Middle Stone Age (MSA) rock shelter site of Sibudu, South Africa, contains multiple strands of evidence for sophisticated fire-related behaviour, including superimposed combustion features and repeated site maintenance such as burning bedding and bones and sweeping ashes (e.g., Cain, 2006; Clark & Ligouis, 2010; Goldberg et al., 2009; Sievers, 2013a; Wadley et al., 2011). Fire use was an important part of everyday life in the MSA in Southern Africa, as well as in other prehistoric periods and geographic areas, and researchers have recently begun to conduct detailed studies fire-related behaviour in the MSA using different approaches (Chapters 2, 5 and 7; see also e.g., Brown et al., 2009; Charrié-Duhaut et al., 2013; Lombard, 2005, 2007; Miller and Sievers, 2012; Miller et al., 2013; Mourre et al., 2010; Schmidt et al., 2013; Sievers, 2013b; Wadley, 2010b, 2012a; Wadley et al., 2009, 2011). This paper presents results from a multidisciplinary study of fire-related behaviour at Sibudu. Specifically, we aim to (1) identify types of combustion features, (2) identify fire-related behaviour such as selection of firewood and sweeping of ashes, (3) identify spatial distribution of artefacts and (4) identify diachronic differences in fire-related behaviour (see e.g., Goldberg et al., 2009; Wadley and Jacobs, 2006). The sample size here is not large enough for firm conclusions, but our work is an example of the detailed information on fire-related behaviour that can be achieved by combining data from field observations, anthracology, micromorphology, organic petrology and spatial analysis.

9.1.1 COMBUSTION FEATURES AND FIRE-RELATED BEHAVIOUR

'Combustion feature' is a generic term that describes the manifestation of fire-related activities, and can be defined spatially (as an ancient surface or stratigraphic unit) and by function (e.g., a domestic hearth used multiple times for cooking) (Mentzer, in press). Well-preserved primarily deposited combustion features, such as domestic hearths, typically consist of a top stratum of white ash, a black stratum rich in charcoal and a heat-affected (rubified) stratum under the combustion feature (see e.g., Schiegl et al., 1996). MSA researchers generally refer to primarily deposited combustion features as *hearths*, which are often described as irregular or circular ash patches of various

sizes, without a stone lining and sometimes concave in profile (see Chapter 2). The MSA hearths were used, amongst other things, for light, warmth and cooking. Another task, identified by Goldberg and colleagues (2009), is maintenance fires for burning used bedding at Sibudu. Bedding is characterised by fibrous, carbonised organic material in addition to the ash and charcoal found in other primarily deposited combustion features. Burning of bedding has also been identified at the MSA site Diepkloof Rock Shelter, South Africa (Miller et al., 2013). Secondly deposited combustion features, such as ash dumps, are created when the contents of a primarily deposited combustion feature are raked out and redeposited in the vicinity of or in a different area than the original combustion feature. Secondly deposited combustion features typically have no distinct strata and items such as charcoal are found randomly orientated in these features and not in a regular, horizontal manner (e.g., Goldberg et al., 2009; Karkanas & Goldberg, 2010; Meignen et al., 2008; Miller et al., 2010).

Combustion features are not necessarily static types used for a single purpose and can have been used and reused several times for different activities. For example, domestic hearths and ash dumps can be laid on top of burnt bedding and an abandoned domestic hearth can be reused as an ash dump. There are superimposed combustion features at MSA sites (e.g., Chapter 2, Table 2.1 and references therein), including Sibudu. The layers at Sibudu are not 'living floors' with completely undisturbed remains from an occupation restricted in time and space and where the remaining clusters of artefacts solely reflect human behaviour (see discussions in e.g., Dibble et al., 1997; Malinsky-Buller et al., 2011). Nevertheless, the deposits are 'largely anthropogenic' (Goldberg et al., 2009, p. 95) and do not represent palimpsests or overlapping anthropogenic and natural processes over long periods (see description and discussions in e.g., Goldberg and Macphail, 2007; Malinsky-Buller et al., 2011; Stern, 1993).

Modern fire-makers can have distinct opinions on preferred firewood taxa and properties (e.g., Abbot et al., 1997; Archer, 1990; Tabuti et al., 2003). Proficient fire-users would be familiar with factors that affect the performance of the fire and would

take measures to control them when needed. Previous charcoal analyses from MSA sites do not, as yet, suggest a strong selection for one taxon or a few taxa for firewood (e.g., Allott, 2005, 2006; Cartwright and Parkington, 1997; Cowling et al., 1999), but the exploitation of plant resources nonetheless shows that people were acquainted with the properties of various plants (e.g., Albert and Marean, 2012; Goldberg et al., 2009; Mercader, 2009; Miller et al., 2013; Sievers, 2006; Sievers and Muasya, 2011; Wadley et al., 2011). Regarding fuel, Th  ry-Parisot (2001, 2002) demonstrated in her fire experiments that burning bones in fires can be a deliberate act because they produce much light, and heat transfer through radiation and convection is more important than conduction when bone is burned than in wood fires. An abundance of burned bone has been found at MSA sites, including Sibudu (see e.g., Chapter 2). However, bones may have been thrown into the fire as a cleaning strategy and not intentionally been used as fuel at the site (Cain, 2005; Clark & Ligouis, 2010), which is why we focus on wood as fuel in this paper.

Combustion features, as well as the archaeological deposits around them, may be affected by syn-depositional and post-depositional processes. Such processes include chemical alterations; for example, accumulations of bat guano can alter the pH of archaeological sediments (Shahack-Gross et al., 2004), thereby altering the conditions for preservation, and also cause shell fragments and similar organic matter to dissolve (see e.g. Karkanas and Goldberg, 2010). Site management by people in the past, such as cleaning, raking out ashes and preparing the surface, can have a blurring effect and make it difficult to recognise combustion features visually (e.g., Goldberg et al., 2012), and experimental results imply that trampled combustion features can retain their strata and there may be little horizontal displacement of sediments, although the underlying sediments are compacted and artefacts can be pressed downwards (Miller et al., 2010). Researchers have also conducted experimental studies of trampling and horizontal movement of artefacts. For example, Nielsen's (1991) experiments imply that dense and heavy objects like large lithics move less than large and light objects such as bone, and Villa and Courtin (1983) conclude in their study that objects weighing less than 50 g move more than heavier objects. Yet an experimental study involving goat trampling

implies that factors other than the size of the object cause its displacement (Pargeter and Bradfield, 2012). Both syn-depositional and post-depositional trampling and other processes are thus important to keep in mind when studying site organisation and the distribution of material. Evidence for processes such as trampling at Sibudu has previously been identified through micromorphology (e.g., Goldberg et al., 2009), and combining this method with the spatial analysis will help interpret the spatial distribution of artefacts.

9.2 EXCAVATION AND SELECTED MATERIAL

A general description of Sibudu, the excavation and the selected layers and are provided in Chapter 3, but some information is repeated or expanded on below because this information is important to the discussion (Section 9.5).

The layers Brown under Yellow Ash 2(i) (BYA2(i)) and Brown/Grey mix (B/Gmix) from the lower part of the post-Howiesons Poort (post-HP) sequence, dated to ca. 58 ka (Jacobs et al., 2008b), and the layers Pinkish Grey Sand (PGS) and Pinkish Grey Sand 2 (PGS2) within the Howiesons Poort Industry (HP), dated to 64.7 ± 1.9 ka (Jacobs et al. 2008b), have been selected for analysis here. These layers were selected because they represent the time frame when the proposed change in fire-related behaviour happened (Goldberg et al., 2009). The *i* in BYA2(i) refers to an arbitrary division of a layer during excavation, as does the "2" in PGS2. In the east profile of B4, the layers including combustion features have the following thickness: BYA2(i) is 4 – 10 cm thick, B/Gmix is 6 – 12 cm thick, PGS is 4 – 5 cm thick and PGS2 is 8 – 15 cm thick (see also the site stratigraphy in Figure 3.4). Six combustion features were selected for detailed analyses and bone, stone and charcoal from all the combustion features was included in the spatial analysis (see the description in Section 9.3).

Bone, charcoal and stone from the selected layers were excavated in quadrants, as explained in Chapter 3. By 'stone', we refer to knapped stone (lithics) from every stage in the operational chain – from cores to discarded tools. When referring to 'material' or 'archaeological material' in the following text, we refer to bone, charcoal and stone. Lithics > 2 cm, as well as large bone fragments, were drawn on the site plans before removal, but smaller pieces were not. In order to get as comprehensive picture of Sibudu as possible, we include all the excavated bone, charcoal and stones in this study. This means that we do not have the exact coordinates for small objects, but we do know which quadrant and, where applicable, which combustion feature the bones, charcoal and stones are from. We can use this information to place archaeological material on the site plan (see the description of the spatial method below). Furthermore, as much as 80 – 95% of the bone fragments in some layers at Sibudu are burned (e.g., Cain, 2005; Clark & Ligouis, 2010) and all fragments are included in the spatial analysis. We chose to weigh the material in order to quantify it because the bone was very fragmented (numerous fragments were < 2 cm, even < 1 cm), which would give a meaningless count, but a useful mass. As a result of this approach, heavy objects will have the most impact on the spatial analysis and we are aware of this shortcoming.

9.3 MATERIAL AND METHODS

This section contains brief descriptions of the methods chosen in this study.

9.3.1 ANTHRACOLOGY

Charcoal fragments from H1 in BYA2(i), H in B/Gmix, H1 in PGS, H1 and H2 in PGS2 and layers PGS in square B5 and PGS2 in square C4 were analysed by Dr. L. Allott using standardised procedures for woody taxon identification (see Allott, 2005, 2006). These features and layers were selected because they contained sufficiently large charcoal fragments for potential taxon analysis. Sixty pieces of charcoal were randomly selected from each of the combustion features. Anatomical features of charcoal

specimens were recorded and compared to modern reference material. Species identifications are rare, but genera and families are named where species identification was not possible.

9.3.2 MICROMORPHOLOGY

Sediment blocks for micromorphological analysis of H1 in BYA2(i), H in B/Gmix, H1 in PGS and H5 in PGS2 were collected and prepared for analysis by Dr. C. Miller. This means that the sediment blocks were cut out from the profile column and wrapped in plaster bandages. The samples were oven dried in the field at a temperature of c. 60°C for c. 24 hours, before being immersed in a mixture of unpromoted polyester resin, styrene and MEKP-hardener. They were left in the mixture until it had a gel-like consistency, after which the samples were reheated at 60°C overnight. The resulting hardened blocks were sliced and subsampled for thin sectioning. Spectrum Petrographics (Vancouver, WA, USA) produced the thin sections by grinding the samples to 30µ thickness, each sample measuring 50 x 70 mm (see also description of method in Miller et al., 2013). The thin sections produced from the blocks were observed by CM under the naked eye and under magnification (25x-200x) using a Zeiss Axioimager petrographic microscope with plane-polarized light (PPL), cross-polarized light (XPL), oblique incident light (OIL), dark field illumination and blue-light fluorescence. Analysis of the thin sections followed procedures described by Stoops (2003) and Courty et al. (1989).

9.3.3 ORGANIC PETROLOGY

In this study, organic petrological analysis consists principally of determining the reflectance of the plant tissues in order to recognise whether plant remains have been burnt or not. Terms used in the description of organic petrology have the following definitions: 'Maceral' describes a component, originally organic, of coal. An important group of macerals is 'inertinite', which has a higher reflectance in low- and medium-rank coals and sedimentary rocks than other groups of macerals (ICCP, 2001, p. 459).

Two types of macerals in this group are relevant here: fusinite and secretinite. Fusinite macerals have plant cell structure preserved, while the plant cell structure is not preserved in secretinite macerals (ICCP, 2001).

The determination of reflectance of plant tissues (huminite reflectance, vitrinite reflectance) is an established means of measuring the maturation degree of organic matter in peats, brown coals, coals, and sedimentary rocks (Borrego et al., 2006). In soil and palaeoenvironmental studies, measurements of reflectance on huminitic tissues and fusinite tissues are used, respectively, to characterise the humification process (Jacob, 1972, 1980; Schwaar et al., 1990) and to characterize charcoal particles (Bustin and Guo, 1999; Guo and Bustin, 1998; Jones et al., 1993). The organic petrological studies of H1 in BYA2(i), H in B/Gmix, H1 in PGS and H5 in PGS2 were carried out by Dr. B. Ligouis on pre-existing thin sections, whose surface had been re-polished following dry polishing procedures similar to those used in organic petrology (Taylor et al., 1998). Dry polishing avoids the loss of material caused by contact with a lubricant.

Description of the organic micro-components (macerals) in the thin section is based on the classification of macerals in brown coal and coal (ICCP, 1998, 2001; Sýkorová et al., 2005; Taylor et al., 1998). Identification and characterization of the macerals in the soil samples or hearth sediments allow us to determine the presence or absence of organic components, their origin and the microfacies of the sediments. Fluorescence examination was used to identify and classify the macerals of the huminite (huminitic tissues) and liptinite groups (pollen, spores, cuticles, resin bodies, etc.) as well as to recognize their alteration through burning. The fluorescence properties of macerals of the huminite group and the liptinite group alter by contact with fire or heat from fire (Ligouis et al., 2006).

Random reflectance in oil (mean %R) of the tissues (cell walls and fillings) was measured according to the standard procedures published in Taylor et al. (1998). Tissue

fragments or cell walls smaller than 3µm were not measured, and one measurement was made per tissue. Charcoal reflectance is used to estimate the temperature of charcoal formation (Jones and Lim, 2000) according to the formula determined by Jones (1991):

$$\text{Temperature (}^{\circ}\text{C)} = 184 + 118 \times [\text{light reflectance (\%)}] \quad (R^2 = 0.93).$$

The microscopic investigations were carried out by BL in incident white light and UV blue light using a Leitz DMRX MPVSP microscope photometer. Oil immersion objectives were used to obtain a magnification range of 200-500x.

9.3.4 SPATIAL ANALYSIS

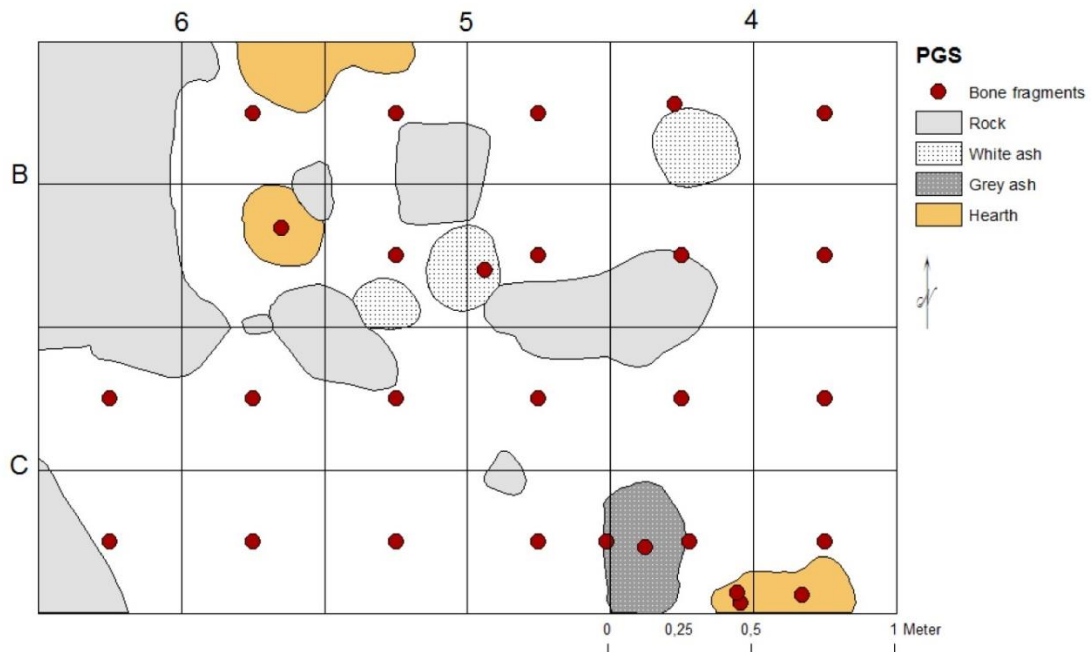
The contents of each square excavated at Sibudu were drawn to scale for every layer and feature, and often also for different parts (e.g., hearth strata or middle of layer) of the layer and features, as mentioned in Chapter 3. After being combined to site plans by LW, the drawings were scanned and added to a base map for each layer in ArcMap by SEB. Objects such as combustion features and large rocks were drawn as polygons. The charcoal and stone from each selected layer and combustion feature was weighed by SEB. Dr. J. Clark from University of Alaska, Fairbanks, had already performed basic analysis of the faunal material from the selected layers and combustion features, including dividing the bone fragments into the categories identifiable/non-identifiable fragments and the size categories > 2 cm/< 2 cm and weighing the bone fragments in each category, before the weight data was needed for this study. She allowed the use of her weights of non-identifiable bone fragments for the purposes of this paper. The identifiable bone fragments, however, were few and too light to register on the scale and they are not included here.

