The analysis of xylem anatomy of wood charcoal in archaeological deposits as a tool in climatic reconstruction

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Cape Town

Report to the Water Research Commission on the project:-

The reconstruction of the climatic history of the last 2000 years in the summer rainfall area of South Africa

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Introduction

The emphasis of this project was the development of a new technique in climate reconstruction using wood charcoal recovered from archaeological sites. Incorporated within this design is the reconstruction of the climatic history of the last 2000 years in the summer rainfall area of South Africa.

The main objectives of the project were:

1. The positive identification of the most common tree species represented in the archaeological record over the last 2000 years using the wood charcoal from archaeological fires.
2. A study of the anatomy of a contemporary wood sample to determine the relationship between wood anatomy and climate.
3. Using the relationship between rainfall and wood anatomy, to reconstruct the climatic history of the summer rainfall area.

Rationale for this project

Climate change, whether natural or anthropogenic will have important effects on water availability. In southern Africa where large agricultural districts are in marginal rainfall areas these changes can and do have significant socioeconomic consequences. To assess the socioeconomic implications of climate change an understanding of the range of climatic variation which can be expected in the future is required. Such projections are made on the basis of what has occurred in the past. At present regional rainfall data sets do not extend over more than 100 years (35 stations in 1880) and register relatively short oscillations of climate (Tyson 1986). Since all climate research in South Africa is based on this very limited data set, the interpretation of results is uncertain.

In the northern hemisphere, dendrochronology provides a good climate record going back in time for thousands of years. The longest available tree ring sequence for the summer rainfall region of South Africa is that described by Hall (1976) for a single Karkloof, Natal *Podocarpus falcatus* specimen dating back to the thirteenth century. In an assessment of the dendrochronological potential of South African indigenous tree species, Lilly (1977) concluded that a combination of very indistinct growth rings, discontinuous rings, indistinct boundaries and deceptive macroscopic ring patterns makes tree ring analysis in South Africa very difficult.

According to Lilly (1977) complete sections of trunk have to be used in order to determine a tree ring series from South African trees. Despite this, attempts to obtain a corroborative series for the Karkloof *Podocarpus* specimen failed because of a lack of definition in the rings of the trees felled for the study (Tyson 1986).

This report describes an original method of climate research which provides a new means of obtaining reliable proxy climatic data beyond the reach of the historic record.

Xylem analysis

During the process of transpiration, trees conduct water and dissolved minerals from the roots to the leaves via vessels and tracheids. Minerals and water are stored in a separate group of cells (parenchyma) which also serve as depositories for waste material such as dissolved silicates. Trees and shrubs require mechanical support which is attained by yet another group of cells the fibre cells. It is the characteristic arrangement of these various groups of cells in both horizontal and vertical planes that makes it possible to identify wood to genus or species level. Wood when burned maintains its anatomical structure so that wood charcoal can also be identified to genus or species level by the characteristic arrangement of different cell types (February 1992).

Wood anatomists have increasingly emphasized the extent to which vessel size and number varies with climate (Carlquist 1977, Baas & Schweingruber 1987, Wilkins & Papassotiriou 1989). All of these studies show that vessel size decreases while vessel frequency increases with increasing drought. It was Scholtz (1986) who first realized that measurements on the wood anatomy of charcoal from archaeological sites may be related to climate when compared to the same measurements on an extant sample from areas with known temperature and rainfall.

The present project is a systematic application of Scholtz's (1986) methods designed to test the precision and practicability of his hypothesis. The project addresses three questions:

(1) What relationship can be found between vessel size, vessel frequency and climate? If so, what approximately is this relationship?

(2) Do the same factors hold true for fresh wood and charcoaled wood? If so, can one use analyses of vessel size and frequency in wood charcoal to determine changes in rainfall or temperature?

(3) In a reconstruction of climate change using xylem analysis of wood charcoal what is the precision with which one can reconstruct rainfall from the archaeological record?

To answer these three questions, the charcoal from 12 archaeological sites is identified as a first step. Once the wood has been identified, data are presented which indicate that vessel size of *Protea* sp. and *Combretum apiculatum* increases while vessel frequency decreases with increasing rainfall. A further set of data is then presented which shows that this relationship is still evident when wood is charcoaled. Finally, using the charcoal from archaeological sites, this relationship is used to determine oscillations in rainfall through time.

Charcoal identification

Positive identification of the charcoal recovered from archaeological sites was achieved by comparison with identified modern samples. Woody species growing in the vicinity of the archaeological sites were sampled to provide this extant reference collection. In identifying the most common woody species in the archaeological record, the wood charcoal from seven archaeological sites in Natal and five sites in the Transvaal was superficially examined. Sample sizes varied from 20 pieces to 390 of charcoal at any given site. The results of the charcoal identification recognized *Acacia* sp., *?Buddleia* sp., *Combretum apiculatum* and *Protea* sp. as important species in the archaeological record. The difficulty of precise identification of fossil charcoal meant that not all charcoal could be identified to genus level, hence the ? before *Buddleia.*

Modern sample

As previously discussed a number of studies have shown the relationship between vessel size, vessel frequency and climate. In the present study the wood anatomy of a number of trees and shrubs was analysed across a rainfall gradient in order to determine the relationship between vessel size, vessel frequency and rainfall for a number of woody species endemic to the summer rainfall region of South Africa. In this analysis the cross sectional xylem anatomy of *Acacia tortillis, Acacia karoo, Acacia nilotica, Combretum apiculatum, Protea roupelliae, Protea caffra* and *Buddleia saligna* was related to rainfall.

Results: modern sample

The results for the *Acacia karoo* and *Acacia nilotica* sample indicate a general tendency for vessel size to increase and vessel frequency to decrease with increases in rainfall. Sample sizes are however, too small to obtain statistically significant results. Results for the much larger sample of *Acacia tortillis* do not, however, show any statistically significant trends.

Table 1. Mean values and standard error for radial (Radv) and tangential (Tangv) vessel diameter and number of vessels (Numv) for *Combretum apiculatum* across a rainfall gradient within the research area. **, *** and **** denote significant differences between means at P<0.01, 0.001 and 0.0001 respectively.

Location	N	Rainfall in mm	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Messina	12	281	106.6	5.5	94.1	4.7	28.3	1.5
Letaba	9	385	92.0	4.1	81.0	2.6	33.0	2.6
Serala	9	400	99.3	4.5	86.4	2.9	23.5	1.2
Bourkes Luck	10	401	103.6	4.1	84.0	3.7	27.2	2.1
Dzata	6	412	103.8	5.8	86.7	1.5	28.0	3.1
Phalaborwa	10	420	99.3	6.0	85.2	3.4	27.5	2.1
Pafuri	10	434	102.6	7.3	89.5	4.2	33.8	2.8
Timbavati	14	439	103.1	3.6	89.0	2.8	26.6	2.1
Punda Maria	13	493	116.6	3.6	95.6	3.3	22.7	1.4
Hans Merensky	15	538	108.7	3.0	92.1	2.9	24.3	1.2
Rust de Winterdam	10	600	109.1	3.6	95.0	2.8	28.1	1.6
Ben Lavin	10	631	111.2	3.5	94.6	2.9	24.7	0.9
Nylsvlei	4	663	121.3	12.5	97.0	9.8	17.2	1.4
Barberton	9	815	115.9	7.1	95.1	6.3	22.8	1.6
Itala	10	940	131.5	7.0	105.1	4.2	18.8	1.1
Correlation coefficient (R)			0.83		0.77		-0.66	
R^2			0.69		0.60		0.44	
Probability (P)			****		***		**	

Multiple regression (Radv, Tangv, Numv) R^2 = 0.69, **.

In *Combretum apiculatum, Protea roupelliae* and *Protea caffra* the relationship between xylem morphology and rainfall indicates that xylem vessel size is positively while vessel frequency is negatively correlated with rainfall (Tables 1 & 2). Vessel diameter of *Buddleia saligna* does not show any correlation with rainfall. Rather, it is vessel frequency that is positively correlated.

Table 2. Mean values and standard error for radial (Radv) and tangential (Tangv) vessel diameter and number of vessels (Numv) for *Protea roupelliae and Protea caffra* across a rainfall gradient within the research area. NS *, **, *** and **** denote no significant difference between means and significant differences between means at P < 0.05, 0.01, 0.001 and 0.0001 respectively.

Protea roupelliae

Location	N	Rainfall in mm	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Suikerbosrand	10	765	50.1	1.2	46.6	1.9	142.3	12.9
Origstad dam	10	841	53.3	1.0	48.0	1.5	78.9	5.5
Mhlwazini Cave	12	868	44.9	1.6	41.1	2.3	165.6	12.1
Itala	10	942	47.7	1.5	48.5	1.2	164.0	10.7
Sterkspruit	10	1005	52.1	1.3	45.7	1.7	94.0	6.8
Kamberg	20	1105	47.0	2.1	44.3	1.2	156.2	13.4
Mikes Pass	6	1153	45.6	1.2	51.2	3.9	124.0	18.5
Gillits	11	1368	59.8	2.1	55.6	2.0	78.8	6.2
Ngome frest	9	1410	57.8	1.0	53.4	1.1	104.2	7.7
Bourkes Luck	10	1411	56.3	1.5	52.0	1.9	106.1	5.9
Serala	9	1600	57.2	1.8	60.7	2.9	85.6	6.3
Umtamvuma	15	1664	65.6	1.3	62.6	1.5	64.5	3.0
Correlation coefficient (R)			0.77		0.88		-0.61	
R^2			0.60		0.78		0.38	
Probability (P)			**		****		*	

Multiple regression (Radv, Tangv, Numv) R^2 = 0.79, **.

Protea caffra

Location	N	Rainfall in mm	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Oog van Malemane	5	546	59.9	4.0	54.4	2.3	53.2	7.2
Suikerbosrand	10	765	60.2	2.6	58.2	3.1	89.2	4.9
Kamberg	10	1100	63.1	2.4	65.7	1.7	55.0	5.8
Cathedral Peak	9	1153	62.8	2.8	60.1	3.2	54.2	4.4
Hluhluwe	10	1170	77.2	1.6	64.8	2.2	44.5	3.1
Umtamvuma	10	1664	71.3	2.4	71.3	2.2	56.1	3.6
Correlation coefficient (R)			0.66		0.93		-0.33	
R^2			0.44		0.88		0.10	
Probability (P)			NS		**		NS	

Multiple regression (Radv, Tangv, Numv) R^2 = 0.88, NS.

From the above it was concluded that vessel size increases while vessel frequency decreases in *C. apiculatum, P. roupelliae and P. caffra*, with increasing rainfall. *Buddleia siligna* is an exception to the general rule. Further research is needed to establish the ecological component in vessel size and frequency variations of *Acacia* sp.

The different responses of the various species to rainfall means that all archaeological samples have to be positively identified to species level before comparisons can be made between an extant wood sample and a prehistoric sample.

Shrinkages accompanying carbonization

Wood shrinks when charcoaled. These shrinkages are considered to be uniform, as the ratio between cell diameter and cell wall thickness does not change in the charcoaling process. With carbonization the number of vessels per square mm should increase while vessel diameter should decrease.

To ascertain the relationship between rainfall, vessel size and vessel frequency in charcoaled wood along a climate gradient five samples of *C. apiculatum, P. roupelliae*, and *P. caffra* per collecting site were charcoaled and analysed.

The results of this experiment indicate that in the *Protea* samples there is a strong correlation between vessel size vessel frequency and rainfall, even when wood is charcoaled. The results of a correlation coefficient analysis on the relationship between rainfall and vessel diameter for charcoaled samples of *C. apiculatum* are not statistically significant although the general trends still hold true. It is felt that the statistical significance of the *Combretum* sample should improve with an increase in sample size. A priority for future research should be to assess the reasons for lack of significance in the correlation between rainfall and vessel diameter for the present sample of charcoaled *C. apiculatum.*

Archaeological sample

On the basis of the above results, a well identified archaeological sample may be analysed in order to reconstruct the rainfall history of the summer rainfall region. The statistically significant correlations between rainfall, vessel size and vessel frequency for charcoaled wood are assumed to hold true for an archaeological charcoal sample. Wood charcoal identified as *Protea roupelliae* from two archaeological sites in the Natal

Drakensberg (Mhlwazini Cave & Collingham Shelter) and *Combretum apiculatum* from Dzata in Venda shows a general decrease in rainfall from a peak 2500 years ago to about 800 A.D. after which followed a dry period for about 900 years to 1700 A.D., when rainfall increased briefly before declining to present levels.

There is a good regional fit between the results of this study and other evidence documenting climate change in southern Africa (Butzer *et al.*, 1978, Butzer, 1984, Klein 1980, Cooke & Verstappen 1984, Tyson 1986, Avery 1991, Smith 1992, and others). Apparent time discrepancies can probably be explained by geographic variations, lag times and dating problems. The resolution of the time series is apparently insufficient to allow detailed time-related interpretation of rainfall conditions over the last 2000 years.

Some generalized patterns of wetter and drier periods can be postulated, however, which suggest that it may be possible to use wood charcoal from archaeological sites to determine patterns in rainfall through time. As there are abundant assemblages of charcoal from archaeological sites, the only limitation on this method of obtaining proxy rainfall data is the resolution of the radiocarbon dates and a possible difficulty in identifying a suitable distribution of sites in time.

During the course of this project the question arose as to whether stable carbon isotope ratios of wood and charcoal samples could provide corroborative and additional information useful for purposes of climatic reconstruction. A pilot study in this regard showed a strong relationship between stable carbon isotope values of *Combretum apiculatum* and rainfall. Within the research objectives of a follow-up project is an assessment of the potential for using stable isotope ratios of wood charcoal as a climate indicator.

Conclusion and recommendations

The major objectives of the project as set out on page 5 of this report have been met.

(1) The most common tree species represented in the charcoal of five archaeological sites in the Transvaal and seven sites in Natal have been identified.

(2) A comparative suite of five woody species have been collected and analysed across a climate gradient in the summer rainfall area (*Acacia* sp., *Buddleia saligna*, *Combretum apiculatum, Protea roupelliae, Protea caffra*).

(3) A comparison has been made between a modern sample and an archaeological sample to develop a preliminary reconstruction of the climatic history of the summer rainfall area.

As the methods have now been established, future research efforts should focus on expanding the archaeological database both spatially and temporally so that a more comprehensive reconstruction of the climatic history of the last 2000 years can be made. A major emphasis of this research should be to determine the range in rainfall over the last 300 - 400 years. From the evidence presented in this study it is suggested that when colonial farmers first moved into the summer rainfall region mean annual rainfall was much higher than at present.

The results are site specific and there are gaps in the dating, but encouraging correlations with other evidence suggests that the methods used in this study are providing useful rainfall data. With a larger sample of well dated charcoal it may be possible to obtain a more comprehensive picture of rainfall change through time. The use of stable carbon isotope ratios of wood charcoal from archaeological sites as an adjunct to xylem analysis should be investigated further in view of its potential as a valuable means for determining changes in rainfall patterns through time.

Technology transfer of results

To date various sections of the results of the project have been published in the following forms:

1. In 1990 an article was published in the *SA Water Bulletin* with the assistance of Mr Scholtz.
2. In January 1991 Mr February attended the biennial meeting of the South African Association of Botanists where he presented a paper: The Effects of Water and Soil Nutrients on the Wood Anatomy of Cape Fynbos and Forest Plants.
3. In June 1991 Mr February attended the 10th biannual conference of the South African society for Quaternary Research where he presented a paper: Climate reconstruction from wood charcoal.
4. In July 1991 Mr February participated in the Second palaeoenvironments workshop of the western Cape palaeoenvironments working group.

5. In August 1991 Mr February presented a seminar at the Archaeology Department, University of Cape Town. The title of the seminar was: Wood charcoal as a palaeoclimatic indicator.
6. In October 1991 Mr February presented a seminar at the South African Museum. The title of the seminar was: Archaeological charcoals as indicators of climatic change and human fuel choice in the Late Holocene at Elands Bay
7. In November 1991 Mr February attended the Arid Zone Ecology Forum Research meeting where he presented a paper: Stable carbon isotope ratios of wood charcoal as a climate indicator.
8. In February 1992 Mr February presented a paper at the annual meeting of the Water Institute of South Africa: Rainfall reconstruction using wood charcoal from archaeological sites.
9. In March 1992 Mr February attended a seminar held in Pretoria on Stable Isotopes in plant nutrition, soil fertility and environmental studies.
10. In March 1992 Mr February presented a seminar at the National Museum in Bloemfontein: Rainfall reconstruction using wood charcoal from archaeological sites.
11. In April 1992 a number of newspapers ran articles of various lengths reporting on the results of the research for the project.
12. In May 1992 a publication by Mr February appeared in the *Journal of Archaeological Science*. Archaeological charcoals as indicators of vegetation change and human fuel choice in the Late Holocene at Elands Bay, western Cape Province, South Africa.
13. In June 1992 a publication by Mr February in collaboration with Prof N.J. van der Merwe appeared in the *South African Journal of Science*. Stable carbon isotope ratios of wood charcoal during the past 4000 years: anthropogenic and climatic influences.
14. In July 1992 Mr February attended the Biennial conference of the Southern African Association of Archaeologists where he presented a paper: The archaeological past from an analysis of wood charcoal.
15. In August 1992 Mr February participated in the Conservation Biology course (MSc) at U.C.T. lecturing on methods of analyzing climate and environmental change through time.

References

Avery, D.M. 1991. Micromammals, owls and vegetation change in the Eastern Cape Midlands, South Africa, during the last millennium. *Journal of Arid Environments* **20**: 357-369.

Baas, P. & Schweingruber, F.H. 1987. Ecological trends in the wood anatomy of trees, shrubs and climbers from Europe. *IAWA Bulletin* n.s. **8** (3): 245-274.

Butzer, K.W. 1984. Late Quaternary environments in South Africa. *In* Vogel, J.C. *ed., Late Cainozoic palaeoclimates of the southern hemisphere*, 235-264. Rotterdam: A.A. Balkema.

Butzer, K.W., Stuckenrath, R., Bruzewicz, A. & Helgren, D.M. 1978. Late Cenozoic palaeoclimates of the Gaap Escarpment, Kalahari margin, South Africa. *Quaternary Research* **10**: 210-339.

Carlquist, S. 1977. Wood anatomy of Peneaceae (Myrtales): comparative, phylogenetic and ecological implications. *Botanical Journal of the Linnaean Society* **75**: 211-227.

Cooke, H.J. & Verstappen, H.T., 1984. The landforms of the western Makgadgadi basin in northern Botswana, with a consideration of the chronology of the evolution of Lake Palaeo-Makgadigadi. *Zeitschrift für Geomorphologie* **28**: 1-19.

February, E.C. 1992. Archaeological charcoals as indicators of vegetation change and human fuel choice in the late Holocene at Elands Bay, western Cape Province, South Africa. *Journal of Archaeological Science* **19**: 347-354.

Hall, M. 1976. Dendroclimatology, rainfall and human adaptation in the Late Iron Age of Natal and Zululand. *Annals of the Natal Museum* **23**(3): 693-703.

Klein, R. G. 1980. Environmental and ecological implications of large mammals from Upper Pleistocene and Holocene sites in southern Africa. *Annals of the South African Museum* **81**: 223-283.

Lilly, M.A. 1977. An assessment of the dendrochronological potential of indigenous tree species in South Africa. *Dept. of Geographical and Environmental Studies, University of the Witwatersrand Occasional Paper* **18**.

Scholtz, A. 1986. Palynological and palaeobotanical studies in the southern Cape. University of Stellenbosch: Unpublished M.A. thesis.

Smith, A.M. 1992. Holocene palaeoclimatic trends from palaeoflood analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section)* **97**: 235-240.

Tyson, P.D. 1986. *Climatic change and variability in southern Africa*. Cape Town: Oxford University Press.

Wilkins, A.P. & Papassotiriou, S. 1989. Wood anatomical variation of *Acacia melanoxylon* in relation to latitude. *IAWA Bulletin* n.s. **10(2)**: 201-207.

ABSTRACT

The purpose of this report is to present the findings of a study which was undertaken to improve on existing rainfall data sets, and provide a better understanding of temporal aspects of climate change within the summer rainfall region of South Africa. To this end, the project concentrated on extending the rainfall record back in time by using the xylem anatomy of radiocarbon dated charcoal.

It is possible to identify wood charcoal to genus and even species level by microscopic examination of xylem anatomy. A preliminary identification of the charcoal from a number of archaeological sites in the Drakensberg and northern Transvaal shows that the most common woody species today are also evident in the archaeological record over the last 2000 years, indicating a relatively stable plant community composition. Previous wood anatomical studies have shown that there are links between vessel diameter, vessel frequency and climate. The present study demonstrates that in relation to rainfall, vessel diameter in the species *Protea caffra, Protea roupelliae* and *Combretum apiculatum* correlated positively while vessel frequency correlated negatively. In *Protea roupelliae*, mean vessel diameter increases from 46 μm to 62 μm along a rainfall gradient ranging from 760 mm at Suikerbosrand to 1665 mm at Umtamvuma ($R = 0.88$, $P < 0.001$, $N = 12$). Indications are that this correlation is observed even when wood is charcoaled, and although the results for *Combretum apiculatum* are not statistically significant, those for *Protea roupelliae* ($R = 0.68$, $P < 0.01$, $N = 12$) are. The resolution of the time series is insufficient to allow detailed interpretation of rainfall conditions over the last 2000 years. Some generalized patterns of wetter and drier periods can be postulated, however, suggesting that it is possible to use well-dated archaeological charcoal samples of *Protea* spp. and *Combretum apiculatum* to determine patterns in rainfall through time.

The range in vessel diameter for the archaeological sample of *Protea* spp. and *Combretum apiculatum* is within the expected ranges for the contemporary specimens analysed from the Drakensberg and Venda respectively. This suggests that mean rainfall values in these areas have not altered radically during the last 2000 years. Implications are that rather than directional change, there have been fluctuations in

amounts of available moisture around a mean. When compared to contemporary values, the implications are that at 200 B.P. and 2400 B.P. the area was wetter than at present. A dry phase is registered between 1700 B.P. and 300 B.P., but values for the contemporary wood sample are the lowest observed.