The weight data for bone, charcoal and stone from each selected layer were entered into a database that was connected to ArcMap and displayed on the site plans for the layer. Not all layers at Sibudu cover the entire excavated area, and this means that there are not data for all excavated squares for all the selected material even if all the bone, charcoal and stone from the selected layers are included here. BYA2(i) and B/Gmix

covered 4 m² (squares B4, B5, B6 and C4), although the majority of the bone, charcoal and stone was found within combustion features and in squares B4 and C4 in these layers. PGS covered 6 m² (squares B4, B5, B6, C4, C5 and C6) and PGS2 covered 2 m² (squares B4 and C4). This difference is taken into account in the spatial analyses. Each material category was shown separately in ArcMap, and I will describe the spatial representation of bone in PGS in detail here as an example. (The method for other layers and material categories were identical.) The weight of bone in PGS was ordered by quadrant and the weight of bone from each combustion feature in the layer was ordered by feature and quadrant. All weights were represented by points in ArcMap (illustrated in Figure 9.1). The data point for the bone in PGS for each quadrant was given coordinates that corresponded to the middle of the quadrant because this approach gave the smallest margin of error for bone originating from the different parts of the quadrant (see e.g., Weiss et al., 2008 for a similar approach). Furthermore, the data point for the bone in each combustion feature was given coordinates that corresponded to the middle of the part of the quadrant covered by the combustion feature (illustrated in Figure 9.1).

There are many potential methods for analysing and displaying the distribution and density of material in ArcMap. Displaying the weights of bones using simple symbology (Figure 9.1I) would not give a suitable impression of the weights of bone. Another method that could have been used here was to display the weights per quadrant and combustion feature as 'proportional symbols', where larger weights of bone are displayed by larger points than smaller weights of bone (Figure 9.1II). However, the more categories one chooses when classifying proportions, the more difficult it is for the reader to see the differences between categories when using this method for displaying data. More importantly, ArcMap contains several methods that can help analyse the spread and density of the material and not just display data points. We chose to use the kernel density estimation (KDE) function from the spatial analyst tools in ArcMap to analyse spatial distribution and display the densities of bone, charcoal and stone as continuous plots (Figure 9.2). Baxter and colleagues (1997, p. 348) use the following analogy to explain KDE:

I



II

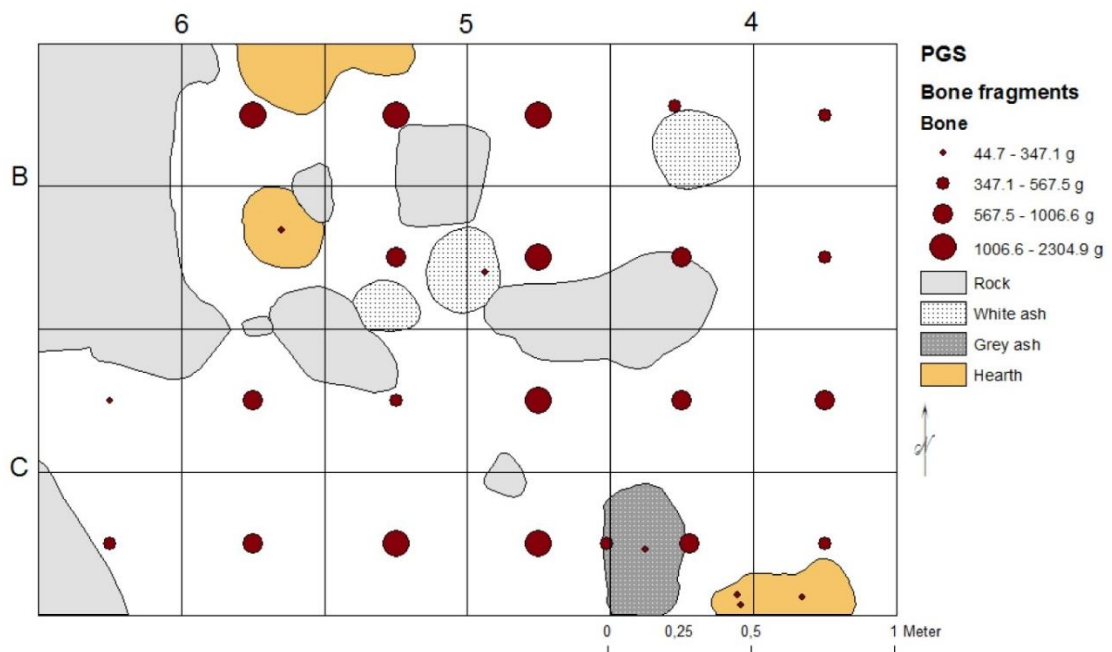


Figure 9.1 Example: Displaying bone data in PGS using points. I: Using simple symbology to mark the placement of the bone data; II: Using proportional symbols to display weights of bone. The categories are quartiles (each category represents 25% of the bone).

Given n points $X_1, X_2, \dots, X_n$ situated on a line a KDE can be obtained by placing a “bump” at each point and then summing the height of each bump at each point on the X -axis. The shape of the bump is defined by a mathematical function, the kernel $K(x)$, that integrates to 1. The spread of the bump is determined by a window- or band-width, h , that is analogous to the bin-width, c , of a histogram. (Baxter et al., 1997, p. 348).

In other words, KDE is based on a statistical weighting probability density function that calculates the density of points around each output cell and presents a locally weighed averaging of the distribution of data (Baxter and Beardah, 1996; Baxter et al., 1997; Silverman, 1986). The result for this study is a map that estimates the spatial distribution (density) of the weights (occurrence) of bone/charcoal/stone in the selected layers at Sibudu (Figure 9.2).

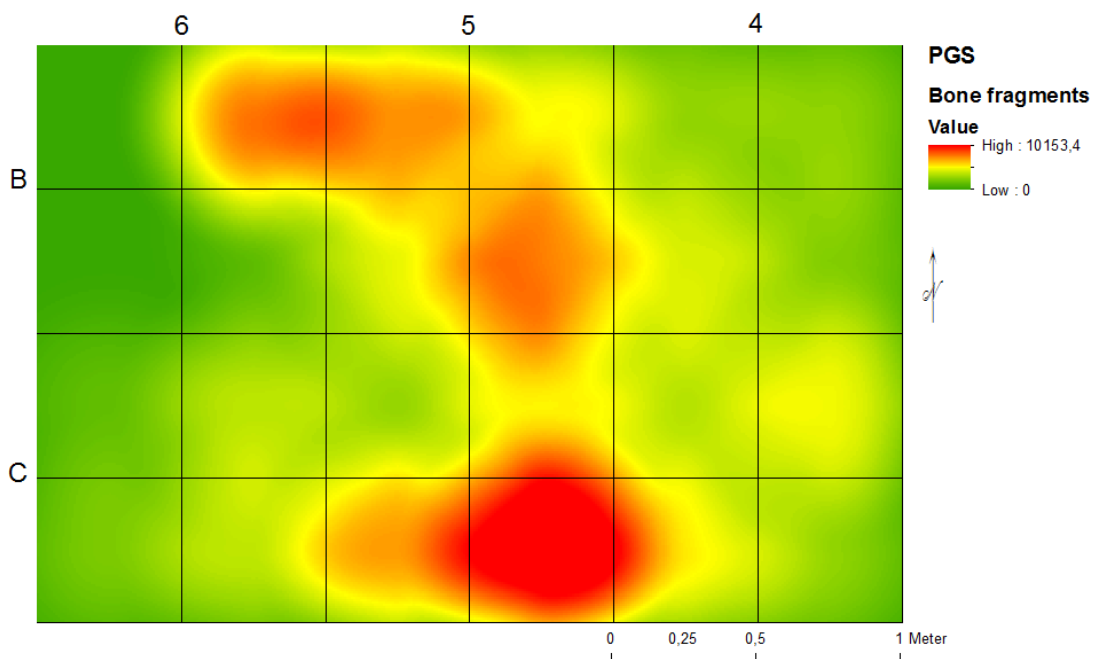


Figure 9.2 Kernel density estimation of bone in PGS2 Using the spatial analyst in ArcGIS, the spread and density of bone in PGS2 has been estimated and is displayed as continuous data.

KDE has been used in other archaeological contexts (e.g., Aldeias et al., 2012; Alperson-Afil et al., 2009; Weiss et al., 2008); for example, it was used to estimate densities of microartifacts at the site Gesher Benot Ya'aqov in the Middle East (Alperson-Afil et al., 2009). The data in this study, as described above and in Chapter 3, are two dimensional (as is Weiss et al., 2008), which do not allow displaying the density from different layers in the same way as three dimensional data would (see Aldeias et al., 2012; Alperson-Afil et al., 2009). Each point on our map (Figure 9.1) represents total weight, not a single artefact, so we used the population field in the dialogue box for kernel density estimation in ArcMap spatial analyst to ensure correct calculation. The value of the search radius was set to 0.5 for all maps. The processing extent was set to cover only the extent of each layer.

9.4 RESULTS

The results from the different methods are summarised in this section. The weights of each material category in each layer and quadrant is summarised in Table 9.1.

9.4.1 FIELD OBSERVATION

Layer PGS2 contains rock fall and nine combustion features (Figure 9.3), while PGS contains three putative hearths and four patches of ashes (Figure 9.4). These layers are densely packed with material. Only material from squares B4 and C4 is included from PGS2, but these 2 m² (including the features in the layer) contained ca. 6.85 kg stone/m² and ca. 4.4 kg bone/m². The 6 m² of PGS, including its features, contained ca. 6.2 kg stone/m² and ca. 3.5 kg bone/m². The charcoal fragments from these layers and their combustion features were generally small (~0.5 cm or smaller) and fragile. All the combustion features in PGS and PGS2 were recorded as distinct hearths during excavation, and some had a discrete white or pinkish top stratum and a middle or basal black stratum with charcoal. A few of the combustion features had a reddish-brown substratum. Many of these combustion features were basin-shaped, or slightly concave.

Table 9.1 Field description and weights of bone, charcoal and stone from the selected combustion features and layers at Sibudu. The HP layers are shaded, while the post-HP layers are not.

Layer	Feature	Field description	Squares included	Total weight (g)		
				Bone	Charcoal	Stone
Pinkish Grey Sand 2		Loose, ashy, sandy.	B4, C4	7030.9	30.8	9924.4
	H1 PGS2	Loose, fine, ashy. 3 strata.	C4	439.8	0.8	633.1
	H2 PGS2	Loose, fine, ashy. 3 strata.	C4	520.0	1.6	833.5
	H3 PGS2	Loose, ashy. 2 strata.	C4	241.1	0.5	375.0
	H4 PGS2	Loose, ashy. 1 stratum.	C4	37.7	0.1	22.3
	H5 PGS2	Loose, ashy. 1 stratum.	B4	122.2	0.7	2.9
	H6 PGS2	Loose, ashy. 2 strata.	B4	4.0	0.4	746.2
	H7 PGS2	Loose, ashy. 2 strata.	B4	36.2	0	60.1
Pinkish Grey Sand		Ashy, sandy.	B4, B5, B6, C4, C5, C6	19524.4	133.8	33229.6
	H1 PGS	Fine, ashy. 2 strata.	C4	162.8	0.3	9.6
	H2 PGS	Fine, ashy. 1 stratum.	B6	295.1	0	2972.6
	H3 PGS	Fine, ashy. 1 stratum.	B5, B6	347.1	3.3	1002.7
	Ash in PGS	Fine, ashy.	C4, C5	493.0	0.5	144.2
	Ash dump in PGS	Fine, ashy.	C4	82.8	0.1	231.6
Brown/Grey mix		Silty, ashy.	B4, B5, B6, C4	2883.5	220.3	8225.3
	H in B/Gmix	Ashy, silty. 2 strata.	B4, B5, C4	1577.8	41.5	1658.6
	H1 in B/Gmix	Ashy, silty. 1 stratum.	B6	0	0	21.4
	Ash dump B/Gmix	Ashy, silty.	B4, C4	382.3	10.3	111.0
	Ash dump 2 in B/Gmix	Ashy, silty.	B4, C4	559.6	6.2	230.9
Brown under Yellow Ash 2(i)		Silty, ashy, greasy.	B4, B5, B6, C4	644.2	144.2	4.3
	H1 BYA2(i)	Fine, ashy. 3 strata.	B4, C4	4718.5	303.1	2502.2
	SW hearth	Fine, ashy. 1 stratum	B6	0	1.6	0
	Grey hearth	Fine, ashy. 1 stratum	B5	0	1.6	0
	Ash dump BYA2(i)	Loose, ashy.	B4, C4	368.7	39.4	188.43
	Ash dump 2 BYA2(i)	Loose, ashy.	B4	19.4	0	0

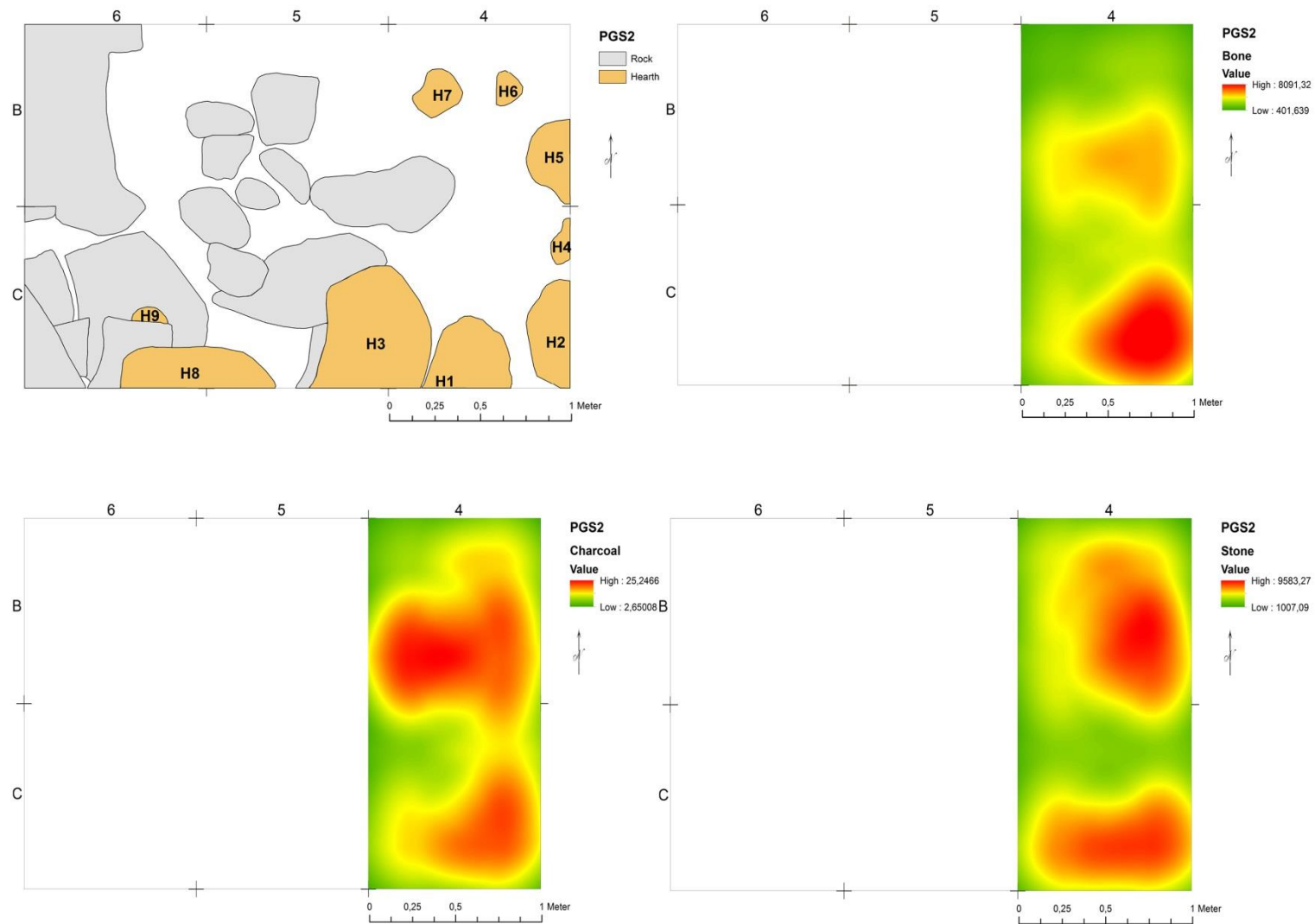


Figure 9.3 Site plan and kernel density estimations of bone, charcoal and stone in layer PGS2