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PREFACE AND ACKNOWLEDGEMENTS

This study arose out of the need to develop a technique to determine changes in rainfall patterns through time in the summer rainfall region of South Africa. The very limited time range of our present regional data sets means that the long-term variability of water supplies in South Africa is poorly understood. We require regional rainfall data sets going back in time for thousands of years in order to develop hypotheses on future water availability.

The research in this report emanated from a project funded by the Water Research Commission. The Steering Committee responsible for the project, consisted of the following persons, in alphabetical order:

Dr M A Cluver	SA Museum
Dr R V Dingle	SA Museum
Dr G C Green	Water Research Commission (Chairman)
Dr P A Hulley	SA Museum
Dr J A Lindesay	University of Witwatersrand
Dr P C Reid	Water Research Commission
Mr G C Schulze	Department of Environment Affairs
Mr S van Biljon	Department of Water Affairs
Prof J van Heerden	University of Pretoria
Mr D B Versfeld	FORESTEK, CSIR
Mr P W Weideman	Water Research Commission (Secretary)
Prof W Zucchini	University of Cape Town

I could not have asked for a more compassionate and understanding Chairman and Steering Committee on this my first major research project. In particular I would like to thank Mr D.B. Versfeld who was always willing to listen to my problems.

The major aims of the project have been to develop a new method of rainfall reconstruction using wood charcoal from archaeological sites and to use this method to plot fluctuations in rainfall over the last two millennia. To this end the project has been successful. This success would not, however, have been possible without the assistance of a great many people. They are too many to mention individually but I am grateful to them all. Inspiration for the project came from Anton Scholtz who had conceived the idea while doing his Masters degree in Archaeology at the University of Stellenbosch.

Figure 1. Locations from which an extant wood sample of *Protea* sp., *Combretum apiculatum* and *Buddleia saligna* was collected.

The research was carried out in the Palaeobotany section of the Department of Micropalaeontology at the South African Museum. Without the use of Museum facilities the project would not have been possible. For this I would like to thank the Director Dr M. Cluver and the Head of Department Dr R. Dingle. I would also like to thank Dr Dingle for coordinating the project, reading and commenting on this and many other manuscripts and for providing encouragement. I would like to thank Dr G. Avery for not only allowing me to develop the photographs in the darkroom of the Archaeology Department but also for his and Dr D.M. Avery's unflagging enthusiasm and support for the project. Dr D.M. Avery helped in the final collation and printing of the manuscript.

This project depended quite considerably upon radiocarbon dates and charcoal samples from a number of archaeological sites which were provided by among others Prof. T.N. Huffman, of Wits University and Drs A. Mazel and T. Maggs of the Natal Museum. Throughout the project I had the close cooperation of Prof. T. Huffman and Drs A. Mazel and T. Maggs. I would like to thank them for sharing their ideas with me and for supplying me with both published and unpublished data.

An extant wood collection came from nature reserves and wildlife parks administered by the National Parks Board, Natal Parks Board and Transvaal Administration as well as from many private farms (Figure 1). For this I am grateful to Dr Richard Newberry of the Transvaal Provincial Administration, Dr W.P.D. Gertenbach of the National Parks board, Dr O. Bourquin of the Natal Parks Board, The Alcocks of Mhlopeni Nature Reserve, David and Dorothy Green of the farm Rensburgspruit, Conrad Rocher of the farm Baviaanskrantz , Ed Hanisch of the Department of Anthropology and Dries Bester of the Department of Sociology at Venda University as well as many park wardens, game rangers and others.

Measurements of vessel size and frequency on an extant sample were correlated with mean annual rainfall. These rainfall figures were obtained from The Weather Bureau (Department of Environment Affairs), The National Parks Board, Transvaal Provincial Administration and Natal Parks Board. The cooperation of these bodies in this regard is gratefully acknowledged.

The backbone of this project has been the work of Noel Fouten and Kenneth Solomons, who have between them microtomed, sectioned, labelled and measured hundreds of pieces of wood to enable us to arrive at the conclusions presented in this report. Nicky Allsopp identified many trees and helped me on the Natal field trip while Colin Potts assisted me on the Transvaal trip. Rina Krynauw helped to obtain many interlibrary loans.

Finally I would like to thank my colleagues who have helped me in many ways. In particular I thank (in no particular order) Madelon Tusenius, Anton Scholtz, John Lanham, Nicky Allsopp, Colin Potts, John Parkington, Clive Booth and Madel Joubert.

CHAPTER ONE

INTRODUCTION

Major components of most archaeological sites are stone, bone and charcoal. Presented here are the results of analysis of the charcoal from the archaeological sites Collingham Shelter and Mhlwazini Cave in the Natal Drakensberg, and Dzata near Louis Trichardt in the northern Transvaal (Figure 2). The emphasis of this study is on the development of a new technique in climate reconstruction using measurements of vessel size and frequency in the cross sectional xylem anatomy of wood charcoal. Incorporated within this objective is the reconstruction of the climatic history of the last 2000 years in the summer rainfall region of South Africa.

Rationale for this project

Climate change, whether natural or anthropogenic, will have important effects on water availability. In southern Africa, where large agricultural districts are in marginal rainfall areas, these changes can and do have significant socioeconomic consequences. To assess the socioeconomic implications of climate change an understanding of the climatic variation which can be expected in the future is required. Such projections are made on the basis of what has occurred in the past. At present, regional rainfall data sets do not extend over more than 100 years (35 stations in 1880) and register relatively short oscillations in climate (Tyson 1986). Since all climate projections for South Africa are based on this very limited data set, there are obvious limits to the probable accuracy of estimates.

In the northern hemisphere, dendrochronology provides a good climate record going back in time for thousands of years. Of the vast number of tree species existent in South Africa, few have dendrochronological potential. The longest available tree ring sequence for the summer rainfall region of South Africa is that described by Hall (1976) for a single *Podocarpus falcatus* specimen from Karkloof, Natal, dating back to the thirteenth century (Figure 1).

Figure 2. Locations of all archaeological sites referred to in the text.

The most basic proposition in tree ring analysis is that a tree forms a new ring each year. This is, however, not a biological certainty and is one of the first suppositions that has to be clarified when assessing the feasibility of a tree species for dendroecology or dendroclimatology. Lilly (1977) concluded that a combination of very indistinct growth rings, discontinuous rings, indistinct boundaries and deceptive macroscopic ring patterns makes tree ring analysis in South Africa very difficult. According to Lilly (1977) complete sections of trunk have to be used in order to determine tree ring series from South African trees. Despite this, attempts to obtain a corroborative series for the Karkloof *Podocarpus* specimen failed because of the lack of definition in the rings of the trees felled for the study (Tyson 1986).

In a preliminary study on the dendrochronological potential of *Newtonia hildebrandtii* I arrived at the same conclusions as Lilly (1977). In addition, the very strong sapwood/heartwood differentiation in *Newtonia* makes it difficult to detect growth rings in the heartwood.

Destructive research on endangered species such as *Podocarpus* cannot continue indefinitely. The development of a new method for determining changes in temperature and rainfall is vitally important, especially for the summer rainfall region. The present project is an attempt to develop such a method. It represents an original technique for climate research which could provide a reliable proxy rainfall record going beyond the reach of the historic record.

Charcoal identification and relative abundance

During the process of transpiration trees conduct water and dissolved minerals from the roots to the leaves via vessels and tracheids. Minerals and water can be stored in a separate group of less specialized cells (parenchyma) which are also depositories for waste material such as dissolved silicates. Trees and shrubs require mechanical support which is attained via another group of cells, the fibre cells. It is the characteristic arrangement of these various groups of cells in both horizontal and vertical planes that makes it possible to identify wood to genus or species level. Wood when burned, maintains its anatomical structure so that wood charcoal can also be identified to genus or species level by the characteristic arrangement of different cell types (Salisbury & Jane 1940, Godwin & Tansley 1941, Slavikova-Vesela 1950, Vernet 1973, Kraus-Marguet 1980 and February 1992).

Charcoal from archaeological sites represents the remains of firewood collected by people, who made specific choices on the types of fuel wood they would use (Gandar

1982, Milton & Bond 1986). The archaeological record will, therefore, always be skewed in the direction of the favoured fuel wood, although environmental conditions will influence the species of wood available for collection. It is on this basis that environmental change can be inferred from changes in the charcoal record of archaeological sites (February 1992).

Xylem analysis: A new approach to rainfall reconstruction

Wood anatomists have increasingly emphasized the extent to which vessel size and number varies with temperature and rainfall (Carlquist 1966, 1975, 1977a, Baas 1982, Zhang *et al.* 1988, Wilkins & Papassotiriou 1989). All of these studies show that vessel size decreases while vessel frequency increases with increasing drought. Scholtz (1986) was the first to realize the potential significance of certain wood anatomical variables for explaining climate change. He proposed a new method by which charcoal from archaeological fires can be used to reconstruct climate. Scholtz's (1986) Ecologically Diagnostic Xylem Analysis (EDXA) is directly based on the relationship between plant anatomy, physiology and ecology. It is not designed to describe the anatomy of wood, but rather to measure a wide range of potentially ecoclimatically significant wood variables observable in a transverse section. The basic premise of Scholtz's hypothesis is that it may be possible to relate measurements on the wood anatomy of charcoal from archaeological sites to climate when compared to similar measurements on a modern sample of the same species from areas of known temperature and rainfall.

In his study, Scholtz (1986), using wood charcoal from Boomplaas Cave, on the southern Cape coast, established differences in wood anatomy which he attributed to climatic change. Because Scholtz's (1986) work was of a pioneering nature, and his research at Boomplaas Cave was a preliminary test for this methodology, few of the electron micrographs he used were suited to this project. He recorded climatic change over thousands rather than hundreds of years, and did not establish a modern database.

The present project is a systematic application of Scholtz's (1986) methods designed to test the precision and practicability of his hypothesis. The main questions addressed are;

(1) Is there in fact a relationship between vessel size, vessel frequency and climate? If so, what is this relationship?

(2) Do the same factors hold true for fresh wood and charcoaled wood? If so, can one use analyses of vessel size and frequency in wood charcoal to determine changes in rainfall or temperature?

(3) In a reconstruction of climate change using xylem analysis of wood charcoal what is the precision with which we can reconstruct rainfall from the archaeological record?

Stable carbon isotope analysis

Recent studies have suggested that stable carbon isotope ratios are good indicators of water available to plants (Freyer & Belacy 1983, Leavitt & Long 1986). During the course of this project the question arose as to whether stable isotope analysis of wood and charcoal samples could provide corroborative and additional information useful for purposes of climatic reconstruction. A pilot study in this regard, undertaken with a view to possible follow-up research, is reported in Appendix 1.

Archiving of data

The large amounts of data generated through labour-intensive sampling and the analytical procedures used in this project are also potentially useful for other research purposes. With a view to orderly storage and access to this data, arrangements for data archiving are detailed in Appendix 2.

CHAPTER TWO

CLIMATE AND ENVIRONMENT

Introduction

The primary objective of this study is the development of a new technique for using wood charcoal from archaeological sites as a palaeoclimatic indicator. To this end, I present an analysis of the results from the charcoal of three archaeological sites, and both fresh and charcoaled wood from more than thirty extant sites within the summer rainfall region of South Africa. For the purposes of this study, the area termed the summer rainfall area has been defined as that area stretching from Messina on the Zimbabwean border in the north, to Umtamvuma on the Transkei border in the south and from the Indian ocean and Moçambique border in the east to Johannesburg in the west (Figure 1).

In general, ambient temperature and water availability appear to be the most important climatic factors affecting plant growth and distribution. Through solar radiation ambient temperature provides the necessary energy for plant growth, while water availability determines the degree to which plants can meet the evaporative and physiological demands posed by their particular structures (Box 1981). It was, however, not possible to ascertain the extent to which xylem anatomy and temperature correlate because the extant wood collection was assembled from a number of nature reserves, most of which do not collect temperature data. The pronounced seasonal nature of the rainfall in the summer rainfall region of South Africa means that within this region evaporation exceeds rainfall over a large part of the year. As a result, the plants live under water stress for most of the year indicating that rainfall is probably the most important influence on plant form and structure. In addition, Hall (1976) cites Gillooly (1975) as having determined a strong correlation between rainfall and growth increments of trees in the Rustenburg district of the Transvaal. Although the evidence is circumstantial it does support the argument that the major limitation on plant growth in the research area is rainfall rather than temperature. Xylem vessel size and frequency should therefore correlate directly with rainfall.

Table 1. Locations from which an extant wood sample of *P. caffra* (P.caff), *P. roupelliae* (P.roup), *B. saligna* (B.sal), *C. apiculatum* (C.apic), *A. karoo* (A.kar), *A. tortillis* (A.tort) and *A. nilotica* (A.nil) was collected. Mean annual rainfall (in mm) was calculated over a four year period to December 1990 (see page 20).

Location	Rainfall	Lat	Long	B.sal	P.caff	P.roup	C.apic	A.kar	A.tort	A.nil
Barberton	815	3059	24.58				√			
Ben Lavin	631	23.06	29.57				√			
Bluegumspoort	599	23.00	29.47	√						
*Bourkes Luck	695-1411	30.50	24.40			√	√			
Dzata	412	22.57	30.08				√			
Estcourt	824	28.59	29.58	√				√	√	√
Gillits	1368	29.47	30.48			√				
Hans Merensky	538	23.40	30.40				√			
Hluhluwe	665-1170	28.07	32.02		√			√		√
Itala	942	27.28	31.17			√	√			
Kamberg	1105	29.23	29.38		√	√				
Letaba	400	23.55	31.31				√		√	
Mamba (Dougvale)	820	28.57	31.03				√		√	
Messina	281	22.21	30.02				√		√	
Mhlawula	660	26.12	32.01						√	
Mhlopeni	650	29.01	30.25	√				√	√	
Mhlwazini Cave	868	29.01	30.29			√				
Mikes Pass (Cathedral Peak)	1153	28.57	29.14		√	√				
Mkuze	578	27.36	32.16							√
Ngome Forest	1410	27.49	31.23			√				
Nylsvlei	663	24.40	28.43				√		√	
Olifantspoort	706	25.50	27.16	√						
Oog van Malemane	546	25.51	26.05		√	√	√			
Origstad dam	841	24.58	30.38			√				
Pafuri	434	22.27	31.18				√			
Phalaborwa	420	23.56	31.11				√			
Punda Maria	493	22.40	31.01				√		√	
Rooipoort	420	28.37	24.15						√	
Rust de Winterdam	600	28.30	25.24				√			
Rustenburg	773	25.43	27.12	√						
*Serala	400-1600	30.00	24.03			√	√			
Sodwana Bay	735	27.33	32.40					√		
Sterkspruit	1005	25.09	30.35			√				
Suikerbosrand	765	26.30	28.12	√	√	√				
Timbavati	439	24.28	31.20				√			
Tshongwe	883	27.27	32.25						√	
Tugela Ferry	756	28.47	30.10						√	
Umtamvuma	1664	30.58	30.10		√	√				
Weenen	670	28.51	30.00	√					√	

* Mountain nature reserves which include a wide range of habitats with differing rainfall conditions

Rainfall statistics were calculated for some thirty stations close to extant wood sample sites from data supplied by the Weather Bureau, Transvaal Provincial Administration, Natal Parks Board and National Parks Board.

The research area from which archaeological samples were obtained is focussed at Mhlwazini Cave (29° 02' 52": 29° 23' 23") and Collingham Shelter (29° 27' 35": 29° 47' 45") both at an altitude of approximately 1800 m (6000 ft) in the Natal Drakensberg and at the iron age village of Dzata, home of the legendary Singo leader Thoho-ya-Ndou (22° 52' 10": 30° 08' 30") in Venda (Mazel 1990, Mazel 1992, and Loubser (1991). (Figure 2)).

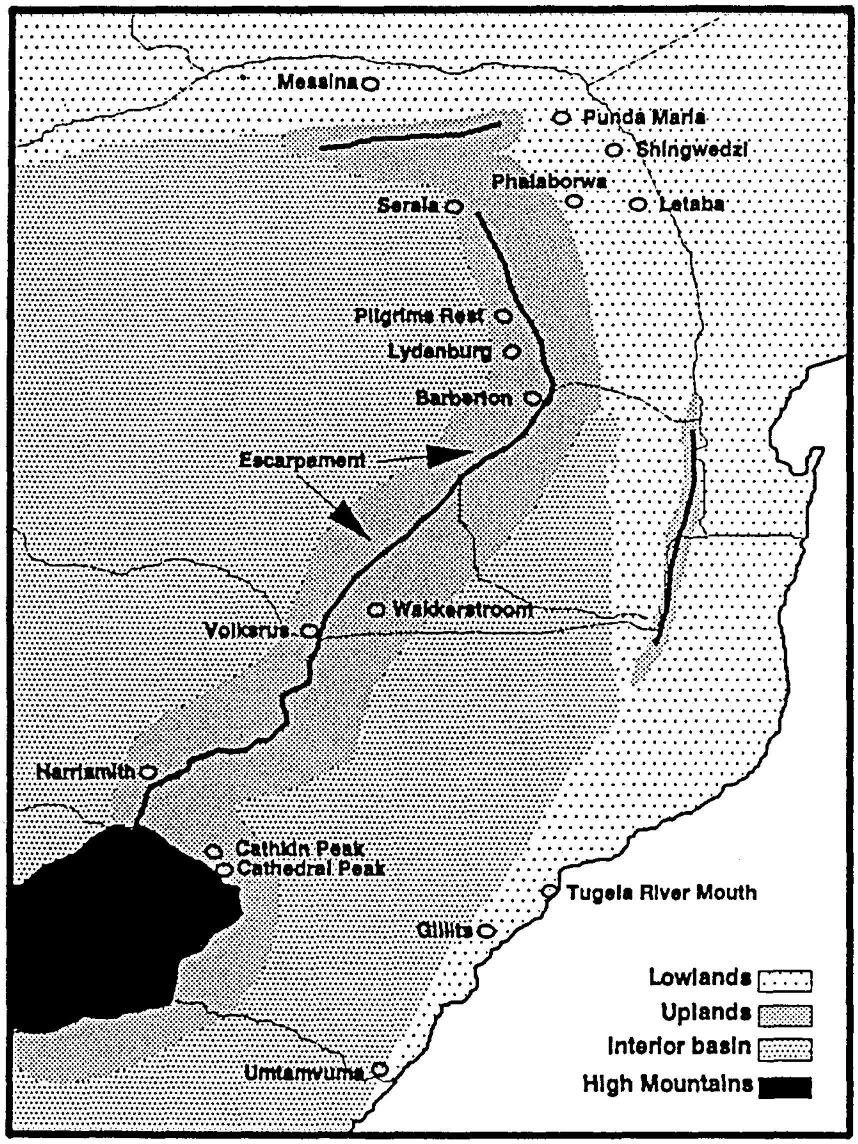

Figure 3. Position of the Drakensberg escarpment and ecoclimatic zones of the research area.

The ecological zonation of the research area runs roughly north-south parallel to the Drakensberg escarpment (Figure 3.). There are four broad ecoclimatic zones within this area. These zones can be defined as coastal and interior lowlands, uplands region, interior plateau and high mountains. The rest of this chapter is a description of the environment, temperature and rainfall within each of these broad zones.

Coastal and interior lowlands

Coastal lowlands

The coastal region extends along the whole of the Natal coastal belt, including most of northern Zululand, the low lying regions of the Tugela river valley and the Valley of a Thousand Hills. At the Transkei border it forms a narrow band only about 25 kms wide. Altitude ranges from sea level to 1000 m. Temperatures are high with mean daily maxima about 30°C during January and February and over 25°C for at least 9 months of the year. Mean daily minima are also high, between 10°C and 20°C for winter and summer, respectively.

The coastal lowlands have a high but extremely varied mean annual rainfall ranging from 1000 mm to 1600 mm. Mean values are, however, closer to 1000 mm with higher rainfall areas occurring in relatively small pockets such as at the Tugela River mouth (1200 mm), Gillits (1400 mm) and Umtamvuma (1600 mm). Within this area samples of *Protea* spp. were collected at Gillits and Umtamvuma.

Interior lowlands

The ameliorating effect of the Indian Ocean on temperature and rainfall is lost in the interior of the country. The area east of the Drakensberg escarpment, north of the Soutpansberg to the Limpopo river and east of Messina, is known as the Transvaal Lowveld. This area falls within that zone termed by Huntley (1982) as arid savanna. Mean daily maxima are high at just over 30°C from September through April. Absolute maximum temperatures from 40°C to 45°C have been recorded for all of these months. During June and July, Letaba, where a sample of *Combretum apiculatum* was collected, and Shingwedzi in the Kruger National Park have the lowest mean daily minima at 5.8°C and 4.5°C, respectively. The daily minima at Messina and Punda Maria further north, where samples of *Combretum apiculatum* were also collected, are much higher at 10°C and 11°C respectively.

The major difference between the interior and coastal lowlands is in the rainfall, which in the interior ranges between 300 mm at Messina (*C. apiculatum* collected here) to a maximum of 600 mm at Phalaborwa (*C. apiculatum* collected here), and is often well over 1000 mm at the coast.

Uplands Region

West of the Lowveld, the Drakensberg escarpment rises steeply 800 to 1500 mm above the interior lowlands. It is from this region that the sample of *Protea spp.* used in this study was collected (Table 1). In Natal, the Uplands region can be defined as that area of the Drakensberg known as the Little Berg. This region approximately follows the 2000 m contour from the Natal Drakensberg through Harrismith, Volksrus, Wakkerstroom and Barberton to Belfast, Dullstroom, Lydenberg and Pilgrims Rest in the Transvaal. The escarpment drops down to the north at Tzaneen before rising again to form the Soutpansberg in Venda. There are few temperature stations available for this area. At Lydenberg and Pilgrims Rest in the Transvaal, mean daily maxima are between 21°C and 23°C. The mean daily maxima for Volksrus and Wakkerstroom are the same at 21°C, and for Cathedral Peak at the upper altitude limit of the region, mean daily maxima are between 18°C and 21°C. Apart from Cathedral Peak, lowest recorded temperatures (according to Edward 1967) are -7.8°C at Cathkin Peak and -13.3°C at Wakkerstroom.