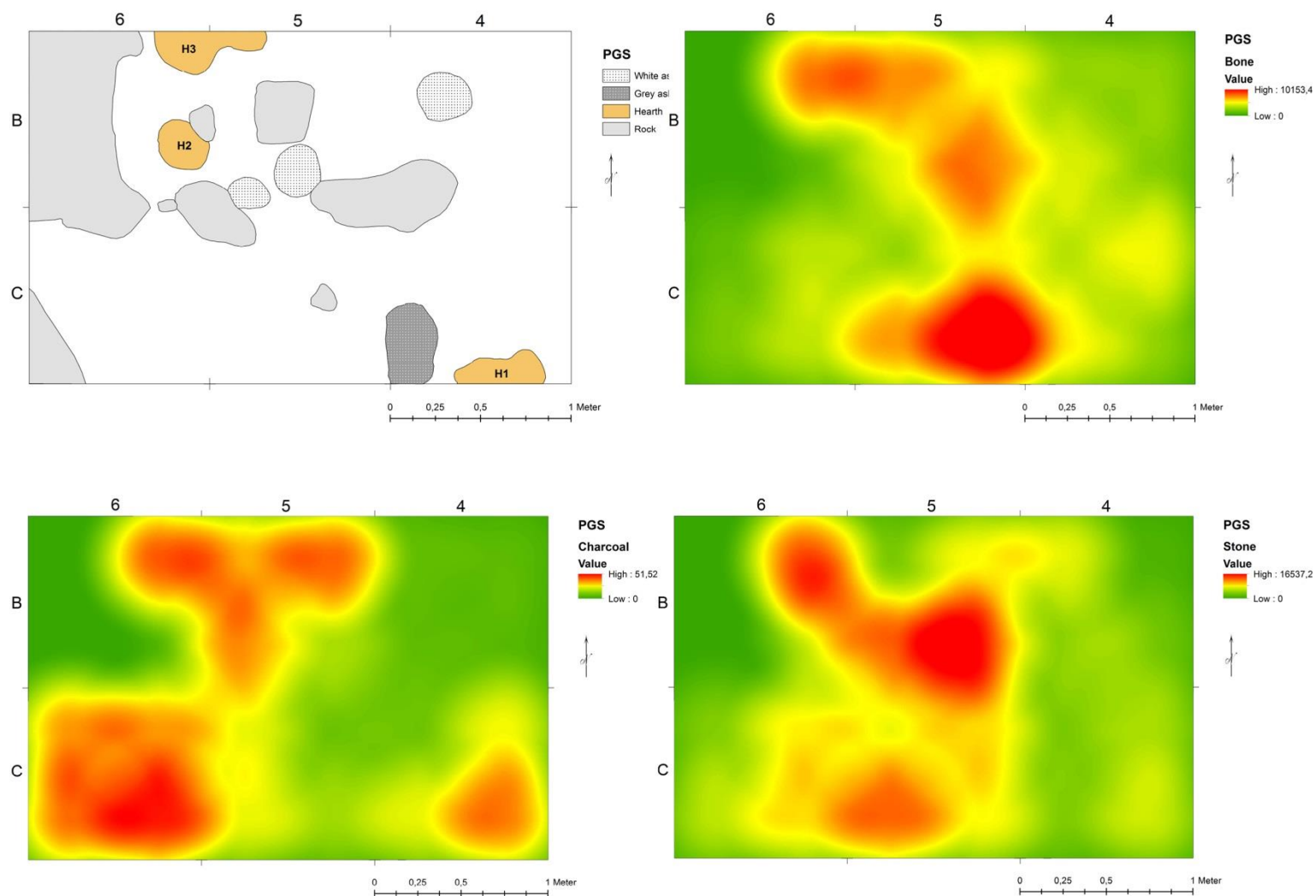


Figure 9.4 Site plan and kernel density estimation of bone, charcoal and stone in layer PGS.

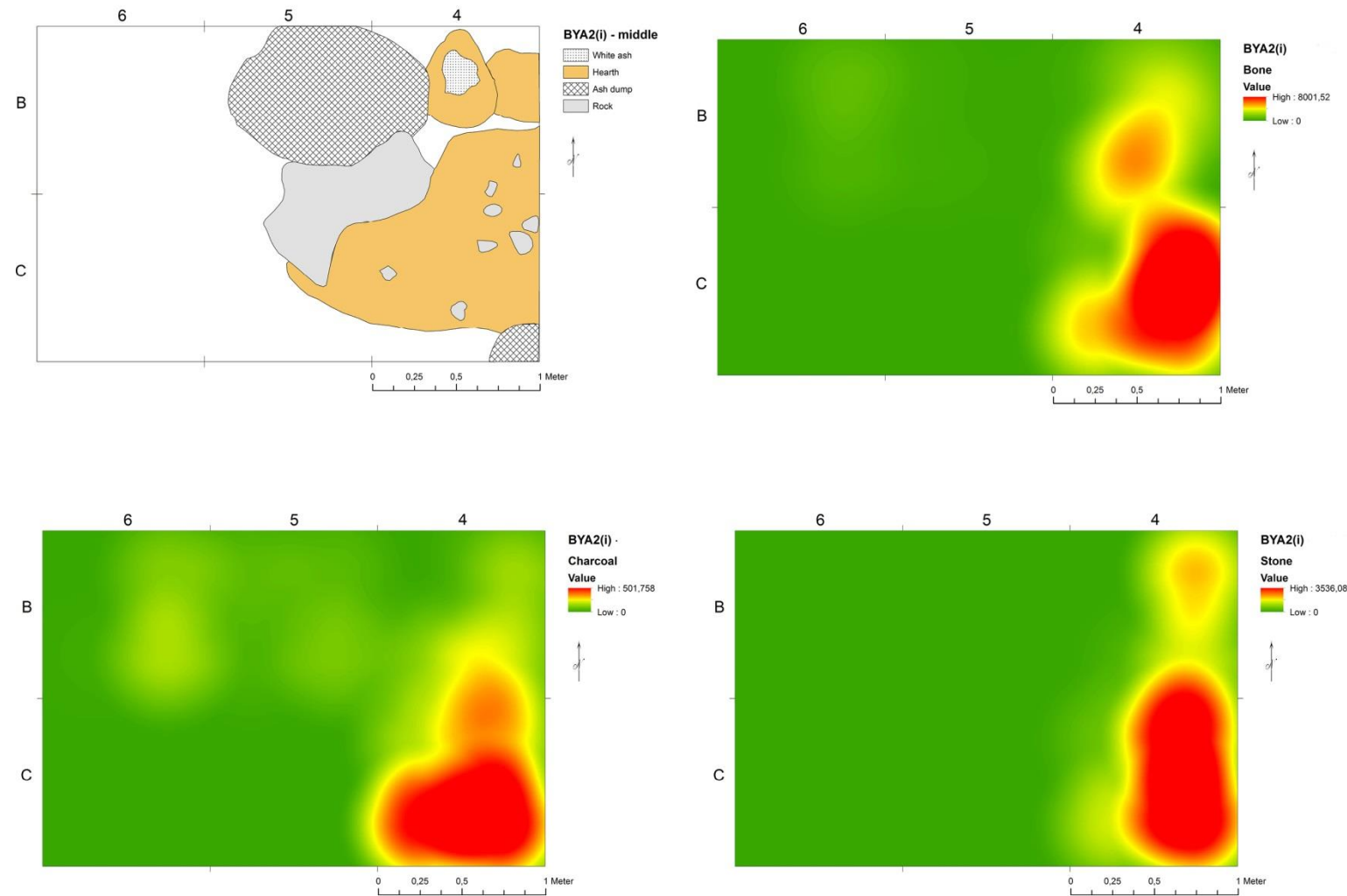


Figure 9.5 Site plan and kernel density estimation of bone, charcoal and stone in layer BYA2(i)

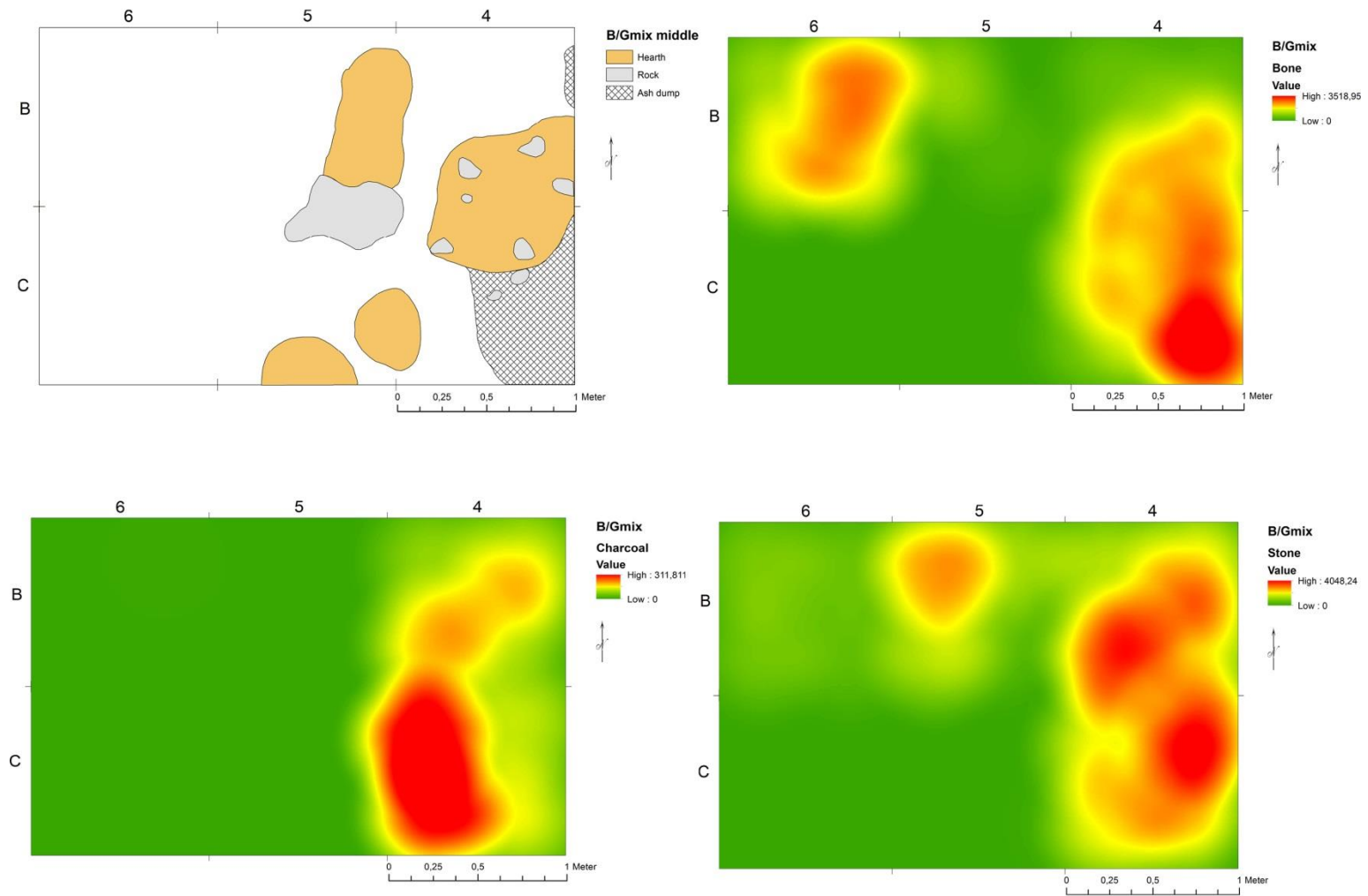


Figure 9.6 Site plan and kernel density estimation of layer B/Gmix

Five combustion features were recorded in BYA2(i) (Figure 9.5), including three putative hearths and two ash dumps, while four putative hearths and two ash dumps were recorded in B/Gmix (Figure 9.6). The matrix and combustion features of BYA2(i) contained ca. 0.45 kg stone/m² and ca. 0.97 kg bone/m², although the majority of this material was found in the combustion feature H1 in BYA2(i). B/Gmix, including combustion features, contained ca. 1.2 kg stone/m² and ca. 0.9 kg bone/m². Both these layers contained more charcoal than the HP layers, and the charcoal in the post-HP layers generally consisted of large fragments (1 cm or larger). Furthermore, H in B/Gmix stands out from the other combustion features in this and other layers because five large cobbles, likely manuports, formed a circle within the edge of the feature. H in B/Gmix was slightly concave, and the cobble bases dipped towards the centre of the feature at angles of between 10 – 23 degrees.

9.4.2 ANTHRACOLOGY

Some of the charcoal selected for taxon identification was badly preserved, and many of the identifications were restricted to family level. More taxa types (26) were recognised in the post-Howiesons Poort layers than in the Howiesons Poort (21) (Table 9.2), but there was also more charcoal suitable for analysis from the post-Howiesons Poort layers. The results from the charcoal analysis confirm previous vegetation studies, with many evergreen taxa and some riverine and forest taxa (see e.g., Allott, 2005, 2006; Sievers, 2006). The focus of this paper is, however, the anthropogenic selection of plants and the properties of the plants selected.

9.4.3 MICROMORPHOLOGICAL ANALYSIS

In thin section, H5 in PGS2 consists of a 1 cm thick, whitish layer, with evidence of rubification below. The whitish layer is largely siliceous (possibly siliceous aggregates), and the base of this combustion feature consists of ash which rests directly on a previous surface. The lack of a charcoal base appears not to be a result of diagenesis, but rather suggests that the fuel was burnt to completion. This is based on the

Table 9.2 Charcoal identifications. The HP layers and combustion features are shaded, while the post-HP layers and combustion features are not.

Identification	H in B/G mix	H1 in BYA2(i)	PGS	H1 in PGS2	H2 in PGS2	PGS2
ANACARDIACEAE		2				
ANACARDIACEAE/BURSERACEAE			4			
APOCYNACEAE	1		2			
ASTERACEAE / <i>Brachylaena</i> sp.			4			
<i>Buxus</i> sp.	5	3		1		
CELASTRACEAE					1	4
cf. CELASTRACEAE		1			4	
cf. <i>Cola</i> sp.	1	1				
cf. <i>Commiphora</i> sp.					1	
cf. <i>Commiphora</i> sp. / <i>Rhus</i> sp.	1					
cf. <i>Cryptocarya</i> sp.	7	2				
cf. <i>Curtisia dentata</i>				2		
cf. <i>Erica</i> sp.		1		1		
EUPHORBIACEAE	3					
FABACEAE	2					
cf. FABACEAE	1					
FABACEAE: <i>Baphia</i> type					1	
FABACEAE: cf. <i>Milletia</i> sp.	1					
FLACOURTIACEAE: cf. <i>Dovyalis</i> sp.					2	
cf. <i>Justicea</i> sp.	3					
cf. LOGANIACEAE	2					
<i>Morella</i> sp.	6	1				1
<i>Mundulea sericea</i>	2					
<i>Mystroxydon</i> sp.	2		2			
<i>Ochna</i> sp.		3				
cf. <i>Ochna</i> sp.	6					1
cf. <i>Olea</i> sp.	1	1				
<i>Podocarpus</i> sp.	2		3	1		
PROTEACEAE	2	3	3			
cf. PROTEACEAE				1		
<i>Protea</i> sp.		1				
RHIZOPHORACEAE: <i>Cassipourea</i> ?			1			
cf. ROSACEAE		1				
SAPINDACEAE: <i>Deinbollia</i> sp.			4			
SAPOTACEAE			4			
cf. <i>Spirostachys</i> sp.		2				
cf. <i>Trichilia</i> sp.		2		1		
Total fragments identified	48	24	27	7	9	6
Identifiable			36			
Unidentifiable	11	13	17	5	21	12

observation that charcoal is well preserved outside, not within, the combustion features. The surface on which the feature was built has a chestnut to reddish-brown colour directly beneath it. The reddening seems largely the result of heating of sand-sized fragments of burnt bone contained within the material directly below the surface. The deposits below and above the feature appear trampled.