The Drakensberg escarpment has some of the highest rainfall figures for the study area. In the Transvaal, the high mountain region of the Wolkberg Nature Reserve (Serala) receives a mean annual rainfall of 1600 mm, whilst Bourkes Luck Potholes gets 1400 mm. The Cathedral Peak area receives 1200 mm per year, but annual rainfall can total more than 2000 mm.

The interior basin and Highveld

At an altitude between 1000 and 1500 metres, the interior basin of Natal and the Highveld region of the Transvaal forms the largest ecoclimatic section of the study area. Some *Combretum apiculatum* was collected in this area where it occurs on shallow stony soils, on steep north facing slopes.

To the west of the Lowveld, the Drakensberg escarpment falls off gradually to form the flat interior of the Transvaal known as the Highveld. Temperatures for this area are mild, mean daily maxima being between 26°C and 29°C at Nylsvlei and between 25°C and 27°C in the Soutpansberg. Mean daily minima are between 3°C and 6°C. Typical Highveld mean annual precipitation values are between 600 mm (Potgietersrus) and 650 mm (Nylsvlei). In Natal, the interior basin lies to the west of the Drakensberg and to the east of the coastal lowlands. Temperature and rainfall for this area are very similar to that in the Transvaal, although rainfall does vary with altitude and can be as high as 800 mm (Dundee) and even 1000 mm (Boshoek).

CHAPTER THREE

CHARCOAL IDENTIFICATION AND RELATIVE ABUNDANCE

Introduction

This chapter details the results of analyses of charcoal from a number of archaeological sites in the Transvaal and Natal in terms of species composition and relative abundance of wood morphological types. The emphasis is on determining the wood morphological type common to a number of archaeological sites, and using these species for comparison with the extant specimens.

Materials and Methods

Extant comparative material

Positive identification of the charcoal recovered from archaeological sites is achieved by comparison with identified modern samples which have been charcoaled. Although wood retains its distinctive anatomical features when charcoaled, positive identification is hampered by wood anatomical variability. This variation is due to a number of ecological as well as physiological causes which have led researchers to emphasis the need for exhaustive tests on a single piece of wood to classify it taxonomically (Rendle & Clarke 1934, Carlquist 1980, Barefoot & Hankins 1982, Zimmerman 1983).

Woody species growing in the vicinity of the archaeological sites were sampled to provide the extant reference collection. In the laboratory discs approximately three centimetres in length were cut and wrapped in tinfoil. These parcels were placed in a muffle furnace, the temperature of which was gradually taken up to a maximum of 500°C after 1 hour. The furnace was then switched off and allowed to cool slowly. Charcoal was prepared for examination by physical fracture of each piece. A knife with a very fine serrated edge was used to make an incision perpendicular to the grain and through 360° around the circumference of the piece of charcoal. The section was then snapped by placing the incision on a thumbnail and applying pressure with the left and right index fingers. The smoothest half of each section was mounted in "Prestik" on a glass slide. Once mounted the charcoal was ready for examination under a microscope.

As this method never leaves an absolutely flat surface all the physical examination of charcoal was done using a Nikon Optiphot M darkfield reflected light microscope.

Table 2. Major woody species identified from a sample of the available charcoal and the location of the archaeological sites (see Figure 2).

Archaeological site	Number of samples	Location of site	Most common genera	Percentage of total
Begwa	68	Venda	*Combretum apiculatum*	15
Collingham Shelter	180	Natal Drakensberg	*Protea*	43
Dzata	50	Venda	*Combretum apiculatum*	16
eSinhlonhlweni	240	Central Natal	?*Buddleia* Radial type	25
Magogo	20	Central Natal	*Olea*	35
Manavhela	45	Venda	*Combretum apiculatum*	13
Mbabane	240	Central Natal	?*Buddleia* Radial type	26
Mhlwazini Cave	390	Natal Drakensberg	*Protea*	14
Ndondondwane	58	Central Natal	*Acacia*	45
Ntshekane	40	Central Natal	*Acacia*	33
ŢSH 1.1	20	Kruger Park	*Combretum apiculatum*	25
Tshitaka	40	North Transvaal	*Mopane*	40

The difficulty of precise identification of fossil charcoal meant that not all charcoal could be identified to genus level hence the ? before *Buddleia*.

Archaeological samples

In order to determine rainfall change through time, the wood charcoal from a number of archaeological assemblages radiocarbon dated within the last 2000 years were examined (Table 2 & 3). The resolution of the radiocarbon dates is unfortunately variable over this period. The calculated radiocarbon age of a sample does not compare directly with the actual age of that sample. The calculation of the radiocarbon age assumes that the levels of ^{14}C in the atmosphere have been constant. This is, however, not so as the ^{14}C activity in the atmosphere has varied through time. With this range in atmospheric levels of ^{14}C comes a range in radiocarbon ages. It is possible to calibrate for this range in radiocarbon ages by measuring the radiocarbon ages of tree rings of known age. This calibration has been achieved for most of the Northern hemisphere. It is assumed that the ^{14}C activity in the atmosphere is constant around the world so that it is possible to use the North American dendrochronological calibration curve in South Africa. The calibration curve is not a uniform smooth curve but has a number of peaks and troughs. Thus a sample with a radiocarbon age of 152 B.P. ±30 could calibrate to anywhere between 1650 A.D. and 1955 A.D., a range of 300 years. On the other hand a sample with a radiocarbon age of 500 B.P. ±20 would calibrate to 1427 ±12 A.D. Note that in this case the standard deviation has decreased.

Table 3. Archaeological sites mentioned in the text with associated radiocarbon dates.

Archaeological site	layer	calibrated ^{14}C date (AD)	uncalibrated ^{14}C date (BP)	lab number
Tshitaka	Layer 3	1550	400±100	Wits 1619
Tshitaka	layer 5	1350	600±90	Wits 1674
Tshitaka	Layer 5	1320	630±70	Wits 1592
Begwa		±1900	±1900	
Dzata	T2 Layer 2	1810	140±80	Wits 1601
Dzata	T2 Layer 2	1660	290±50	Wits 1665
Dzata	T1 Layer 2	1630	320±40	Wits 1668
Dzata	T2 Layer 4	1590	360±50	Wits 1660
Dzata	T2 Layer 4	1580	370±40	Wits 1597
Dzata	T2 layer 7b	1690	260±70	Wits 1599
Manavhela	Layer 4	1600	350±80	Wits 1460
TSH 1.1		1440	600±50	Pta 3825
Magogo	Pit 1	590	1360±50	Pta 2874
Magogo	Pit 13b	760	1190±50	Pta 2875
Ndondondwane	50-60cm	730	1220±50	Pta 2388
Ndondondwane	40-50cm	760	1190±50	Pta 2389
Ntshekane	20-40cm	800	1150±45	Pta 1058
Ntshekane	1.4-2.2m	850	1100±50	Pta 1057
Mbabane	Layer 3	1480	470±40	Pta 3848
Mbabane	Layer 3	1450	500±50	Pta 3684
Mbabane	Layer 4	430	1520±50	Pta 3678
eSinhlonhlweni	Layer 3	1500	330±45	Pta 3851
eSinhlonhlweni	Layer 3	1700	170±50	Pta 3584
Mhlwazini Cave	Layer 2	1700	190±45	Pta 5102
Mhlwazini Cave	Layer 3	1630	320±40	Pta 4850
Mhlwazini Cave	Layer 4	1370	580±50	Pta 4864
Mhlwazini Cave	Layer 5	330BC	2280±50	Pta 4868
Collingham Shelter	TBS	740	1260±50	Pta 5408
Collingham Shelter	BSV1	140	1810±60	Pta 5265
Collingham Shelter	BSV2	150	1800±50	Pta 5096
Collingham Shelter	BSV3	70	1880±45	Pta 5101

The accuracy of the radiocarbon date depends very largely on where it falls on the curve. For example any sample from the last 300 years will not give a very accurate result because of the nature of the curve. Radiocarbon dating is, nonetheless, very important in order to place a set of assemblages within a specific age group (Table 3).

Most of the charcoal examined was selectively sampled from the exposed surfaces of excavations specifically for radiocarbon dating, rather than for ecological research. There is, however, no apparent bias in fragment size between the sites. Samples range in size from ± 3 mm to ± 15 mm in cross sectional diameter.

In identifying the most common woody species in the archaeological record, the wood charcoal from 7 archaeological sites in Natal and 5 sites in the Transvaal was superficially examined (Figure 2). Sample sizes vary from 20 pieces of charcoal at Magogo and TSH 1.1, to 390 at Mhlwazini (see Table 2). The archaeological charcoal samples were prepared for microscopy by physical fracture in exactly the same manner as the extant samples. Results were satisfactory in that most of the common wood types in the archaeological record could be grouped into morphological types. Where possible these morphological types were associated with specific genera.

Results

In Natal, the most common woody species in the charcoal at the archaeological sites of Ndondondwane and Nshekane, is *Acacia* sp (Table 2) (excavation report Maggs & Michael 1976 and Maggs 1984). At eSinhlonhlweni and Mbabane in the Natal midlands near Estcourt and Weenen, it is an unidentified radial type similar to *Buddleia* sp (Table 2) (excavation report Mazel 1986). In the Drakensberg Mhlwazini Cave (also known as Zulu cave) and Collingham Shelter have a high percentage of *Protea* sp (Table 2) and *Leucosidea* sp (excavation report Mazel 1990 and Mazel 1992). The woody species common to a number of Transvaal archaeological sites is *Combretum apiculatum* (Table 2, Figure 2).

Conclusion

The results of the charcoal identification recognized *Acacia, Buddleia, Protea, Leucosidea* and *Combretum* as the most common genera in 12 archaeological sites across the Transvaal and Natal (Table 2 Figure 2).

Leucosidea sericeae is the most common species of *Leucosidea* in the Natal Drakensberg. Not only does this species grow along stream banks, it also has a distribution range restricted to a specific altitude in the Drakensberg. A combination of its restricted distribution range and proximity to water makes it undesirable as a species for determining changes in xylem anatomy related to climate.

The radial type identified at eSinhlonhlweni and Mbabane is very similar to the *Buddleia* species. *Buddleia salviifolia* and *Buddleia saligna* are the two most common *Buddleia* species in the summer rainfall area. *Buddleia salviifolia* is extremely softstemmed, and as with *Leucosidea sericeae*, is often associated with the flora along stream banks. *Buddleia salviifolia* is therefore not suitable for the purposes of this project. *Buddleia saligna*, however, grows on the drier mountain slopes. A suitably sized sample has the potential to indicate changes in vessel size and frequency across a climate gradient. In an attempt, ultimately unsuccessful, to positively identify the radial type a small *Buddleia* sample was analysed.

The most common *Protea* spp. in the research area are *Protea roupelliae* and *Protea caffra.* These two species grow over a wide range of ecoclimatic regimes within the summer rainfall region and it was felt that both would be suitable for further analysis.

Liegme (1983) reported that in her area of study in Gazunkulu *Colophospermum mopane* and *Combretum apiculatum* were regarded as the best fuel wood species. This observation confirmed previous observations by Gandar (1982) and later by Eberhard and Poynton (1987). *Colophospermum mopane* has a very restricted distribution range, whereas *Combretum apiculatum* is more widespread. *Combretum* is also easily recognizable. Among the different species of Combretaceae identified (Table 2), *Combretum apiculatum* is evident in a number of sites in the northern Transvaal and Venda. Consequently this species was also chosen for further analysis.