H1 in PGS was also described in Wadley et al (2011). The slide consists of a thin lens of laminated fibrous charcoal and laminated, articulated phytoliths that appear partially altered. Secondary phosphates are present. The deposits above and below this thin feature are composed of trampled deposits of sand (derived from granular disaggregation of the shelter wall), charcoal, organic material, and sub-rounded sand-sized fragments of burnt bone, which are interpreted as forming through trampling (Goldberg et al., 2009).

As previously described (Wadley et al., 2011), H1 in BYA2(i) consists of multiple layers of laminated fibrous charcoal and laminated phytoliths, typical of burnt bedding deposits (Goldberg et al., 2009). The phytolith layers here contain secondary phosphates and the phytoliths appear altered, but less so than those in H in B/Gmix. Interestingly, some of the plant layers are separated by thin layers of clay. The clay does not resemble the clay aggregates found within the bedding deposits and described in detail elsewhere (Goldberg et al, 2009, Wadley et al, 2011). It comprises microgranules, or massive aggregates with finely comminuted organic material and weathered mica.

H in B/Gmix comprises multiple depositional events, homogenized through post-depositional chemical alteration. Some strata within the sample contain higher proportions of organic material than others. In those sections, most material appears siliceous and is likely derived from the alteration of phytoliths, siliceous aggregates, or other combustion-derived residues. Secondary mineral formations, in the form of gypsum and phosphate nodules, are numerous and account for the physical disturbance

of distinct layers within the sample. Although combustion activities undoubtedly account for the anthropogenic input into these deposits, there is no calcareous ash preserved. Laminated phytolith layers are identifiable, but the phytoliths appear highly altered.

9.4.4 ORGANIC PETROLOGICAL ANALYSIS

Reflectance measurements and temperatures calculated from the mean reflectance values of fusinite and secretinite macerals (see definitions in Section 9.3.3) in the analysed samples are summarised in Table 9.3. Further observations from the organic petrological analysis follow below, ordered by feature.

Table 9.3 Reflectance measurements from the selected combustion features. The HP combustion features are shaded, and the post-HP features are not.

Combustion feature	Sample	No. of measurements	Reflectance values (%)		Temp. (°C)
			Range	Mean	
H5 in PGS2	YIR15	100	0.71 – 1.14	0.89	292
H1 in PGS	YIR23	100	0.71 – 1.31	0.91	299
H1 in PGS	YIR23B	100	0.74 – 1.22	0.89	289
H1 in PGS	YIR23C	100	0.73 – 1.22	0.91	292
H1 in BYA2(i)	YIR11A	100	0.80 – 1.40	1.11	300
H1 in BYA2(i)	YIR11B	55	0.82 – 1.13	0.98	315
H1 in BYA2(i)	YIR11C	83	0.76 – 1.21	0.97	300
H in B/G mix	YIR5	31	0.88 – 1.43	1.14	319
H in B/G mix	YIR6	48	0.77 – 1.57	1.00	302
H in B/G mix	YIR7	62	0.82 – 1.28	1.03	306

Plant tissues are regularly distributed in the thin section of H5 in PGS2, but are less abundant in a light brown section of the slide. Fragments of the tissues are generally smaller than 50µm and those smaller than 10µm are common. Most tissues are fissured, strongly fragmented and often compressed and many have fine structures with thin cell walls like those of herbaceous plants. Few tissues are derived from seeds, and woody tissues are rare. Homogeneous and heterogeneous char particles (Goldberg et al., 2009) are frequent. Their size can reach up to 300µm. Anisotropic char particles with low heterogeneity are common. The reflectance value (Table 9.3) is characteristic of a low reflecting fusinite and secretinite, and the reflectance histogram exhibits a unimodal population. Low reflecting fusinite/secretinite $R \sim 0.7-1.14\%$ forms under low temperature in comparison to high reflecting fusinite/secretinite, for example $R = 4.00\%$. A unimodal population means the origin of fusinite/secretinite is related to only one source, such as only one burning event with no mixing or more or less constant conditions during burning (e.g., oxygen supply, air humidity, wind influence, low diversity in plant materials). Secretinite recorded in these sediments is, on the basis of its morphology, size and association with tissues, probably related to the incomplete combustion of humic gels from seeds (seed coating tissues).

The thin section of H1 in PGS could be divided into three parts: The obliquely dark brown discontinuous basal layer (YIR23B), the middle of the feature (YIR23) and the top lighter layer (YIR23C). Tissue fragments in YIR23B (the base) were strongly dispersed and mostly smaller than 50µm, although fragments smaller than 10µm are well represented. Inertodetrinite (fragmented intertinite; see (ICCP, 2001) for definition) and partly permineralized (fossilized) tissues are common. Seed-derived tissues are regularly present, but most tissues comprise thin structures which seem to belong to stem tissues of herbaceous plants. Homogeneous and heterogeneous char particles are also very dispersed in the layer. Fine heterogeneous char has been encountered in band morphology. This type of char could have originated from seed tissues. Huminite and liptinite particles are absent. The reflectance values (Table 9.3) are characteristic of a low reflecting fusinite and secretinite. The reflectance histogram exhibits a unimodal population with a well-defined peak (see above).

YIR23 (the middle of H1 in PGS) is rich in tissue and char fragments smaller than 10µm as well as those in the sizes range from 10 to 50µm. Tissue remains are mixed with micro-fragments of bones. Most tissues have thin structures or perforations and may originate from herbaceous plants. The other tissues are seed-derived, but there are rare woody tissues. The largest tissues are so compressed and strongly fissured that their architecture is no longer recognizable. Cell walls and cell fillings (reflecting gels) are intermingled. The size of the char particles can reach up to 500µm. Both types of char, homogeneous and heterogeneous, are represented. The reflectance value (Table 9.3) is characteristic of a low reflecting fusinite and secretinite. The reflectance histogram exhibits a unimodal population with a well-defined peak (see above).

The tissues encountered in YIR23C (the top of H1 in PGS) are mostly smaller than 50µm, while tissues larger than 100µm are rare. Fragments smaller than 10µm (inertodetrinite) comprise cell walls and cell fillings (reflecting gel particles). A few strip-shaped reflecting gel particles may be from seed tissues. Homogeneous char particles with large pores morphology (pore diameter up to 100µm) are common. Heterogeneous char particles are often elongated and their size can reach up to 400µm. Few partly permineralized char particles have been observed. Huminite and liptinite particles are absent. The reflectance value (Table 9.3) is characteristic of a low reflecting fusinite. The mean reflectance value correlates very well to that of the other layers 23B and 23. However, the reflectance histogram is skewed, which could reflect a bimodal distribution. Our observations confirm that two types of tissues forming two reflectance populations occur in the layer. The first type consists of finely structured tissues characterized by thin cell walls possibly derived from herbaceous plants and having a reflectance ranging from 0.73% to 0.90%. The second type of tissues shows thick cell walls (similar to seed tissues) with reflectance ranging from 0.85% to 1.10%. Both tissue types include small and large fragments (up to 100µm).

The slides YIR11A, B and C, from H1 in BYA2(i), show four dark organic-rich layers. In the lowest layer, there is reflecting fusinite. The thin structures resemble those in herbaceous plants. A few fragments of seed tissues and woody tissues were observed. Char particles which probably derived from bone fat are present in the top layer. The reflectance value for YIR11 (Table 9.3) is characteristic of low reflecting fusinite and secretinite. The reflectance histogram exhibits a unimodal population with a well-defined peak. For YIR11A, the reflectance value (Table 9.3) is again characteristic of low reflecting fusinite and secretinite, but the histogram of reflectance measurements exhibits a slightly bimodal distribution that seems to be related to the types of tissues. A particular type of tissue showing a very fine structure with thin cell walls has lower reflectance values than the other tissues. This phenomenon could be due to differences in the composition of the tissue cell walls or varying states of dryness before burning. The reflectance values for YIR11B and YIR11C (Table 9.3) are characteristic of low reflecting fusinite. They correlate very well with the mean reflectance value obtained for ample YIR11. The histogram of reflectance measurements from YIR11C exhibits a slightly bimodal distribution as in YIR11A.

H in B/Gmix was represented in three slides; YIR5, 6 and 7. The samples appeared macroscopically as light grey, (light) brown, reddish-brown and pale yellowish. The top of YIR5 showed numerous reddish-brown inclusions, and all samples had fine black grains and a rough horizontal stratification. Little organic matter was present, except for fragments of tissues, large homogeneous reflecting gel particles and few char particles. The reflectance value for YIR5 (Table 9.3) is characteristic of a low reflecting fusinite. Huminite and liptinite particles are absent. The histogram of reflectance exhibits a plurimodal distribution. For YIR6, the reflectance value is characteristic of a low reflecting secretinite and fusinite. The histogram of reflectance exhibits a bimodal distribution. The reflectance value for YIR7 is characteristic of a low reflecting fusinite and its histogram of reflectance measurements exhibits a bimodal distribution that seems to be related to the types of tissues in sample YIR11A.

9.4.5 SPATIAL ANALYSIS

The results of the kernel density estimation are shown as amount per unit area on the density maps (Figures 9.3, 9.4, 9.5 and 9.6), where red marks areas with high densities of material, yellow/orange medium densities and green low densities. There is a high density of bone, charcoal, and stone by H1 and H2 in square C4 in PGS2 (Figure 9.3). There are also high densities of bone and charcoal by H5, H6, and H7 in PGS2. The highest density of bone in PGS was found in square C5, next to the grey ash in square C4 (Figure 9.4). There are medium densities of bone and charcoal and high densities of stone by H2, H3, and the white ash patches in square B5 in PGS. A high density of charcoal in PGS was also found in square C6, where no combustion features were registered, and by H1 in square C4. In BYA2(i), there are high densities of bone, stone, and charcoal in square C4 (Figure 9.5). High densities of bone in B/Gmix (Figure 9.6) were found in square C4, where there is an ash dump, and B6, where no combustion features were registered during excavation. There was also a medium density of bone in B/Gmix square B4. In B/Gmix, a high density of charcoal was found by the ash dump and hearth registered in square C4, and high densities of stone were found by the ash dump and hearth in square B4 in B/Gmix.

9.5 DISCUSSION

The discussion of results is structured by the questions outlined in the introduction. The sample size is small, however, and the interpretations are suggestive rather than conclusive.

9.5.1 TYPES OF COMBUSTION FEATURES REPRESENTED AT SIBUDU

The combustion features analysed here were recorded as hearths during excavation. Nevertheless, only H5 in PGS2 was recognised as a classic hearth through micromorphological analysis and organic petrology. This illustrates the difficulty of making correct interpretations of combustion features during excavation. Furthermore,

the micromorphological analysis of H5 in PGS2 suggests that it, like some of the other hearths in the HP layers (Christopher Miller, personal communication), were burnt to completion and then abandoned. The hearth appears to have been used for a relatively short time, not only because it is a thin feature, but because there is no evidence of raking ashes from it. The reflectance histogram produced during the organic petrological analysis exhibits a unimodal distribution, which implies single use of the hearth. The organic petrological analysis also revealed many tissues in H5 in PGS2 similar to herbaceous plants. Herbaceous plants might be used as tinder in domestic hearths (see e.g., Albert & Marean, 2012) or be brought to the shelter as food or for other purposes and the remnants might be thrown in the fire as a disposal method. It is more surprising that the organic petrological analysis detected few woody tissues in any of the features analysed. Burning plants implies a short fire.

The micromorphological analyses of H1 in PGS, H1 in BYA2(i), and H in B/Gmix suggest that these combustion features are burnt bedding, and possibly a result of site maintenance (Goldberg et al., 2009). The organic petrological analysis supports the impression that many herbaceous plants were burnt in these features. Nevertheless, the micromorphological results point to differences between the features. H1 in PGS probably represents a single episode of constructing and burning of bedding. This combustion feature has an unusually small diameter for a bedding patch; however, it is not completely excavated because it lies against the section wall, so it may represent only part of the bedding area. The reflectance histogram of the top layer of H1 in PGS is skewed, which may be due to the different tissue types in the feature and not point to evidence for several burning events.

Based on micromorphology, H1 in BYA2(i) appears to represent repeated construction and burning of bedding in the same location, suggesting intensive use, several occupation episodes and/or long stays at the site. H in B/Gmix also likely represents several episodes of bedding construction and burning; however, it is difficult to interpret because these sediments were significantly altered by post-depositional chemical

diagenesis. The micromorphological sample for H in B/Gmix was removed from B4b just outside of the circle of cobbles interpreted as hearth stones during excavation. The implication is that this combustion feature is more complex than was recognised during excavation, for example, bedding may have been burned in a domestic hearth. The charcoal analysis (Table 9.2) shows that woody taxa was burned in this feature, which suggests that wood or glowing charcoal was used to set the bedding alight or that the bedding was burned in or on top of a hearth. With hindsight, we realise that a small micromorphological block removed inside the circle of cobbles would have resolved this issue.

9.5.2 FIRE-RELATED BEHAVIOUR

Some suggestions about fire-related behaviour and the selection of firewood and fuel can be made from our analyses because the properties of some of the identified plants are known or implied by modern sources. Relatively few of the identified taxa represented bear edible fruits. The people living at Sibudu could have burned plants bearing edible fruits even if they did not eat the fruit, and it is thus difficult to use taxa identified from charcoal to interpret plants gathered for their food value. Analysis of seeds (see e.g., Sievers, 2006, 2013a; Sievers & Muasya, 2011) is better suited for this purpose, but is beyond the scope of this paper.

Quite a high proportion of represented taxa have aromatic leaves and/or bark and wood (Palgrave, 1977). Such taxa discourage insects and they can be used in bedding (Wadley et al., 2011) or in fires to create smoke that dispels, for example, mosquitoes (see discussion in Wadley, 2012b, p. 92). Most of these aromatic taxa occur within the post-Howiesons Poort layers ($n = 6$; 23%); in the Howiesons Poort only three aromatic taxa (14%) occur. However, this difference in the proportion of aromatic taxa might be influenced by the sample size.

The charcoal analysis does not suggest clear preferences for one taxon or a group of taxa for firewood in any of the layers and features examined, but about half of the taxa identified are suitable as firewood and/or for implements and wood handles. In modern times, woods favoured for use as implement handles include *Curtisia dentata*, *Mystroxydon* sp. and *Baphia racemosa*, as well as some SAPOTACEAE, such as *Englerophytum natalense* (Palgrave, 1977).

The reflectance measurements imply that the Sibudu combustion features selected for analysis burned at maximum temperatures of 289 - 319°C (Table 9.3). These temperatures are well within the range that can be recorded with reflectance values from charcoal. A reflectance study including experimentally produced charcoal, could recognise high temperatures (up to 1100°C) in anthropogenic fires (McParland et al., 2009). The Sibudu temperatures are much lower and have a smaller range than the surface temperatures of ten experimental wood fires that varied from 466 - 760°C (Chapters 5, 6, 7). They also have a much smaller range than experimental sedge and grass fires that produced maximum temperatures between 157 and >800°C (Miller & Sievers, 2012).

Moderate temperatures reached in combustion features can suggest particular conditions, such as damp bedding that smouldered (see also Goldberg et al., 2009) or they can be a result of controlling and managing the fire. The people living at Sibudu do not seem to have been selective about the plant taxa for their fires; however, there are also other ways to control and manage a fire. For example, physical properties such as wood moisture, the size of the burning logs, and the level of decay of the wood can affect combustion (e.g., Nurmi, 1992; Ragland et al., 1991; Théry-Parisot, 2001; Théry-Parisot & Henry, 2012) and in turn attributes such as temperatures. Management techniques such as adding logs at particular intervals can also affect temperatures (Chapter 5). Nevertheless, organic petrology demonstrated that some bone from HP and post-HP layers at Sibudu burned at 300 - >800°C (Clark & Ligouis, 2010), and Herries (2009) found that rocks at Sibudu had been heated to 400 - 500°C. These results suggest

fires with varying temperatures, unlike the tightly controlled fires suggested by the organic petrological analysis of the selected fires for this chapter. There are several possible interpretations of the varying temperatures from the fires, for example, some fires may have been tightly controlled whereas others were not, or it was not important to achieve a specific temperature range in (some of) the fires. More experiments are needed to understand fully the management of fire at Sibudu.

The slightly bimodal histogram distribution of reflectance values from H1 in BYA2(i) suggests burning of poorly dried tissues, mostly herbaceous plants. On the one hand, this could be interpreted as burning bedding that had not dried completely, for example, by cleaning out herbaceous plants that were used for a short time and replacing them with new plants. In other Sibudu layers sedges and rushes were used for bedding (see e.g., Wadley et al., 2011) and Sievers (2013a) demonstrates that it can take several months to dry sedges properly. Sievers also show that it can be very difficult, if possible at all, to start a fire with green sedges alone. It is plausible, however, that wood fires may generate high enough temperatures to ignite green sedges and, consequently, that even poorly dried bedding could burn if thrown into a wood fire. In conclusion, the organic petrological analysis suggests that bedding material was burned, although we do not yet know whether the bedding was damp or well dried before burning.

9.5.3 SPATIAL DISTRIBUTION

Turning now to the spatial distributions of material, different densities at an archaeological site may have several interpretations. An area with a low density of material may be the result of few or no activities, but can also be created through site maintenance such as removing refuse to a dumping area (see e.g., Binford, 1983; Stevenson, 1991). However, squares C5 and C6 were not included in the kernel density estimation analysis of BYA2(i) and B/Gmix (see Section 9.3.4), so the apparent lack of material in these squares is artificial (Figures 9.5 and 9.6). The low densities of bone, charcoal and stone in squares B5 and B6 in BYA2(i) may be due to site maintenance

activities or simply few other activities in the area. Rocks can also be barriers for the spatial distribution of archaeological material and they prevent the accumulation of material. For example, a large rock occupied much space in square B6 in layer PGS (Figure 9.4), so this area also has a low density of bone, charcoal and stone.

The distribution of archaeological material can give insight into the disturbance of a site. For example, good correlation between observed combustion features and high densities of charcoal suggests little disturbance by trampling and other post-depositional processes (see e.g., Balme & Beck, 2002; Goldberg, 2000). In the post-HP layers BYA2(i) and B/Gmix at Sibudu, the high densities of charcoal coincide with combustion features identified through micromorphology as burned bedding (Figures 9.5 and 9.6). The high density of charcoal in BYA2(i) is a more discrete cluster than that in B/Gmix, where chemical diagenesis and trampling are potential agents. It is also possible, however, that the charcoal in BYA2(i) represents a more contained event that resulted in charcoal spread over a smaller area than in B/Gmix. The HP combustion feature H1 in PGS, also identified through micromorphology as burned bedding, contains a high density of charcoal. The combustion features H2 and H3 in PGS, as well as ash patches in square B5 in PGS, also have high densities of charcoal. Yet these clusters are not as contained as the ones in the post-HP layers. Furthermore, there are high densities of charcoal in squares C6 and B5 in PGS and this area does not correspond to any large combustion features. It is possible that these clusters represent combustion features (hearths or ash dumps) that could not be distinguished during excavation, but they may also have formed through redistribution of material. The kernel density estimation of PGS2 (Figure 9.3) shows a high density of charcoal in square C4, partly overlapping H2 in PGS2, and a high density of charcoal in B4 that partly overlaps H5, H6 and H7 in PGS2, but also covers a much larger area than these combustion features. This pattern suggests some redistribution of material and a similar situation to that in layer PGS.

Clusters of archaeological material intermingled with bedding have been identified at other sites, for example, the Middle East site Ohalo II (Nadel et al., 2004), and accumulations of bone and stone in and on top of the bedding would be expected if activities such as bone smashing and stone tool production were conducted on top of the bedding. The bedding might also contribute to containing objects to protect them against redistribution by trampling. However, objects such as bone could snap in the bedding when trampled (see e.g., Goldberg et al., 2009). The areas with high densities of bone and stone in layer BYA2(i) (Figure 9.5) are discrete and they overlap with H1 in BYA2(i), identified through micromorphology as burned bedding. There is also an area with high and medium-high densities of bone and stone in B/Gmix (Figure 9.6), on top of the combustion feature that likely represents multiple episodes of burned bedding, although these clusters are less contained and cover a larger area than the ones in BYA2(i). On the one hand, post-depositional processes may have shaped BYA2(i) and B/Gmix differently, thus contributing to different distributions of material. We know, for example from the micromorphological analysis, that B/Gmix was affected by chemical diagenesis, which may have influenced the distribution of bone and stone. On the other hand, the contained clusters in BYA2(i) could be the result of a very restricted activity area, or the dumping of waste in one spot, whereas a larger activity area or dumping area might have resulted in the less contained high densities on top of bedding in B/Gmix. The bedding patch H1 in PGS (Figure 9.4) has little bone and stone and may represent only one or a few episodes of burning bedding. However this combustion feature is not fully excavated and it may extend beyond the excavated area.

High densities of bone, charcoal or stone appear to be concentrated in the bedding zone of layer BYA2(i) (Figure 9.5). Outside the presumed bedding area in layer B/Gmix, there is one area with a high density of bone (within square B6) and one with a high density of stone (square B5) (Figure 9.6). The lack of charcoal in these squares suggests that there was no combustion features in the area or that the wood was entirely ashed. No micromorphological samples were taken in this part of B/Gmix, so we do not have analyses that could explain the microstratigraphy in squares B5 and B6. Nevertheless, there are some possible explanations for the high densities of material in

these squares. One possibility is that the high density of bone in square B6 was created when bones were thrown into a fire and that the high density of stone in square B5 represents a knapping event. Another possibility is that the bone and stone in squares B5 and B6 represent discarded and dumped material and not activity areas, but this is less likely because of the separation of the two materials. A detailed study of the contents in the clusters may provide more information on the contents and whether it has been dumped or not. Furthermore, and regardless of whether the two clusters in squares B5 and B6 in B/Gmix represent a fire with an associated activity area or dumping events, these clusters may have formed before, during or after the activities in squares B4 and C4.

The high densities of bone and stone in the HP layers appear less contained than the clusters in the post-HP layers. There is a high density of bone in squares B5 and B6 in PGS (Figure 9.4), partly overlapping the combustion features H2 and H3 and the ash patches in square B5. These bones could have been thrown into or processed next to the combustion features, although the bones appear to have been redistributed when compared to the placement of the combustion features. Similarly, the high densities of stone in squares B5 and B6 in PGS may represent stone tool production by the combustion features and ash patches in this area and possible redistribution of the material. However, it is also possible that the ash patches in square B5 represent material that was dumped by H2 and H3 in PGS and that dumping and subsequent redistribution have merged the material from the different events (burning and dumping). In square C5 in layer PGS, there is a high density of bone and a medium high density of stone that partly overlap. These high densities of bone and stone could represent activities connected with the ash patch and H1 in C4, the high density of charcoal in C6 and/or the ash patches and combustion features in B5 squares B5 and B6, or they could represent separate activities.

The area studied in PGS2 is smaller than in PGS, yet there are partly overlapping clusters of high density of bone and stone in PGS2. A high density of bones is

overlapping H1 and H2 in PGS2 and could be bones thrown into these combustion features, and the medium high density of bones in square B4 in PGS2 could represent bones burned in H5 or one of the other combustion features in this area. The high densities of stone in PGS2 coincide with combustion features. It is possible that both the stone and bone have been dumped in this area, but also that this material is redistributed by trampling or subsequent activities in the area. Furthermore, H5 in PGS2 was the only combustion feature identified as a hearth through micromorphological analysis. H5 contains a smaller proportion of stone than the other combustion features in PGS2 (Table 9.1), though there is a high density of stone next to H5. This might represent stone tool production next to this hearth or others in the same square.

9.5.4 DIACHRONIC DIFFERENCES

We have discussed data and interpretations of types of combustion features, fire-related behaviour and spatial distribution in the selected post-HP and HP layers in the previous sections. Diachronic differences between post-HP and HP layers at Sibudu have been suggested (Goldberg et al., 2009; Wadley & Jacobs, 2006; Wadley et al., 2011), and the following hypotheses for the differences have been put forward:

Since the vast majority of sediments at Sibudu result from anthropogenic deposition, the homogenous Howiesons Poort and earlier layers, representing lower deposition rates, would suggest that there was an increase in the intensity of occupation at Sibudu during the post-Howiesons Poort occupation. Another possible, but not mutually exclusive, hypothesis is that the use of sedge and/or grass bedding influenced the effects of trampling on the different types of deposit. (Goldberg et al., 2009, p. 120)

In this section, while being aware of the small data sample in this paper, we shall discuss to what extent our data support these hypotheses.

H1 in BYA2(i) and H1 in PGS are previously interpreted as, respectively, multiple or single episodes of burning bedding (Goldberg et al., 2009; Wadley et al., 2011), which is the same conclusion as we offer in this paper. Multiple episodes of burning bedding suggest intensive occupation not only because of the many burning events and effort spent on site maintenance, but also takes into account the time spent on processes such as gathering the large amounts of plant material needed to produce thick layers of bedding (see Miller & Sievers, 2012; Sievers, 2013a). Our analysis of H in B/Gmix (post-HP) suggests that it contains multiple episodes of burning, thus supporting the interpretation of repeated or intensive occupation during the post-HP.

The last combustion feature included in the micromorphological analysis, H5 in PGS2, was found to be a classic hearth. The organic petrological analysis implies the placement of many herbaceous plants, but little wood in the hearth, although the charcoal analysis identified woody genera such as *Podocarpus* in layer PGS2. Wood generally produces fires that last longer than herbaceous plants, and these soft plants may be used as tinder and not as primary fuel (see e.g., Albert & Marean, 2012). The use of many herbaceous plants with little wood thus suggests short fires. A similar observation has previously been made at Sibudu where it was suggested that there were few signs of deliberate selection of taxa, implying minimal knowledge of wood properties and/or short occupations (Allott, 2005). However, the lithic component in the HP technocomplex includes backed blades and segments thought to be hafted (see e.g., Lombard, 2005, 2007; Lombard & Phillipson, 2010; Wadley, 2005a; Wadley et al., 2009) and Allott (2005) points out that people that produce wooden shafts for hafting would be expected to be familiar with wood qualities. Furthermore, our charcoal analysis shows selection of taxa with aromatic leaves and/or bark and wood (Section 9.5.2 and Table 9.2), which implies knowledge of plant properties. Aromatic taxa have been identified in 77 ka pre-Still Bay layers (Wadley et al., 2011), suggesting this property in plants was known before the HP. Selection of plants for bedding (see Sievers, 2013a) also suggests an awareness of the environment and the qualities of different plants. It is thus likely that people living during the HP had knowledge of

wood properties and that brief occupation spans with short-lived fires are the reason for little charcoal in the HP layers.

Allott (2005) observed more selection of woody taxa known as good firewood in post-HP layers than in HP layers. The new charcoal analysis presented here did not distinguish a clear difference through time in the selection of firewood taxa, but the sample size was small and the sample contained less charcoal suitable for analysis from the HP layers than from the post-HP layers (see Section 9.4.2). The post-HP sample did contain more aromatic taxa than the HP sample, suggesting more use of such plants. More aromatic taxa may point towards intensified use and more need for insect repellents, although the difference in aromatic taxa might also be a result of sample size.

There is little difference between temperatures in HP and post-HP layers as suggested by the organic petrological analysis (Section 9.4.4 and Table 9.3). On the one hand, the similar temperatures could suggest similar maintenance techniques for fire in the HP and post-HP. On the other hand, we saw in Section 9.5.2 that other studies from other layers have identified a wider range of temperatures at Sibudu (Clark & Ligouis, 2010; Herries, 2009). The range of temperatures in fires at Sibudu and the differences between temperatures in HP and post-HP layers might thus be larger than represented by our analysis.

There are some differences in the weights of bone, charcoal and stone and the spatial distribution in HP and post-HP layers. Much of the bone, charcoal and stone in the post-HP layers BYA2(i) and B/Gmix was found inside combustion features (see Table 9.1), but much material in the HP layers PGS and PGS2 was found outside combustion features. Redistribution of material through trampling has been observed in the HP micromorphological slides (Goldberg et al., 2009), which may explain the different distributions. However, the percentage of material found inside combustion features also raises the question of the protective effect of the bedding material (see Goldberg et

al., 2009) in the post-HP layers, for example layer BYA2(i). The other post-HP layer included here, B/Gmix, does not contain clusters of material that are as well-defined in the bedding area, perhaps due to chemical diagenesis or to more widespread activity there. The bedding area of H1 in PGS did contain little bone and stone, suggesting even fewer activities there. These observations appear to support the idea that bedding holds material in place and that there were intensive activities carried out in the post-HP layers.

9.6 CONCLUSION

In general, this study confirms results from previous studies (e.g., Allott, 2005, 2006; Goldberg et al., 2009; Wadley et al., 2011). The first aim here was to identify types of combustion features at Sibudu. Our sample consisted of two combustion features from post-HP layers, both of which represented multiple episodes of burned bedding, and two combustion features from HP layers. One of the latter was identified as a single episode of burning bedding, while the other was interpreted as a classic hearth. These results illustrate the importance of using micromorphology in addition to field observations from archaeological sites, because all of the combustion features were interpreted as hearths in the field.

The second aim of the paper was to examine fire-related activities. Aromatic taxa that might function as insect repellents were identified from charcoal fragments, which did not demonstrate clear preferences for firewood taxa. Many herbaceous plants were burned in the combustion features, and the organic petrological analysis also suggested a limited temperature range for the fires.

The third aim was to identify spatial distributions of artefacts. High densities of charcoal were recognised within combustion features in the post-HP layers, but not in the HP layers. Bone and stone were clustered within the bedding area in BYA2(i) and

B/Gmix, although the latter layer contained a cluster of bone and a cluster of stone implying activities outside of the bedding area. The high density clusters in PGS and PGS2 may represent activity areas near hearths, although redistribution of material may also have occurred.

The last and fourth aim was to identify diachronic differences in fire-related behaviour. Multiple episodes of burning bedding, lots of charcoal, aromatic woody taxa and clusters of material suggest rapid accumulation and intensive occupations of the post-HP layers. Single episodes of burned bedding, little charcoal and lots of herbaceous plants imply short fires. Scatters (as opposed to clusters) of material can imply redistribution from trampling or rake-out, or they can imply short and ephemeral occupation. However, our sample size is limited and these conclusions are therefore speculative and need confirmation with larger samples.

This study provides an example of the strengths of a multi-disciplinary approach in which many methods complement each other. For example, the organic petrological analysis could distinguish herbaceous plants from wood in the HP samples, while the woody taxa burned could be identified by charcoal analysis. The combination of the kernel density analysis and the micro stratigraphic analysis using micromorphology combines data of different resolutions, and allows different perspectives on the site. The multi-disciplinary approach thus allows detailed information on many aspects of the site and helps build different strands of evidence. In the next chapter, I shall study the pH and charcoal in selected archaeological and experimental combustion features to see whether these data can provide insight into the formation processes at Sibudu.

9.7 ACKNOWLEDGEMENTS

We thank Dr L. Allott for the charcoal identifications, completed as a contract and Dr. Jamie Clark for providing us with the weights of unidentified bone fragments. SEB

thanks PAST – Palaeontological Scientific Trust and their Scatterlings of Africa programme for funding. LW thanks the National Research Foundation for research grants that enabled the excavation of Sibudu. Results and inferences are, however, those of the authors and not the funding or supporting institutions.