There are a number of *Acacia* species in South Africa, all of which have a wide distribution range. Differences between these species are not easy to establish from wood charcoal. It was therefore decided that only a small sample of the three major species of *Acacia* would be collected for further analysis, and no major effort would be made to determine the relationship between xylem anatomy and climate.

Summary

Charcoal has been identified from 12 archaeological sites in the summer rainfall area in terms of relative abundance of wood morphological types. From this analysis, six morphological types were identified as most common in the archaeological record over the last 2000 years (Tables 2 & 3). Of these, four types, (*Buddleia saligna*, *Protea* sp, *Combretum apiculatum* and *Acacia* spp.) were considered as suitable for further analysis to determine the exact nature of the changes in xylem vessel size and frequency along a rainfall gradient.

CHAPTER FOUR

XYLEM ANALYSIS: METHODOLOGY AND APPLICATION TO MODERN SAMPLES

Introduction

Woody plants conduct water and dissolved mineral salts from the roots to the leaves via the xylem vessels. It was Scholtz (1986) who first realized that measurements of xylem vessel size and frequency on charcoal from archaeological sites may be related to climate when compared to the same measurements on an extant sample from areas of known temperature and rainfall. Scholtz's (1986) methods of xylem analysis are directly based on the relationships between plant anatomy, physiology and ecology. These methods are not designed to describe the anatomy of wood, but rather to measure a wide range of potentially ecoclimatically significant wood variables observable in a cross section. The most important of these variables are assumed to be vessel diameter and number of vessels, as a number of researchers have demonstrated that the diameter of the xylem vessels decreases whilst vessel frequency increases with increasing drought (Carlquist 1977a, Baas & Schweingruber 1987, van der Walt 1988, Wilkins & Papassotiriou 1989). This chapter reports on the analysis of vessel size and frequency for a number of trees and shrubs from the summer rainfall region of South Africa. Also included in this chapter is the rationale behind xylem analysis and a description of the methods used.

Relationship between xylem vessels and climate

In order to establish the predictive value of certain vessel element features, Baas *et al.*, (1983) related cambial activity, maximum vessel diameter and transpiration rates for samples of woody flora from Israel and adjacent regions. They noted high values for maximum vessel diameter, and related this pattern to high transpiration rates in the hot summers and ample water supply to the root system. More specifically, vessel diameter increases with increases in transpiration rates due to high temperatures and ample water supply. This logical adaptation had been stressed by Carlquist (1980) who concluded that the occurrence of wide vessels in these trees represents an adaptation to the environmental conditions under which they grow.

The advantage of wide vessels to plants is explained by Zimmerman (1978, 1982, 1983) according to the Hagen-Poiseuille equation for ideal capillaries. Hydraulic conductivity is proportional to the sum of the vessels radius raised to the power of four. This r^4 relationship means that a slight increase in vessel radius is equivalent to an enormous increase in ability to transport sap. For example, three vessels with relative diameters of 1, 2 and 4 and having cross-sectional areas proportional to 1, 4 and 16 will have relative conductivities of 1, 16 and 256. The proportional percentage of sap transported by three such vessels will be 0.4, 5.9 and 93.7 (Zimmerman 1978, 1982, 1983).

If wide vessels are so much more efficient than narrow vessels why is it that all plants do not have wide vessels? The disadvantages of wide vessels to plants is again best explained by Zimmerman (1983). Increased vessel diameter may increase conductivity, but concomitant with this increase in conductivity is a decrease in safety. In the event of any vessel injury causing the permanent blockage of a vessel, and given the r^4 relationship between flow rate and vessel radius, the damage done to a tree with wide vessels will be very much greater than in a tree with narrow vessels. The more numerous the vessels, the smaller the chance that the disabling of a given number will seriously affect conduction (Zimmerman 1983).

In the above discussion it is suggested that the major factors affecting conductivity are vessel diameter and vessel frequency. An analysis of vessel diameter and vessel frequency should be sufficient to indicate changes in plant conductivity across a rainfall gradient.

None of the studies quoted address the relationship between specific vessel characteristics and mean annual rainfall. Carlquist (1977b) compared the wood anatomy of the Peneaceae across a wide amplitude of ecological habitats. In his study, however, no attempt was made to obtain actual rainfall figures. Baas and Schweingruber (1987) also did not determine mean annual rainfall figures. Instead they determined ecological trends for occurrence of certain vessel characteristics along a macroclimatic gradient from boreal through temperate to Mediterranean. Wilkins and Papassotiriou (1989) compared wood samples of *Acacia melanoxylon* from Queensland and Tasmania. All of these studies refer to macroclimate rather than a gradient of mean annual rainfall or/and temperature.

Table 4. The number of individual specimens of *Combretum apiculatum* (Apic), *Buddleia saligna* (Sal), *Acacia Tortillis* (Tort), *Acacia karoo* (Kar), *Acacia nilotica* (Nil), *Protea Roupelliae* (Roup) and *Protea caffra* (Caff) from each location within the study area.

Location	Apic	Sal	Tort	Kar	Nil	Roup	Caff
Barberton	10						
Ben Lavin	10						
Bluegumspoort		11					
Bourkes Luck	10					10	
Dzata	7						
Estcourt		10	3	8			
Gillits					5	11	
Hans Merensky	15						
Hluhluwe				4	4		10
Itala	10					10	
Kamberg						20	10
Letaba	17		2				
Mamba			3				
Messina	14		2				
Mhlawula			3				
Mhlopeni		13	8	6			
Mhlwazini cave						11	1
Mikes Pass						6	9
Mkuze					2		
Tugela Ferry			4				
Ngome forest						9	
Nylsvlei	4		5				
Olifantspoort		10					
Oog van Malemane							5
Origstad Dam						10	
Pafuri	10						
Phalaborwa	10						
Punda Maria	17						
Rooipoort			5				
Rust de Winterdam	10						
Rustenburg		12					
Serala	10					10	
Sodwana Bay				2			
Sterkspruit						10	
Suikerbosrand		10				10	10
Timbavati	15						
Tshongwe			6				
Umtamvuma						15	10
Weenen		10	2				
TOTAL	169	76	43	20	11	132	55

Methods

In our analysis we relate the cross sectional xylem anatomy of *Acacia tortillis, Acacia karoo, Acacia nilotica, Combretum apiculatum, Protea roupelliae, Protea caffra* and

Buddleia saligna to mean annual rainfall. The general hypothesis is that with high transpiration rates in the hot summers of the research area maximum vessel diameters should correlate with increases in rainfall.

Within a tree, vessel diameters tend to be greater in roots than in stems, and greater in the stem than in the branches. Vessel diameters also tend to increase with increasing branch diameter (Zimmerman 1978, 1983). In order to restrict this variation samples collected in the field all have diameters of approximately 2 - 3 cm. Wood from archaeological sites reflects the firewood gathering strategies of prehistoric people. Firewood was probably not gathered randomly as pieces would have been selected specifically for ease of transport and management. The average diameter of branches collected by women in the rural areas of South Africa today is 2 to 4 cm (*pers. obs.*) and it is assumed that this would reflect the most common dimensions for firewood used by prehistoric people.

To relate the anatomy of wood to climate, samples have to be collected from undisturbed sites, as close to weather stations as possible. Roads, buildings and other constructions have to be avoided as increased runoff, as well as watering of domestic plants, does affect vessel size and frequency. In order to fulfill these requirements most of the samples were collected in either private nature reserves or reserves administered by the Transvaal Provincial Administration, National Parks Board or Natal Parks Board. These reserves are less disturbed by development and generally have good rainfall records. For the purposes of this study rainfall was averaged over four years to December 1990 when the samples were collected (see Table 1, Page 8). Measurements of vessel size and number are taken on that section of wood immediately related to the previous four years of growth. On the archaeological sample measurements are taken closest to the outer edge of the charcoal. The locations of collected samples are given in Figure 1 and Tables 1 & 4.

Sample preparation

In the laboratory a 2 cm thick disc was cut off the end of each piece of wood and then split into sections about 5 - 8 mm wide, incorporating both the pith and the cambium. These sections were stored in vials containing a 50% glycerol/alcohol solution. Prior to photography, the wood was softened by boiling before samples were cut in transverse section at thicknesses of between 25 and 30 μm using a base sledge microtome. The thin sections were stained over two days in a mixture of alcohol, glycerol and safrinin red, mounted in Kaisers gelatin-glycerin on glass microscope slides and photographed using a Wild-Leitz photomicroscope at a magnification of 40 X. A graticule was also photographed at the same magnification so that exact magnifications could be calculated when the photographs were developed and printed. Measurements of vessel size and number were then made using a custom written computer programme linked to a Summagraphics digitizing tablet.

Table 5. Mean values and standard error for radial vessel diameter (Radv), tangential vessel diameter (Tangv) and number of vessels (Numv) for three species of *Acacia* across a rainfall gradient within the research area. NS denotes no significant difference between means.

Acacia karoo

Location	N	Rainfall in mm	Radv in µm	Std Error in µm	Tangv in µm	Std Error in µm	Numv per mm^2	Std Error per mm^2
Mhlopeni	6	650	130.9	6.8	113.0	2.5	14.1	1.2
Sodwana Bay	2	735	147.7	5.5	141.3	8.1	09.1	0.4
Estcourt	8	824	112.6	7.3	110.9	4.8	18.3	2.7
Hluhluwe	4	869	153.7	13.8	131.0	11.6	11.6	1.5

Acacia tortillis

Location	N	Rainfall in mm	Radv in µm	Std Error in µm	Tangv in µm	Std Error in µm	Numv per mm^2	Std Error per mm^2
Messina	2	281	203.4	20.1	160.6	17.3	06.0	0.2
Letaba	2	400	152.4	6.8	150.5	0.4	09.0	0.5
Rooipoort	5	420	132.1	2.2	120.4	5.5	10.7	1.4
Punda Maria	2	493	139.2	14.2	128.6	5.4	11.8	0.4
Mhlopeni	8	650	126.1	4.2	115.8	7.4	13.5	2.2
Mhlawula	3	660	161.2	5.6	156.5	7.9	09.7	1.9
Nylsvlei	5	663	157.0	7.5	144.5	3.6	10.3	0.9
Weenen	2	669	169.7	8.5	159.9	2.4	10.3	2.7
Tugela Ferry	4	756	164.9	8.8	150.1	6.1	10.6	0.4
Mamba	3	820	180.6	15.5	153.5	10.2	08.2	0.8
Estcourt	3	824	139.7	7.9	134.4	8.8	11.3	1.4
Tshongwe	6	883	149.1	12.1	133.0	7.6	11.3	1.2
Correlation coefficient (R)			-0.14		-0.04		0.40	
R^2			0.02		0.00		0.16	
Probability (P)			NS		NS		NS	

Multiple regression (Radv, Tangv, Numv) $R^2 = 0.40$, NS.

Acacia nilotica

Location	N	Rainfall in mm	Radv in µm	Std Error in µm	Tangv in µm	Std Error in µm	Numv per mm^2	Std Error per mm^2
Mkuze	2	578	122.9	0.8	119.7	0.4	13.4	1.5
Estcourt	5	824	111.1	8.5	90.8	7.1	21.0	2.8
Hluhluwe	4	869	121.5	9.5	121.4	6.4	17.0	1.5

Xylem Analysis

The three most important variables measured were radial vessel diameter (the diameter of a vessel in the same plane as the direction of the rays) and tangential vessel diameter (the diameter of a vessel at right angles to the direction of the rays) both in microns, and the number of vessels per square millimeter. Diameters were measured for a maximum of 50 vessels per section of wood. Mean values for radial and tangential vessel diameters were calculated by taking the respective means of the five largest vessels measured. The rationale behind using the means for the five largest vessels lies in our original hypothesis which stated that maximum vessel diameter should increase with increasing transpiration rates and therefore greater water availability during the hot summers.

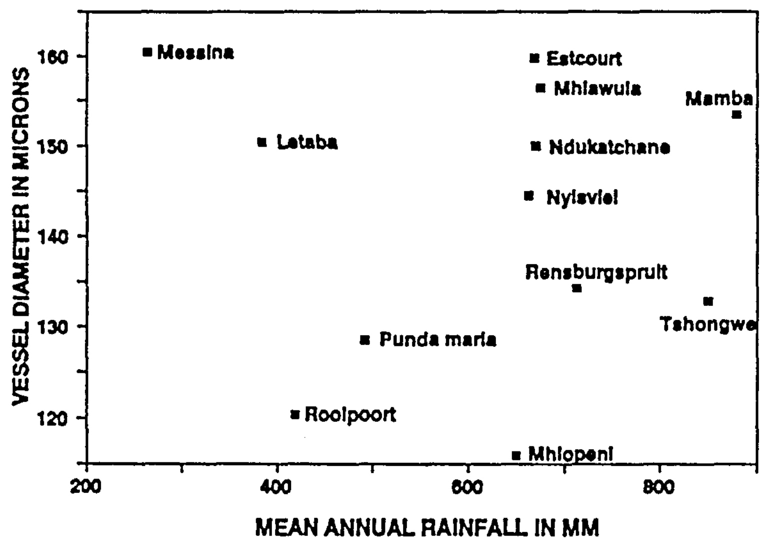

Figure 4. Means for tangential vessel diameter of an extant sample of *Acacia tortillis* along a rainfall gradient in the summer rainfall region of South Africa.

The International Association of Wood Anatomists recommends that vessel diameters are measured in the tangential direction at the widest part of the opening excluding the cell wall (Wheeler *et al.* 1989). In this study both tangential and radial vessel diameters are measured because of the need for these values in calculating vessel area. Using the measurements for radial and tangential vessel diameters, the computer programme applies the area formula for an ellipse to calculate vessel area for each vessel. Total vessel area for the section is measured by means of a points count, the rationale and methodology of which is well documented (e.g. Clark 1982). A plastic sheet marked out in a 10 mm square grid is placed over the photographic image to be digitized. Total vessel area is counted using the number of point intersects. Mean vessel area is then calculated by dividing the sum of the areas of the measured vessels by the number of vessels measured. This value (i.e. mean vessel area) is then divided into the total vessel area to obtain a figure for the number of vessels in a 10 mm x 10 mm square.

Table 6. Mean values and standard error for radial (Radv) and tangential (Tangv) vessel diameter and number of vessels (Numv) for *Combretum apiculatum* across a rainfall gradient within the research area. **, *** and **** denote significant differences between means at $P < 0.01$, 0.001 and 0.0001 respectively.

Location	N	Rainfall in mm	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Messina	12	281	106.6	5.5	94.1	4.7	28.3	1.5
Letaba	9	385	92.0	4.1	81.0	2.6	33.0	2.6
Serala	9	400	99.3	4.5	86.4	2.9	23.5	1.2
Bourkes Luck	10	401	103.6	4.1	84.0	3.7	27.2	2.1
Dzata	6	412	103.8	5.8	86.7	1.5	28.0	3.1
Phalaborwa	10	420	99.3	6.0	85.2	3.4	27.5	2.1
Pafuri	10	434	102.6	7.3	89.5	4.2	33.8	2.8
Timbavati	14	439	103.1	3.6	89.0	2.8	26.6	2.1
Punda Maria	13	493	116.6	3.6	95.6	3.3	22.7	1.4
Hans Merensky	15	538	108.7	3.0	92.1	2.9	24.3	1.2
Rust de Winterdam	10	600	109.1	3.6	95.0	2.8	28.1	1.6
Ben Lavin	10	631	111.2	3.5	94.6	2.9	24.7	0.9
Nylsvlei	4	663	121.3	12.5	97.0	9.8	17.2	1.4
Barberton	9	815	115.9	7.1	95.1	6.3	22.8	1.6
Itala	10	940	131.5	7.0	105.1	4.2	18.8	1.1
Correlation coefficient (R)			0.83		0.77		-0.66	
R^2			0.69		0.60		0.44	
Probability (P)			****		***		**	

Multiple regression (Radv, Tangv, Numv) $R^2 = 0.69$, **.

Results and discussion

In a recent article Wilkins and Papassotiriou (1989) found that the wood anatomy of *Acacia melanoxylon* from various locations in eastern Australia was related to general climate. In this study the sample of *Acacia tortillis* covers a rainfall gradient from 300 mm at Messina to 960 mm at Dougvale (Mamba) in Natal. Comparisons between vessel size (Figure 4), vessel frequency and rainfall are not encouraging as the results of a correlation analysis do not show any statistically significant trends (Table 5). The initial conclusion is that the wood anatomy of *Acacia tortillis* is not a good rainfall indicator.

Table 7. Mean values and standard error for radial (Radv) and tangential (Tangv) vessel diameter and number of vessels (Numv) for *Protea roupelliae and Protea caffra* across a rainfall gradient within the research area. NS *, **, *** and **** denote no significant difference between means and significant differences between means at $P < 0.05$, 0.01, 0.001 and 0.0001 respectively.

Protea roupelliae

Location	N	Rainfall in mm	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Suikerbosrand	10	765	50.1	1.2	46.6	1.9	142.3	12.9
Origstad dam	10	841	53.3	1.0	48.0	1.5	78.9	5.5
Mhlwazini Cave	12	868	44.9	1.6	41.1	2.3	165.6	12.1
Itala	10	942	47.7	1.5	48.5	1.2	164.0	10.7
Sterkspruit	10	1005	52.1	1.3	45.7	1.7	94.0	6.8
Kamberg	20	1105	47.0	2.1	44.3	1.2	156.2	13.4
Mikes Pass	6	1153	45.6	1.2	51.2	3.9	124.0	18.5
Gillits	11	1368	59.8	2.1	55.6	2.0	78.8	6.2
Ngome forest	9	1410	57.8	1.0	53.4	1.1	104.2	7.7
Bourkes Luck	10	1411	56.3	1.5	52.0	1.9	106.1	5.9
Serala	9	1600	57.2	1.8	60.7	2.9	85.6	6.3
Umtamvuma	15	1664	65.6	1.3	62.6	1.5	64.5	3.0
Correlation coefficient (R)			0.77		0.88		-0.61	
R^2			0.60		0.78		0.38	
Probability (P)			**		****		*	

Multiple regression (Radv, Tangv, Numv) $R^2 = 0.79$, **.

Protea caffra

Location	N	Rainfall in mm	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Oog van Malemane	5	546	59.9	4.0	54.4	2.3	53.2	7.2
Suikerbosrand	10	765	60.2	2.6	58.2	3.1	89.2	4.9
Kamberg	10	1100	63.1	2.4	65.7	1.7	55.0	5.8
Cathedral Peak	9	1153	62.8	2.8	60.1	3.2	54.2	4.4
Hluhluwe	10	1170	77.2	1.6	64.8	2.2	44.5	3.1
Umtamvuma	10	1664	71.3	2.4	71.3	2.2	56.1	3.6
Correlation coefficient (R)			0.66		0.93		-0.33	
R^2			0.44		0.88		0.10	
Probability (P)			NS		**		NS	

Multiple regression (Radv, Tangv, Numv) $R^2 = 0.88$, NS.

The results of analysis of *A. karoo* (Table 5) and *A. nilotica* (Table 5) are more promising but sample sizes are not as large as that of *A. tortillis.* Linear regression analysis on twenty specimens from four locations is not statistically reliable. General trends, however, follow the rules established in the literature, that vessel size increases while vessel number decreases, as rainfall increases. But, until more samples of *Acacia* spp. are analyzed no categoric statements can be made on the relationship between vessel morphology and climate.

In *Combretum apiculatum* (Table 6), *Protea roupelliae* (Table 7) and *Protea caffra* (Table 7) the relationship between xylem morphology and rainfall is in accordance with the findings of previous studies (Carlquist 1966, 1977 a & b, Baas *et al.*, 1983, Zhang *et al.*, 1988 and Wilkins & Papassotiriou 1989). Those plants growing in wet environments have larger and fewer vessels than conspecifics growing in a more xeric environment (Table 6 & 7 and Figure 5). The results of a correlation coefficient analysis show very strong correlations between vessel diameter and rainfall (*C. apiculatum* N = 15, R = 0.77, P <0.001 (Table 6), *P. roupelliae* N = 12, R = 0.88, P ≤0.0001 (Table 7, Figure 5), *P. caffra* N = 6, R = 0.93, P < 0.01, (Table 7)). There are also significant correlations between rainfall and vessel frequency (*C. apiculatum* N = 15, R = - 0.66, P <0.01, *P. roupelliae* N = 12, R = -0.61, P <0.5 , *P. caffra* N = 6, R = -0.33, P not significant (Table 7)).

Table 8. Mean values for radial (Radv) and tangential (Tangv) vessel diameter and number of vessels (Numv) for *Buddleia saligna* across a rainfall gradient within the research area. NS, *, ** denote no significant difference between means and significant difference between means at P <0.05 and 0.01 respectively.

Location	N	Rainfall in mm	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Bluegumspoort	11	599	59.1	2.4	52.3	1.7	67.9	5.4
Mhlopeni	13	650	56.2	1.0	49.7	0.8	85.0	3.8
eSinhlonhlweni	10	669	54.4	1.2	49.4	1.2	92.4	5.4
Olifantspoort	10	706	59.8	2.2	47.5	1.0	86.5	9.9
Suikerbosrand	10	765	57.6	1.3	51.5	1.4	88.6	5.4
Rustenburg	12	773	60.0	1.3	54.2	1.2	86.7	4.4
Estcourt	10	824	53.5	1.5	49.6	1.4	113.3	13.9
Correlation coefficients (R)			-0.22		0.08		0.80	
R^2			0.05		0.00		0.63	
Probability (P)			NS		NS		*	

Multiple regression (Radv, Tangv, Numv) R^2 = 0.96, **.