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10 ASH pH AND CHARCOAL FROM ARCHAEOLOGICAL SAMPLES AND EXPERIMENTAL COMBUSTION FEATURES

The previous chapter analysed some diachronic differences between features and layers at Sibudu. In this chapter, I shall include both experimental and archaeological samples to further describe selected archaeological combustion features and examine if predictions about prehistoric fire use and site formation can be made from experimental fires (see aims for this thesis in Section 1.1). More specifically, I want to examine if different types of combustion features (hearths, ash dumps, burned bedding) and layers containing selected lithic industries (HP and post-HP) can be recognised using selected contents (ash pH and weight of charcoal) of combustion features. This is important because it might help researchers identify different types of combustion features and formation processes, and it can also contribute to the understanding of differences identified through other methods, such as the diachronic differences in fire-related behaviour identified through micromorphological analysis and seed and plant identifications as described in Chapter 10 (see also Goldberg et al., 2009; Sievers, 2013a; Wadley et al., 2011). This chapter consists of 2 sections (10.1 Ash pH and 10.2 Charcoal), which both are structured similarly: First a short introduction to the section, followed by the method used, results, discussion of results and a short comment on the archaeological implications.

10.1 ASH pH

Ash is alkaline, although the constituents of ash and its surrounds can vary. The properties of the local topsoil horizon affect the pH value, but post-depositional processes can also reduce the pH value (see e.g., Canti, 2003; Goldberg & Macphail, 2007 and references therein). For example, the pH of bat guano can affect sediments

and the diagenesis in caves occupied by bats and the degradation of organic matter in the bat guano can contribute to a reduction in pH values by ca. 1.5 pH points, dependent on the diet of the bats (Shahack-Gross et al., 2004). Ash and pH can also affect the preservation of objects such as bone (e.g., Berna et al., 2004; Karkanas et al., 2007) that are embedded in the sediments. I measured the pH values of ash from selected combustion features at Sibudu as well as some of the combustion features from my experiments to examine if there are differences in pH values between hearth strata in combustion features, different types of combustion features or features formed under different archaeological industries. Note that some of the pH values below were also presented by Sievers (2013a), who noted that the damage observed on phytoliths from Sibudu is consistent with the alkaline pH values recorded in some of my experiments (Sievers, 2013a, p. 31). The relationship between pH values and preservation will not be discussed here.

10.1.1 METHOD

Soil samples were taken from combustion features during excavation and during my fire experiments. Some of these samples were analysed by Prof. Mary Scholes at the University of the Witwatersrand for research projects conducted by Dr. Christine Sievers and Prof. Lyn Wadley. These samples are named Sib and a number (Table 10.1). The samples named # and a number were analysed by me in the soil laboratory at the School of Geography, Archaeology and Environmental Studies, and I selected experimental samples for this analysis to ensure that I included samples from all hearth strata and from fires burning different wood taxa. Both the samples analysed by Prof. Scholes and samples analysed by me were diluted in 5:1 distilled water. Missing numbers from the Sib samples belong to samples not relevant for this thesis and missing numbers from the # samples belong to modern samples that are not included in my project.

10.1.2 RESULTS AND DISCUSSION

The pH values are given in Table 10.1. The average pH value for the archaeological samples was 6.73 and the average value for the experimental samples from combustion features (excluding samples #11 and #17 taken from clean topsoil horizons) was 8.85. The top hearth stratum of white ash in experimental combustion features had a higher pH value than the topsoil horizon. For example, the top of the combustion feature produced in E1 (#18) was very alkaline with a pH value of 10.51, whereas the topsoil horizon in the experiment was neutral with a pH value of 7.45. The pH values of the middle and bases of hearths were closer to the value of the topsoil horizon they were started on.

Table 10.1 Experimental and archaeological pH readings. Values from HP layers are shaded light grey, values from post-HP layers are not shaded and the experimental samples are shaded dark grey. Part 1 of 2.

Label	Type	Context	pH value
#6	Arch	PGS2	7.36
#2	Arch	Top of H2 in PGS2	6.62
#3	Arch	Top of H1 in PGS2	6.81
#4	Arch	Middle of H1 in PGS2	7.45
#5	Arch	Base of H1 in PGS2	7.50
Sib17	Arch	PGS	7.54
<i>Average pH value from HP layers</i>			6.18
Sib23	Arch	Top of H1 in Brown under YA2(i)	6.08
Sib24	Arch	Middle of H1 in Brown under Ya2(i)	6.09
Sib25	Arch	Base of H1 in Brown under YA2(i) – black lens	5.83
#7	Arch	Brown under YA2(i) Ash dump	5.86
Sib8	Arch	Top of Hearth in B/Gmix	5.81
Sib26	Arch	Base of H in B/Gmix	5.90
#1	Arch	Ash dump from H1 on B/G mix	5.29
<i>Average pH value from post-HP layers</i>			5.84

Table 10.1 (continued). Part 2 of 2.

Label	Type	Context	pH value
#11	Exp	Topsoil horizon E1 – E10	7.45
#18	Exp	E1 top of hearth	10.51
#21	Exp	E1 middle of hearth (red lens)	8.43
#20	Exp	E1 middle of hearth	7.88
#19	Exp	E1 base of hearth	7.78
#26	Exp	E9 top of hearth	11.02
#14	Exp	E9 top of hearth (beige lens)	8.80
#16	Exp	E9 middle of hearth (red lens)	8.85
#27	Exp	E9 base of hearth	7.52
#24	Exp	E10 top of hearth	10.70
#13	Exp	E10 middle of hearth	8.36
#28	Exp	E10 base of hearth	6.24
#17	Exp	Topsoil horizon F4 and F5	5.62
#23	Exp	F4 top of hearth	10.32
#22	Exp	F4 top of hearth (grey lens)	10.09
#15	Exp	F4 middle of hearth	9.56
#25	Exp	F4 black base	8.08
#12	Exp	F4 ash dump	8.38
Sib27	Exp	F1 Ash dump	9.70
Sib28	Exp	F3 top of hearth	10.86
Sib30	Exp	F3 middle of hearth	9.55
Sib29	Exp	F3 base of hearth	8.05

We have seen in Chapters 7 and 8 that the white top hearth stratum produced in my experimental hearths consists of white ash and charcoal, while the black and rubified strata represent heat-induced changes of the topsoil horizon (see also Mallol et al., 2013a). The pH values from the experimental hearth strata support this suggestion. For the purposes of the statistical analysis, I ranked hearth strata by their inherent order

from top to base so that the top stratum has value 1, the middle stratum 2 and the base stratum of a feature has value 3. The strong relationship between ashy strata (that is, the top stratum of the features), middle and base strata in my experiments on the one hand and pH values on the other is statistically significant ($r_s = -.80, p > .01$). Furthermore, the few exceptions to this rule in Table 10.1 are related to where the sample was collected. Sample #14, for example, was taken from a beige lens in the top of E9 and returned a lower value (8.80) than the other samples from top strata in other experimental combustion features and also a lower value than sample #26, which was taken from the proper white ash in the same feature (pH value 11.02). Sample #14 was taken closer to the middle strata than sample #26, which could be the reason for the lower pH value.

The pH values of the experimental combustion features do not appear to have a relationship to the wood taxon burnt, even when I sample only the strata containing the most ash (top of hearth and ash dump) from my experiments. However, the sample size of many wood taxa is very small. The statistical results after comparing pH value with wood mass ($r = -.13, p = .59$) or the number of fires in the hearth ($r = .09, p = .72$) in the experimental sample were not significant and did not reveal a strong relationship between the variables.

There is a difference between the pH values for the ashy strata (ash dumps and top strata) on the one hand and the values for other hearth strata (middle and base) and the matrix of the layer on the other hand for the archaeological samples. The relationship between these variables is moderate and not statistically significant ($r_s = .58, p > .05$), but the sample size is also small. The tops of hearths in PGS2 (samples #2 and #3) were acidic compared to the sample from the matrix of layer PGS2. The samples from the post-Howiesons Poort layers B/Gmix and BYA2(i) were generally more acidic than the samples from the HP layers. There is a very strong and statistically significant difference between the pH values of the two archaeological industries ($r = .91, p = .00$), although the sample sizes are small. The more acidic conditions in the post-HP layers

could be related to more burning of bedding and plant material in these layers than in the HP layers (Chapter 9; see also Goldberg et al., 2009; Wadley et al., 2011), and Sievers (2013a, p. 31) has previously noted that different plant material burned at Sibudu should be considered together with pH values at the site.

On the one hand, the pH values of the two archaeological ash dumps tested (Ash dump in BYA2(i) and Ash dump from H1 on B/Gmix) are similar to the pH values from other combustion features in these layers. Furthermore, the experimental ash dump from F1 (sample Sib27) has a pH value of 9.7, which is slightly lower than the tops of the other experimental hearths tested, but higher than the middle and bases of the other selected experimental hearths. These data imply that there is little difference in pH value between ash dumps and the tops of primarily deposited combustion features, perhaps because of the volume of ash in ash dumps and in the tops of combustion features. On the other hand, the pH value of the ash dump from experiment F4 (sample #12, pH value 8.38) is lower than the pH value of the top of the hearth in the same experiment (sample #23, pH value 10.32), which suggest some differences in pH values between ash dumps and other combustion features. As described in Chapters 7 and 8, however, F4 produced very little ash, and Table 10.1 shows that the pH value for the topsoil horizon for experiment F4 (sample #17) was acidic (pH value 5.62). Sediments from the topsoil horizon (acidic) were raked out with the ash (alkaline) from F4 to create an ash dump, and mixing these two components would affect the pH value. The wood taxon used in F1 produced much ash, so the ash dump from F1 would mainly consist of ash and thus have a pH value close to the top ashy stratum in a combustion feature. It appears that pH values can be used to distinguish the top stratum of combustion features from the topsoil horizon, but not to distinguish secondarily and primarily deposited combustion features because the pH value of ash dumps is dependent on the volume of ash and sediments raked out and dumped.

10.1.3 ARCHAEOLOGICAL IMPLICATIONS

These results have the following implications:

- The top white ash hearth stratum in experimental combustion features is generally more alkaline than the other hearth strata. This difference can sometimes be distinguished in archaeological samples.
- The pH value of primarily deposited combustion features cannot always be distinguished from the pH value of secondarily deposited combustion features because high volume of ash in an ash dump will have a similar pH value to the top stratum of a primarily deposited combustion feature.
- A significant difference in pH in HP and post-HP layers at Sibudu is suggested by the samples included in this study, although the sample size is small. Possible reasons for different pH values include different diagenesis and moisture content, but future studies will have to examine this diachronic difference. The relationship between the plant material burned and the pH values should be examined in the future.

10.2 THE CHARCOAL CONTENT OF COMBUSTION FEATURES

In addition to measuring the pH values, I weighed the charcoal content of archaeological and experimental combustion features. In this section, I shall use the charcoal content from archaeological and experimental hearths to examine (1) any diachronic differences in charcoal content between HP and post-HP layers and (2) if there are differences in the weight of charcoal within the different hearth strata of primarily deposited combustion features.

10.2.1 METHOD

As described in Chapter 9, I weighed the charcoal from layers PGS and PGS2 (HP industry) and B/Gmix and BYA2(i) (post-HP industry). The total mass of bone, charcoal and stone was also weighed (see Chapter 9). Some combustion features were small and/or it was not possible to separate different hearth layers, and the charcoal content from such combustion features was combined and weighed as one unit. In other combustion features, it was possible to distinguish hearth strata during excavation, and the charcoal content from each stratum was weighed separately. In experiments F3, F4, F5 and F6, I scraped half the experimental hearth to the side as an ash dump and excavated the remaining half of the experimental hearth by hearth strata (see Section 4.3.6). I do not include charcoal from the experimental ash dumps here.

10.2.2 RESULTS AND DISCUSSION

The total weights of charcoal from all the archaeological combustion features are given in Table 10.2. The table also shows the total mass of contents (bone, charcoal and stone) from the features and the percentage of charcoal as a reference because the combustion features have different sizes and, consequently, a heavy weight of charcoal in a feature can be a result of the size of the feature. The 12 HP combustion features contained on average 0.69 g charcoal, and charcoal constituted on average 0.1% of the total mass of contents from the HP features. The nine post-HP combustion features contained on average 44.18 g charcoal, and charcoal constituted on average 23.8% of the total mass of contents from the post-HP features including the two features with 100% charcoal or 1.9% of the total mass of contents from the post-HP features excluding the two features with 100% charcoal.

The time-related differences in the percentage of charcoal (compared to bone and stone) in combustion features seem large, but they are not statistically significant ($r = .40$, $p = .07$). Nevertheless, we saw in Chapter 9 that a large proportion of the charcoal from the HP layers PGS and PGS2 was found outside of combustion features and that the

Table 10.2 The charcoal content of selected archaeological combustion features. The HP layers are shaded, while the post-HP layers are not.

Feature	Total mass of bone, stone and charcoal (g)	Charcoal	
		g	% ¹
H1 PGS2	1073.7	0.8	0
H2 PGS2	1355.1	1.6	0.1
H3 PGS2	616.6	0.5	0
H4 PGS2	60.1	0.1	0.2
H5 PGS2	125.8	0.7	0.6
H6 PGS2	750.6	0.4	0
H7 PGS2	96.3	0	0
H1 PGS	172.7	0.3	0.2
H2 PGS	3267.7	0	0
H3 PGS	1353.1	3.3	0.2
Ash in PGS	637.7	0.5	0
Ash dump in PGS	314.5	0.1	0
H in B/Gmix	3277.9	41.5	1.3
H1 in B/Gmix	21.4	0	0
Ash dump B/Gmix	503.6	10.3	2.0
Ash dump 2 B/Gmix	314.5	0.1	0
H1 BYA2(i)	7523.8	303.1	4.0
SW hearth	1.6	1.6	100.0
Gray hearth	1.6	1.6	100.0

micromorphological analysis suggests that trampling and redistribution of material affected the HP layers to a large degree (see also Goldberg et al., 2009). Such processes might also explain why the percentage of charcoal is low in the HP combustion features. Furthermore, the HP layers are more alkaline than the post-HP layers, as seen above in Section 10.1. The alkalinity of the HP layers and features might have affected the preservation of charcoal and contributed to the low volume and small mass of charcoal.

¹ The percentage of charcoal is calculated from the combined content of bone, charcoal and stone in the features. Values < 0.1% are represented by 0.

Braadbaart and colleagues (2009) have demonstrated high fragmentation and, consequently, potential loss of charcoal under alkaline conditions; processes that would not favour preservation of charcoal in the HP combustion features and, at least partly, explain the different weights and percentages of charcoal in the HP and post-HP combustion features.

Other processes that may have affected the mass of charcoal in the combustion features are the wood mass burned, the choice of wood taxa, the number of fires in the hearth, or the temperatures of the fire. For example, it was mentioned in Chapter 4 that high temperatures can reduce all the charcoal to ash and some wood taxa also produce more charcoal than others (see e.g., Smart & Hoffman, 1988; Wattez, 1988, 1992). Furthermore, we have seen in Chapters 7 and 8 that *Eucalyptus globulus* wood produced less ash than the wood taxa used in the other experimental fires I conducted. Although many variables can affect the production of charcoal in a fire (e.g., Smart & Hoffman, 1988 and references therein) and I only include a limited experimental sample here, the total charcoal content from the included experiments (Table 10.3) support previous studies; some wood taxa produce more charcoal than others. For example, experiments F4 and F5, burning *Eucalyptus globulus*, produced more charcoal than the other selected experimental samples (Table 10.3; see also Chapters 7 and 8). F4 burned 15.1 kg wood in total, distributed in three fires, and F5 burned 14.1 kg wood in one fire. Nevertheless, F5 produced more charcoal than F4, suggesting that repeated fires in a hearth and reheating of charcoal can lead to more mass loss than one large fire in the hearth. It appears that the wood taxa and the number of fires in a heart could have contributed to the differences in charcoal content observed in the HP and post-HP layers at Sibudu. However, the differences in pH values identified in Section 10.1 and the different processes (e.g., gypsum formation) identified through micromorphological analysis (Chapter 9; see also e.g., Goldberg et al., 2009; Wadley et al., 2011) suggest different diagenesis in the HP and post-HP layers, which would also affect the charcoal content.

The second research question in this section relates to the hearth strata. We saw in Chapters 7 and 8 that the experimental fires did not produce hearths with a distinct charcoal stratum, and Table 10.3 shows the charcoal content in the hearth strata of the experimental hearths included here. (As described in Chapter 4 and above, one half of these experimental hearths were scraped out to create an ash dump and the weights in Table 10.3 only represents the remaining half of the hearth.) Table 10.3 shows that all the included experimental samples contained more charcoal in the top stratum (38 – 93%) than in the middle (6 – 27%) and base (1 – 35%) strata. This shows that the lack of a distinct charcoal-rich stratum at the base of these experimental hearths was not just an impression during excavation (see also Chapter 4); it is also supported by the weight of charcoal from the hearth strata.

Table 10.3 The charcoal content in the hearth strata of selected experimental hearths. Please note that half the hearth was scraped out to create an ash dump and that charcoal from the ash dump is not included in this table.

		Charcoal content by hearth stratum					
		Total	Top	Top	Middle	Middle	Base
Experiment	(g)	(g)	(%)	(g)	(%)	(g)	(%)
F3	6.65	2.51	38	1.80	27	2.34	35
F4	94.70	88.27	93	5.22	6	1.21	1
F5	105.02	88.45	84	12.93	12	3.64	4
F6	13.97	12.92	92	0.90	6	0.15	1

Field observations from Sibudu suggest a distinct black base stratum rich in charcoal (see e.g., Wadley, 2012a; Wadley & Jacobs, 2006) in primarily deposited archaeological combustion features. Table 10.4 shows the charcoal content from selected archaeological combustion features where it was possible to excavate different hearth strata. The base stratum of the included HP combustion features contains 32 – 100% of the charcoal found in the features, and the base stratum in the post-HP combustion features contains 56 – 90%. The charcoal content of the base stratum in the selected combustion features thus conforms to the expectation of a large proportion of charcoal

in the base stratum of archaeological combustion features. Nevertheless, the top stratum in the post-HP combustion features contains a small proportion of the charcoal (10 – 18%) found in the combustion feature, in contrast to both the experimental sample included (38 – 94%) and the HP sample (30 – 61%, excluding H6 in PGS2). Diagenesis or pyrotechnological techniques have been suggested to influence the distribution of charcoal within combustion features (see Mallol et al., 2013a), and these are possible explanations for the difference between the hearth strata of my experimental hearths and the archaeological sample from Sibudu. Furthermore, my data on charcoal content suggest diachronic differences in the contents of hearth strata which may again be a result of different diagenesis as mentioned above. There is clearly a potential for future studies of the diagenesis at Sibudu, using a combination of different methods.

Table 10.4 Charcoal content in hearth strata from selected archaeological combustion features. The HP features are shaded, while the post-HP features are not.

Combustion feature	Total (g)	Charcoal content by hearth stratum					
		Top (g)	Top (%)	Middle (g)	Middle (%)	Base (g)	Base (%)
H1 PGS2	1.40	0.45	32	0.83	59	0.12	9
H2 PGS2	1.61	0.78	48	-	-	0.83	52
H3 PGS2	0.51	0.31	61	-	-	0.20	39
H6 PGS2	0.42	-	-	-	-	0.42	100
H1 PGS	0.43	0.13	30	-	-	0.30	70
H1 BYA2(i)	287.34	51.29	18	75.61	26	160.44	56
H3 BYA2(i)	1.06	0.11	10	-	-	0.95	90
H in B/Gmix	41.51	4.14	10	-	-	37.37	90

10.2.3 ARCHAEOLOGICAL IMPLICATIONS

These results have the following implications:

- The wood taxon burned and the number of fires in a hearth can affect the total weight of charcoal in a combustion feature.
- There is a difference in the total weight of charcoal in the HP and post-HP features, and this supports other analyses, such as micromorphology, that suggest diachronic differences in fire-related behaviour and, possibly, differences in the post-depositional processes that affect HP and post-HP layers (see e.g., Chapter 9; Goldberg et al., 2009).
- The top stratum of my experimental hearths contains more charcoal than the middle and base strata. In contrast, most of the charcoal in all of the included post-HP combustion features and three of the included HP features was found in the base stratum. The difference between experimental hearths and archaeological combustion features may be a result of diagenesis and should be examined in future studies.
- There is a diachronic difference in charcoal content in the top stratum of the included archaeological combustion features; the top stratum of post-HP combustion features contains less charcoal than the top stratum of HP combustion features.

These implications can be tested in the future, but must also be evaluated in the context of the other results in this thesis. In the following chapter, I shall summarise and discuss results and archaeological implications of the results from all the chapters in this thesis. I shall also summarise suggestions for future studies that arise from this thesis.

11 DISCUSSION AND CONCLUSION

In this thesis, I have examined the characteristics of MSA pyrotechnology through actualistic fire experiments, spatial analysis and an in-depth study of properties of selected combustion features at Sibudu. I have also collaborated with other researchers, who have contributed micromorphological, organic petrology and anthracological results (Chapter 9). In this chapter, I shall summarise and discuss the results presented in previous chapters and the aims presented in Section 1.1.

To give the reader a brief reminder, the main aim of this thesis is to examine, describe and discuss the characteristics of MSA pyrotechnology by studying the use, reuse and discard of selected combustion features. I acknowledge that the sample size is small and not sufficient for a comprehensive understanding of fire use in the MSA, or at Sibudu, but aim to provide insight into this technology at selected occupation phases at the site and thus to provide a foundation for future research on fire-related behaviour at Sibudu and other MSA sites. Properties of selected combustion features are described in terms of their formation and use, but also to gain an understanding of how fire-related behaviour at the site contributed to the formation of Sibudu. A last aim for the thesis is, therefore, to make predictions about prehistoric fire use and site formation through experimental fires. Results from statistical testing are summarised in Tables 11.1, 11.2 and 11.3.

The first three sections in this chapter are structured by important terms from the aims; namely, the use, reuse and discard of fire. These sections also include discussions on the actualistic fire experiments. The fourth section of this chapter contains an evaluation of my results in light of the aims. The fifth section contains some suggestions for future research and Section 11.6 summarises implications for MSA pyrotechnology stemming from this thesis.

Table 11.1 Summary of results from statistical testing in Chapter 6. The results are presented in the same order as they appeared in the text. Analyses of Pearson's product moment correlation are shaded, while analyses of Spearman's Rank correlation coefficient are not.

Relationship tested	Correlation	Significance	N
Wood mass / Maximum surface temperature	.01	.97	37
Number of logs / Maximum surface temperature (all fires)	.32	.05	37
Number of logs / Maximum surface temperature (5 kg wood)	.44	.02	29
Type of fire (primary, secondary, tertiary) / Maximum surface temperature (all experiments)	.43	.01	32
Type of fire (primary, secondary, tertiary) / Maximum surface temperature (only 2 nd cycle of experiments)	.36	>.05	16
Topsoil horizon / Maximum surface temperature (all fires)	.34	<.05	37
Topsoil horizon / Maximum surface fires (primary fires)	.23	>.05	19
Topsoil horizon / Average surface temperature during 1 st hour of temperatures >100°C (all fires)	-.47	<.01	37
Topsoil horizon / Average surface temperature during 1 st hour of temperatures >100°C (primary fires)	-.43	>.05	19
Number of logs / Average surface temperature during 1 st hour of temperatures >100°C (all fires)	.05	.75	37
Maximum surface temperature / Average surface temperature during 1 st hour of temperatures >100°C (all fires)	.55	.00	37
Maximum subsurface (5 cm) temperature / Type of fire (primary, secondary, tertiary fires)	.19	>.05	29
Topsoil horizon / Maximum subsurface (5 cm) temperature	.05	>.05	33
Maximum subsurface (5 cm) temperature / Wood mass (primary, large fires)	.46	.06	17
Maximum subsurface (5 cm) temperature / Wood mass (all fires)	.47	.01	33
Number of logs / Maximum subsurface (5 cm) temperature	.54	.00	33

Table 11.1 (continued). Part 2 of 2.

Relationship tested	Correlation	Significance	N
Maximum surface temperature / Maximum subsurface (5 cm) temperature (all fires)	.11	.53	33
Maximum surface temperature / Maximum subsurface (5 cm) temperature (primary and large fires)	.24	.35	17

11.1 THE USE OF FIRE

I made several observations on the use of fire during my research and I have split this section in two parts to make it easier to read.

11.1.1 USING THE FIRE

The use of fire includes preparations for using fire, such as the selection of firewood. We saw in Chapter 9 that Dr. L. Allott's charcoal analysis did not imply that specific taxa were selected as firewood and this result supports previous charcoal analyses (Allott, 2005, 2006). Lack of a strong selection of firewood taxa could mean that people were not aware of firewood properties; however, Allott's identification of taxa with aromatic leaves and/or bark and wood (Chapter 9; see also Wadley et al., 2011 on aromatic taxa at Sibudu), which could be used as insect repellents, imply that people were knowledgeable about plant and wood properties. The organic petrology analysis by Dr. B. Ligouis presented in Chapter 9 implies that many herbaceous plants were burned in the analysed combustion features, suggesting that long wood burning fires were not always desired at Sibudu. The bones that were thrown into the fire as a method of disposal (see Cain, 2005; Clark & Ligouis, 2010) likely contributed to fires that produced more light than wood burning fires (see Théry-Parisot, 2001, 2002).

Nevertheless, wood was burned at Sibudu, and my experimental results (Chapters 4 – 6) imply that c. 5 kg firewood can produce high surface temperatures for many hours. For example, Fire F6.1 burned 5.1 kg *Acacia erioloba* wood on fine sand (sieavings from Sibudu) and produced a maximum surface temperature of 529°C after 13 hours 15 minutes and Fire E6.1 burned 5 kg *Dichrostachys cinerea* wood on fine/medium sand (in Johannesburg) and produced a maximum surface temperature of 466°C after 3 hours 45 minutes (see Table 4.2). These temperatures are well within the range needed for cooking (see e.g., Wandsnider, 1997), and imply that wood burning fires similar to my experimental fires could be used for a long period. The observation that 5 kg of wood produces heat for several hours also implies that limited effort was needed to gather the wood mass that was strictly necessary for activities such as cooking (see also Chapter 5).

Previous studies demonstrate that the texture of the topsoil horizon only has a minor effect on the thermal conductivity of the soil (Campbell et al., 1994; Canti and Linford, 2000) and thus is less important for the temperatures of a fire than other variables. When examining the temperatures of the primary fires in Chapter 6, I found that there was no relationship between the texture of the topsoil horizon and the maximum surface temperatures or the time taken to reach the maximum surface temperatures in my experimental fires (see also Table 11.1). Although the result is not statistically significant, it does support the previous studies. I showed in Section 6.2.3 that there is a correlation between the average temperatures during the first hour of the primary fires in my experiments and the texture of the topsoil horizon (Table 11.1); however, this correlation is also not statistically significant. In summary, it appears that the texture of the topsoil horizon only has a minor influence on the temperatures and, consequently, the use of fires, but I shall return to this issue when discussing topsoil horizons of ash and reuse of combustion features in Section 11.2.

Furthermore, my experiments demonstrate that the surface temperatures of a fire can vary even when variables such as firewood taxon, wood mass and topsoil horizon are controlled. For example, Fire E1.1 reached a maximum surface temperature of 739°C after 4 hours and Fire E2.1 reached a maximum surface temperature of 594°C after 2 hours 45 minutes (see Table 4.2). Both these fires burned 5 kg *Dichrostachys cinerea* on fine/medium sand in Johannesburg. The different maximum surface temperature and the different time taken to reach peak temperature in Fire E1.1 and E2.1 do not reflect environmental differences because these two fires were started at the same place and at the same time. This result suggests that it can be very difficult to control the surface temperatures of a fire. Yet the organic petrological results presented in Chapter 9 suggest that selected fires at Sibudu produced temperatures within a small range (289 - 319°C). There might be different explanations for this small range of temperatures produced by fires at Sibudu, although these interpretations are not mutually exclusive. Firstly, previous studies of Sibudu have found that bones have burned at 300 - >800°C (Clark & Ligouis, 2010) and that rocks have been heated to 400 – 500°C (Herries, 2009), suggesting that some fires produced a wider range of temperatures than those presented in Chapter 9 and that the small range of temperatures is caused by the sample size. Secondly, particular combustion conditions such as damp bedding that smoulders could produce moderate temperatures (Goldberg et al., 2009) and at least partly explain the temperature range presented in Chapter 9. Thirdly, and lastly, my experiments demonstrate that adding logs to a fire at regular intervals is one method to ensure more even surface temperatures and a longer duration of heat in a fire (Chapter 5). It is possible that maintenance techniques were used to control the temperatures so that at least some fires at Sibudu produced temperatures within a limited range.

I recorded the subsurface temperatures of my experimental fires as well as the surface temperatures. The subsurface temperatures are more predictable than the surface temperatures (see Chapters 5 and 6), suggesting that it would be convenient to use these temperatures for activities where a certain range of temperatures are desirable. We do not, however, yet know if or to what extent subsurface temperatures were used in the MSA. It has been suggested that people in the MSA carefully heat treated silcrete rocks

in sand for easier shaping of tools (see Brown, 2011; Brown et al., 2012, 2009; Mourre et al., 2010), but this interpretation has been challenged because careful heating does not appear to be necessary for South African silcretes (Schmidt et al., 2012, 2013). There are no reports of subsurface combustion features in the MSA (see Chapter 2), which suggests that subsurface temperatures was not exploited. Yet rocks could potentially be heated under heaps of sand or in shallow pits covered by sand and ashes (see e.g., description of method in Brown et al., 2009), which might be impossible to distinguish from ash dumps once the sand and ashes were raked out and the heated rocks retrieved. Nevertheless, my experiments were not designed to examine if subsurface heat treating of rock was conducted; I only examined the predictability of the subsurface temperatures and cannot draw conclusions on their use.

In the spatial analysis of selected layers from Sibudu, presented in Chapter 9, I identified high density clusters of bone and stone that may represent activity areas by combustion features. In layer B/Gmix, for example, I found a high density of bone in square B6 and a high density of stone in square B5 which may represent, respectively, bones thrown into a fire and a knapping area. These two clusters may or may not represent contemporaneous events. Another example is layer PGS, where high densities of bones and stones represent activities by the combustion features H2 and H3 in square B6. The clusters in PGS may, however, represent dumping of material and/or redistribution of material through trampling as well as activity areas. It is hardly surprising that activities were performed next to combustion features; however, my spatial analysis only provided a general picture of the activities in relation to the combustion features. Detailed studies of the contents of each cluster should be conducted to examine the association between the clusters and the combustion features and to identify spatial relationships between specific combustion features and specific activities.

Lastly, turning to the question of diachronic differences at Sibudu (Goldberg et al., 2009; Wadley et al., 2011), there appear to be some differences in the use of fire

between the HP and the post-HP. The organic petrological analysis suggested burning of less woody taxa and more herbaceous plants in the HP layers (Chapter 9), which implies shorter fires than in the post-HP layers. The micromorphological analysis by Dr. C. Miller (Chapter 9; see also Goldberg et al., 2009; Wadley et al., 2011) implies repeated burning of bedding in the post-HP layers compared to single episodes of burning in the HP layers. The spatial analysis presented in Chapter 9 shows that the two combustion features containing burned bedding in the post-HP layers are associated with contained clusters of bone and stone (see Figures 9.5 and 9.6), whereas the one combustion feature containing burned bedding included from a HP context (Figure 9.4) does not contain high densities of bone and stone. The different densities of bone and stone associated with the burned bedding could be a result of intensified dumping activities and/or of more bone and stone being associated with multiple bedding (and activity) episodes than with fewer bedding episodes. Although the sample size is small, the different densities of bone and stone in the post-HP bedding compared to the HP bedding appears to support the interpretation of longer, intensified occupation during the post-HP (as suggested by Goldberg et al., 2009).

Table 11.2 Summary of results from statistical testing in Chapter 8. The results are presented in the same order as they appeared in the text. Analyses of Pearson's product moment correlation are shaded, while analyses of Spearman's Rank correlation coefficient are not.

Relationship tested	Correlation	Significance	N
Number of hearth strata / Number of fires in the hearth	-.23	.35	19
Number of hearth strata / Wood mass	.45	.06	19
Topsoil horizon / Number of hearth strata	.13	>.05	19
Hearth area / Wood mass	.81	.00	20
Topsoil horizon / Hearth area	.50	<.05	20
Hearth area / Hearth depth	.46	.04	20
Topsoil horizon / Hearth depth	-.05	>.05	20
Ash depth / Number of fires	.13	.59	20

11.1.2 THE USE OF FIRE AND SITE FORMATION PROCESSES

This thesis also contributes results that help to explain site formation processes at Sibudu. My experimental fires showed that the production of an upper white ashy stratum in a combustion feature depends on the amount of ash produced by the wood taxon or taxa burned (see Chapters 5, 7 and 8). The thickness of the white ash layer can only be used to estimate the wood mass burned in the fire if the wood taxon produces much ash. In other words, it is necessary to be familiar with the wood taxon (taxa) burned in a fire if one wants to estimate wood mass burned based on the ash produced. Nevertheless, most of my experimental hearths contained a clear white stratum at the top, similar to most of the primarily deposited combustion features at Sibudu (see e.g., Chapter 3).

My experiments also demonstrated that the hearth area, calculated from the extent of the top white ash stratum (see Chapters 4, 7 and 8), is dependent on the wood mass burned (see also Table 11.2). When including all my experimental hearths, fires burning 5 – 10 kg wood produced hearth areas of 962.1 – 1385.4 m² and fires burning 14 – 15 kg wood produced hearth areas of 1590.4 - 1963.5 m² (see Section 8.2). The logs burned in all these fires were arranged in similar tepee formations before the fires were started and it cannot be ruled out that this affected the shape of the experimental hearth and, consequently, the hearth area. My experimental fires only burned wood, and it is plausible that a combination of, for example, wood and herbaceous plants would have affected the shape of the hearth and the hearth area. The experimental burning of sedges to replicate burning bedding conducted by Sievers (2013a; see also Miller and Sievers, 2012; Sievers, 2013b) was not designed to examine the ashy area left after the fire, but Sievers (2013b, p. 204) noted that the ashes, remaining after one of the fires had died, spread and covered a larger area than the dry sedges did before the fire. This suggests that burning bedding may have an effect on the size of the combustion feature, but more work is needed to examine how the arrangement of firewood and the burning of plant material affect hearth area compared to my experiments with wood fires.

Table 11.3 Summary of results from statistical testing in Chapter 10. The results are presented in the same order as they appeared in the text. Analyses of Pearson's product moment correlation are shaded, while analyses of Spearman's Rank correlation coefficient are not.

Relationship tested	Correlatio	Significanc	N
Hearth strata (top, middle, base, topsoil) / pH value	-.80	>.01	22
pH value / Wood mass (experiments)	-.13	.59	20
pH value / Number of fires (experiments)	.09	.72	20
Hearth stratum (ashy or other) / Topsoil horizon (archaeological sample)	.58	>.05	13
pH value / Archaeological industry	.91	.00	13

My analysis of pH values (Chapter 10, Table 11.3) shows that the white ash top stratum generally has a higher pH value than the surrounding matrix. However, the pH values from the selected post-HP combustion features are more acidic than the selected HP combustion features. Sievers (2013a, p. 30) suggests that the type of plant material burned should be studied in combination with the pH values at Sibudu. It is possible that the plant material used for bedding (see e.g., Sievers, 2013a; Sievers and Muasya, 2011) contributed to the acidity in the post-HP layers, where there are multiple bedding episodes, unlike the situation in the HP layers, but this question remains open for future studies.

Combustion features at Sibudu often contain a basal black charcoal stratum (see Chapter 3) and a similar stratum has been observed in classical archaeological hearths (e.g., Schiegl et al., 1996). Yet my experiments did not produce a similar separate stratum rich in charcoal in the experimental hearths (see Chapters 4, 7 and 8), and this is consistent with other experimental results (e.g., Mallol et al., 2013a). It is possible that pyrotechnological techniques are at least partly responsible for the lack of the charcoal-

rich stratum in the experimental hearths (see Mallol et al., 2013a), but post-depositional processes might also have been responsible for altering the archaeological combustion features. There are some signs of different post-depositional processes affecting the HP and post-HP layers. For example, a larger proportion of bone, charcoal and stone was found outside the combustion features in the HP layers than in the post-HP layers (see Table 9.1), which may be the result of trampling and the protective effect of bedding material in the post-HP layers (see Goldberg et al., 2009; Wadley et al., 2011). The HP combustion features also generally contain a smaller proportion of charcoal than the post-HP combustion features (see Table 10.2). The separate black stratum that is rich in charcoal has, however, been found in both HP and post-HP combustion features (see Chapter 3), so there is no diachronic difference in this respect. In conclusion, neither the fire properties, nor maintenance techniques observed and tested in my experiments, nor the evidence for different diagenesis observed in the archaeological sample are variables that affected the formation of a black base hearth stratum that was rich in charcoal. Testing different fire maintenance techniques and fuel types in future experiments may help to explain this issue better.

My experiments also demonstrate that longer fires can have more hearth strata (lenses) than shorter fires. For example, the long fires in experiments E7, E8 and E10 produced four hearth strata and the long fire in E9 produced five strata, but the short fires in experiments E5, E6 and E7 produced three strata each (see Table 4.2). The number of strata is not connected to fuel load because multiple short fires in the same hearth produce the same number of hearth strata as fewer short fires in a hearth. This is important because it provides a means for archaeologists in the field to estimate fast and simply whether a combustion feature being excavated had contained longer or shorter fires. Such an interpretation should preferably be tested through other analyses, such as micromorphology, because the microstratigraphy of a combustion feature can provide even more information on its use (see e.g., Courty et al., 1989; Goldberg and Macphail, 2007).

11.2 THE REUSE OF FIRE AND COMBUSTION FEATURES

The selected HP layers at Sibudu contain multiple combustion features (see Chapter 3) and there could originally have been more combustion features that later were reworked by trampling (see Goldberg et al., 2009). Multiple combustion features could suggest short time use (Goldberg et al., 2009) or a new fire was made whenever needed at a new location and little reuse of combustion features. As a contrast, the selected post-HP combustion features have clearly been used multiple times; for example, through multiple episodes of burning bedding (Chapter 9; see also Goldberg et al., 2009; Wadley et al., 2011). The hearthstones within H in B/Gmix may also represent reuse of a combustion feature for burning bedding (Chapter 9).

My experiments demonstrated that reusing hearths without raking out ashes from previous fires can have an effect on the temperatures of the fire. Depending on the amount of ash in the hearth (and the number of previous fires), temperatures can get higher than in fires lit on a clean surface and the duration of the heat can also be shorter in fires lit on top of ashes (see Chapters 4 and 6). If controlling the heat of a fire is important, cleaning ashes can thus be a good maintenance strategy, and ash dumps from cleaning hearths have been observed at Sibudu (Section 11.3; see also Goldberg et al., 2009).

My experiments also demonstrated properties of combustion features that are not dependent on reuse or the number of stacked, sequential fires in a combustion feature. First, it is not possible to distinguish between multiple fires within a short time span in the same hearth. This result is consistent with previous studies (e.g., Mallol et al., 2013a). Secondly, and as noted in the previous section, the hearth area is a result of fuel load, but not necessarily of the number of fires in the hearth. A long fire burning 15 kg of wood will produce a similar hearth area to three short fires burning a total wood mass of 15 kg, and it is not possible to estimate the number of fires by the hearth area. Thirdly, the number of fires in a hearth does not appear to influence the pH value of the combustion feature (see Chapter 10).

Interestingly, the analysis of charcoal from experimental fires (see Chapter 10) implies that repeated fires in a hearth can lead to more mass loss of charcoal than one long fire in a hearth that burns the same wood mass. This is important because it means that comparing the number of hearth strata and the charcoal mass can give an indication of reuse of a hearth. However, my sample size is small, and should be expanded to examine the mass loss in charcoal further. Perhaps other contents of combustion features, such as bone fragments, could be included in similar analyses.

11.3 DISCARD OF, AND BY, FIRE

The remains of a fire, in the form of ashes and charcoal fragments, can be raked out from the hearth and discarded into ash dumps. The observed ash dumps at Sibudu do not contain distinct strata (see Chapter 3) and the experimental ash dumps (see Chapter 4) had a similar stratigraphy. The lack of distinct strata is thus a property that can be used to recognise ash dumps (see also Goldberg et al., 2009). My analysis also implies that ash dumps generally have a similar pH to the tops of primarily deposited combustion features (Chapter 10) and it is thus not possible to separate the two using pH values.

The spatial analysis (Chapter 9) suggests that the ashes and the contents of combustion features (charcoal, bone and stone) might have been dumped repeatedly in the same area. For example, B/Gmix and BYA2(i) have distinct clusters of bone and stone that could represent discarded material. The HP layers contain less distinct clusters, perhaps due to redistribution of material through trampling, but there are, for example, clusters of material not associated with combustion features in PGS and that may represent an area for discard also in a HP context (see Chapter 9).

Previous studies (Cain, 2005; Clark & Ligouis, 2010; Goldberg et al., 2009; Wadley et al., 2011) have shown that fire was used for discard, such as burning used bedding and bones, in the MSA at Sibudu. However, the contents of the combustion features (see Tables 9.1 and 10.2) and the spatial analysis (Chapter 10) do not suggest that some combustion features were preferred for the discard of bones. There is only a limited sample of combustion features with burned bedding analysed, but the contents of the combustion features containing burned bedding do not appear different from other combustion features. More detailed studies of this issue are needed, but the current analysis does not suggest that discard by fire was limited to certain combustion features.

11.4 EVALUATION OF AIMS ACHIEVED

The title of this thesis, 'By the campfire. Pyrotechnology and Middle Stone Age hearths at Sibudu Cave', alludes both to the fire as the centre of many activities and to the technological importance of fire in the MSA, and these perspectives were also reflected in the aims of this thesis. I aimed to examine the use, reuse and discard of pyrotechnology, to gain an understanding of how fire-related behaviour contributed to the formation of the site and to provide a foundation for future research (see Section 1.1). I achieved these aims through actualistic fire experiments, spatial analysis and descriptions of the contents of selected combustion features. The selection of methods for this thesis put some constraints on the questions it was possible to ask as well as the results it was possible to get, as is the case for any research project. During the course of this project, I did consider using other methods that would provide new types of information for the analysis, and rejected some methods for various reasons. For example, I looked into chemical analysis of sediments and bones from combustion features at Sibudu in collaboration with the chemistry department at University of the Witwatersrand, but the necessary equipment and personnel were not available during the time frame of my project. Therefore, I limited the chemical analysis to recording pH values.

The sample size is another factor that influences the results of a study. The limited number of archaeological layers and combustion features selected for the study made detailed studies possible and it was possible to cooperate with specialist researchers (e.g., in the fields of micromorphology, and organic petrology) to analyse material within the time frame of my project.

The sample size of experimental fires is constrained partly by the time and space required to conduct scientific experiments, because one fire conducted ‘in the field’ is time-consuming and one must have access to a suitable area during the entire duration of the experiment. Fire preparations, which include getting wood, weighing wood and placing thermocouples before the fire, controlling the fire (including recording of temperatures) and subsequent excavation and documentation can last 24 hours per fire, not including the time it takes for the ashes to cool down so that excavation is possible and the subsequent analysis of the data. I learned a lot during the first cycle of experiments that helped me improve the second cycle of experiments (see Chapter 4), and I have gained much experience conducting fire experiments that I shall use to improve future experiments. Some of the questions that have arisen from my experiments are summarised in the section below on future research.

11.5 FUTURE RESEARCH

My research has led to several areas for future studies. These include:

1) Fire experiments

I have examined the properties of wood burning fires in my experiments and thus provided a sample that could be compared to other types of fires. For example, the charcoal analysis (Chapter 9; see also Allott 2005, 2006) shows that many different taxa could be burned in the same combustion feature and Sievers (2013a) has examined the burning of plants used for bedding at Sibudu.

Furthermore, the fires at Sibudu contained burned bones and it is likely that the fires were used for activities such as cooking. Future experiments could examine the properties of MSA fires through, for example, burning different plants, burning the taxa identified in some of the fires at Sibudu and using the fire for cooking. Future experiments could also focus on maintenance techniques that could help control the temperatures and development of a fire, for example, through burning logs of different sizes or arranging the wood in different shapes before starting the fire. Lastly, fire experiments could also contribute more information on the formation of combustion features as well as how archaeologists can make predictions about fire use from the combustion features at a site. Why do archaeological combustion features, for example, contain a basal black stratum rich in charcoal whereas my experimental hearths do not?

2) The contents of the combustion features

I examined the content of experimental and archaeological combustion features in Chapters 9 and 10, but the study was quite limited. The weights of charcoal presented in Chapter 10 suggested a difference between the hearth strata of HP and post-HP combustion features. It might be worthwhile to examine if this diachronic difference is reflected in other contents, such as bone fragments and stone. Perhaps one could examine the contents in more detail and explore the possibility that the different combustion features and hearth strata contain different sizes of bone, stone and charcoal. Such a study might contribute information that could be used in the discussion of diagenesis and post-depositional processes such as trampling.

3) A more detailed spatial analysis

Chapter 9 consists of a collaborative paper that has been reworked for resubmission. The spatial analysis in Chapter 9 is based on general trends in the distribution of bone, charcoal and stone. However, a possible area for future studies is to collaborate with researchers doing detailed studies of the bone and stone and examine whether there are differences, for example, in the distribution of particular animals or lithics from different stages of the chain of production.

Such studies could contribute more information on the use of space in the MSA as well as reveal any preferred areas for certain activities. It would also provide a stronger base for interpretations of dumping areas and activity areas.

11.6 IMPLICATIONS FOR MSA PYROTECHNOLOGY

I have provided the following results that have implications for the study of MSA pyrotechnology:

- 5 kg of firewood can provide temperatures sufficient for cooking for several hours. A limited effort was thus needed to gather the wood mass necessary for such activities.
- Maintenance techniques, such as adding logs to the fire in regular intervals or raking out the ashes from previous fires in the hearth before starting new fires, could be important to control the temperatures of a fire because the surface temperatures of a fire can vary greatly even when controlling variables such as the topsoil horizon, fuel mass and firewood taxon.
- The texture of the topsoil horizon has little effect on the temperatures of a fire.
- Data from organic petrology (Chapter 9) suggests that the temperatures of some fires at Sibudu were tightly controlled, but other studies (Clark & Ligouis, 2010; Herries, 2009) suggest a wider range of temperatures in fires at Sibudu. It remains an open question whether people in the MSA required a certain range of temperatures in their fires, or if the temperatures of the fires were not important to MSA pyrotechnology.
- I present a spatial analysis of four layers at Sibudu, which suggests dumping areas and high densities of bone and stone that imply activity areas nearby hearths. These results can contribute to a model for the use of space in the MSA when more spatial analyses from other sites are available.

- The people in the MSA do not appear to prefer certain combustion features for tasks such as discard of bones and the spatial analysis did not reveal that knapping was confined to specific combustion features.
- I discussed diachronic differences in fire-related behaviour at Sibudu (see also Goldberg et al., 2009). It is suggested that short fires, possibly for short occupations, are associated with the HP occupations, while the post-HP occupations are associated with longer fires and multiple reuse of combustion features (see also Goldberg et al., 2009; Wadley et al., 2011).
- My experimental results imply that it is possible to draw some general conclusions about pyrotechnology based on the combustion features observed in the field. For example, the hearth area is a result of the wood mass burned in the combustion feature and longer fires can produce more hearth strata than multiple small fires.
- My experimental results also show that the reuse of combustion features cannot be recognized through properties of combustion features such as the number of hearth strata and the pH of the ashes.
- Experimental hearths do not produce a black stratum rich in charcoal that is similar to recorded archaeological combustion features. This discrepancy has been noted by others (Mallol et al. 2013), but should be addressed also in future experimental studies because the reasons for the discrepancy have not yet been identified.

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