Contrary to expectations measurements on *Buddleia saligna* show absolutely no correlation between the means of vessel diameter and rainfall (N = 7, R = 0.08, P not significant, Table 8). What is of note is the consistency in tangential vessel diameter which does not vary more than 5 microns, from 49 to 54 microns. It is vessel number that is positively rather than negatively correlated with rainfall. This relationship is not only contrary to all expectations but also contrary to all other studies on ecological change in wood anatomy (Carlquist 1966, 1977, Baas *et al.*, 1983, Zhang *et al.*, 1988 and Wilkins & Papassotiriou 1989). Our sample size is still very small (75 samples from 6 locations, Table 4 & Table 8) with a relatively tight range in rainfall (from 600 mm to 800 mm, Table 1 & Table 8). It may be possible to more clearly identify the results for *Buddleia saligna* with a larger sample from a wider range in rainfall. The correlation between the means for rainfall and vessel frequency of *Buddleia saligna* is, however, very good (N = 7, R = 0.80, P < 0.05).

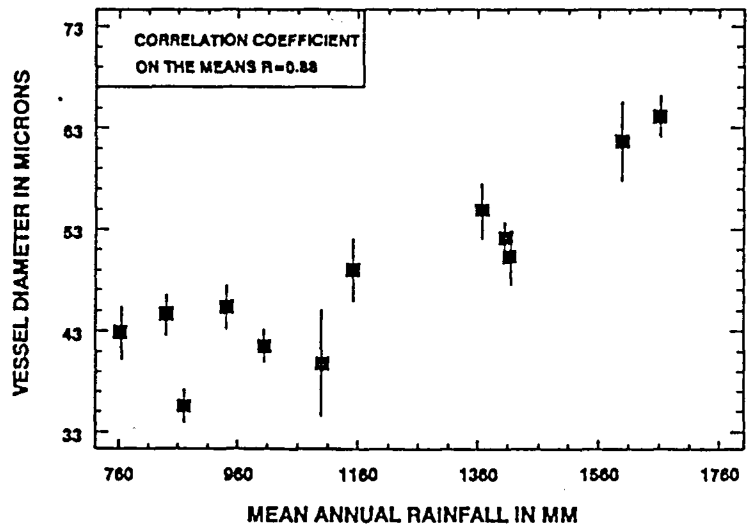

Figure 5. Means and standard error for tangential vessel diameter of an extant sample of *Protea roupelliae* along a rainfall gradient in the summer rainfall region of South Africa.

Conclusion

From the above it was concluded that more research is needed to establish the ecological component in vessel size and frequency variations of *Acacia* spp. There is no relationship between vessel size of *Buddleia saligna* and rainfall. Contrary to expectations, however, vessel frequency and rainfall are positively correlated. With an increase in sample size the results for *Acacia* spp. and *Buddleia saligna* may be improved upon although it is unlikely that *Buddleia saligna* occurs outside of the present rainfall range. Three of the species do, however, conform to expectations in that, with increasing rainfall, vessel size increases while vessel frequency decreases. These species are *Combretum apiculatum, Protea caffra* and *Protea roupelliae* (Table 6 & 7). It is these three species that form the basis of all further analysis in this report.

CHAPTER FIVE

SHRINKAGES ACCOMPANYING CARBONIZATION

Introduction

Wood shrinks when charcoaled. The exact nature of this shrinkage is not quite clear but is approximately 40% by volume. These shrinkages are considered to be uniform, as the ratio between cell diameter and cell wall thickness does not change in the charcoaling process. What does change is the number of vessels in a given area. With carbonization the number of vessels per square millimetre should increase while vessel diameter should decrease. There has, however, been very little work done on the physiological changes of wood with carbonization.

As elaborated on in the previous chapter, there is a good correlation between rainfall, vessel size and vessel frequency for *C. apiculatum, P. roupelliae* and *P. caffra.* This correlation, however, has been achieved using thin sections of fresh rather than charcoaled wood. If wood shrinks when charcoaled then it is only possible to use archaeological charcoal samples if the same trends established in fresh wood can be determined in charcoaled wood from the same climate gradient. To ascertain the relationship between rainfall, vessel size and vessel frequency in charcoaled wood along a climate gradient some of the fresh wood samples were charcoaled and re-analyzed.

Methods

Five samples of *C. apiculatum, P. caffra* and *P. roupelliae* per collecting site were chosen for analysis. Discs approximately three centimetres in length were cut and wrapped in tinfoil. These parcels were placed in a muffle furnace the temperature of which was gradually taken up to a maximum of 500°C after 1 hour. The furnace was then switched off and allowed to cool down slowly. Samples were prepared for electron microscopy as described in Chapter 3 for incident light microscopy. Tusenius (1986:22) describes the preparation procedure necessary for working with charcoal on the SEM. This procedure is the same for most electron microscope work. The only deviation from the normal procedure was the adaptation of a normal electron microscope stub to take a large galvanized iron washer. The charcoal pieces were mounted on the washer using an alkaline glue and the whole was screwed onto the stub with a 3 mm diameter screw. The washers could then be unscrewed from the stub and stored separately while the stub was reused. As with the fresh wood sample measurements of size and number were then made using a custom written computer programme linked to a Summagraphics digitizing tablet.

Results and discussion

Mean values of vessel diameter and vessel frequency for charcoaled wood are substantially different from those for fresh wood (Tables 9 - 11). Shrinkage in tangential vessel diameter compares well with that quoted in McGinnes, Jr. *et al.*, (1971) with a shrinkage ratio of 1.70 times on conversion of wood to charcoal. Shrinkages in radial vessel diameter, however, are much lower and more variable than in the tangential vessel diameters. As mentioned on p. 22, the standard method of measuring vessel diameter according to the *International Association of Wood Anatomists* (IAWA) is in the tangential direction. The consistent shrinkage factor of 40% in tangential vessel diameter between all three species of wood analysed (Tables 9 - 11) confirms the decision to conform to IAWA standards in determining vessel diameter.

The number of vessels in a given area is, of course considerably increased. From the shrinkage factors produced by Beall *et al.*, (1974), Cousins (1975) calculated this increase to be as much as a doubling of cells in a given cross section of the original wood. The results for *P. caffra* and *P. roupelliae* confirm Cousins (1975) calculations in that vessel frequency increases by 1.85 times (40%) for *P. roupelliae* and 1.95 times (46%) for *P. caffra* in the conversion of wood to charcoal (Table 10 & 11).

Table 9. Mean values and standard error for radial vessel diameter (Radv), tangential vessel diameter (Tangv) and number of vessels (Numv) for *Combretum apiculatum* along a rainfall gradient within the research area. Values are both before and after carbonisation at 500°C. NS, * and ** denote no significant difference between means and significant differences between means at $P < 0.05$ and 0.01 respectively.

Mean values

Location	Rainfall	Charcoaled wood Radv	Charcoaled wood Tangv	Charcoaled wood Numv	Fresh wood Radv	Fresh wood Tangv	Fresh wood Numv	% shrinkage Radv	% shrinkage Tangv	% shrinkage Numv
	in mm	in μm	in μm	per mm^2	in μm	in μm	per mm^2	%	%	%
Messina	281	66.1	46.7	125.0	109.2	98.4	30.0	39.5	52.6	76.0
Letaba	385	68.1	49.3	86.8	89.9	78.6	34.3	24.3	37.3	60.5
Serala	400	77.5	46.4	79.2	102.9	88.6	24.4	24.6	47.7	69.2
Bourkes Luck	401	114.5	76.5	41.1	112.2	90.1	21.7	-2.0	15.1	47.1
Dzata	412	64.0	36.6	65.1	105.6	87.5	27.3	39.4	58.2	58.1
Phalaborwa	420	95.6	60.1	56.7	100.2	81.0	26.7	4.6	25.8	53.0
Pafuri	434	72.5	43.5	93.3	101.8	89.9	31.8	28.8	51.6	65.9
Timbavati	439	70.9	47.9	75.0	103.3	91.5	29.4	31.4	47.7	60.8
Punda Maria	493	75.7	45.5	98.3	120.6	99.1	23.8	37.2	54.1	75.8
Hans Merensky	538	81.5	53.0	70.6	110.8	100.0	25.6	26.4	47.0	63.7
Rust der Winter	600	76.1	43.8	89.5	107.3	92.7	29.7	29.0	52.8	66.9
Ben Lavin	631	73.0	46.2	65.8	115.2	99.9	23.5	36.6	53.8	64.2
Barberton	815	104.2	67.4	41.1	114.2	94.3	20.9	8.8	28.6	49.2
Itala	942	84.2	52.2	56.5	117.8	102.1	20.4	28.6	48.8	63.8
Correlation coefficient (R)		0.30	0.19	-0.50	0.56	0.51	-0.61			
R^2		0.09	0.04	0.25	0.31	0.26	0.38			
Probability (P)		NS	NS	NS	NS	NS	**			

Multiple regression (Radv, Tangv, Numv) fresh wood $R^2 = 0.45$, NS.
charcoaled wood $R^2 = 0.31$, NS.

standard error

Location	N	Charcoaled wood Radv	Charcoaled wood Tangv	Charcoaled wood Numv	Fresh wood Radv	Fresh wood Tangv	Fresh wood Numv
Messina	5	4.4	3.7	13.8	9.7	9.5	1.2
Letaba	5	2.1	2.2	5.3	3.8	2.9	3.3
Bourkes Luck	5	4.9	3.4	3.2	5.3	3.9	1.5
Dzata	4	3.4	1.3	16.8	8.6	1.2	4.5
Phalaborwa	5	6.4	6.2	4.6	9.0	4.7	2.7
Pafuri	4	0.8	0.5	12.2	6.5	2.6	2.5
Timbavati	5	3.4	3.1	6.3	4.5	4.8	4.2
Punda Maria	5	4.1	2.0	16.2	4.7	2.0	1.8
Hans Merensky	5	5.1	3.6	5.9	5.7	4.6	1.4
Rust de Winterdam	5	4.5	2.6	7.7	5.7	3.9	2.9
Ben Lavin	5	3.4	1.2	12.7	3.4	2.4	1.4
Serala	5	4.3	1.4	18.4	6.7	4.0	1.8
Barberton	5	4.2	3.5	2.8	4.3	3.4	1.8
Itala	5	4.0	3.6	6.6	3.9	4.0	1.7

Table 10. Mean values and standard error for radial vessel diameter (Radv), tangential vessel diameter (Tangv) and number of vessels (Numv) for *Protea roupelliae* along a rainfall gradient within the research area. Values are both before and after carbonization at 500^{O}C. *, ** and *** denotes significant differences between means at P < 0.05, 0.01 and 0.001 respectively.

mean values

Location	Rain in mm	Charcoaled wood Radv in µm	Tangv in µm	Numv per mm^2	Fresh wood Radv in µm	Tangv in µm	Numv per mm^2	% shrinkage Radv %	Tangv %	Numv %
Suikerbosrand	765	38.6	23.3	352.3	50.5	45.4	154.3	23	48	56
Origstad dam	841	45.8	27.2	324.8	52.9	46.8	81.1	13	41	75
Mhlwazini	868	38.9	31.4	310.9	44.5	42.6	178.0	12	26	42
Itala	942	46.6	28.2	301.8	48.2	49.9	169.5	3	43	43
Sterkspruit	1005	46.2	27.5	265.4	52.9	46.7	81.1	12	41	69
Kamberg	1105	39.4	25.1	383.6	43.9	46.8	186.3	10	46	51
Mikes Pass	1153	41.4	27.2	314.4	46.5	52.6	125.4	11	48	60
Gillits	1368	62.3	40.4	83.4	59.1	53.4	72.5	4	30	20
Ngome forest	1410	54.4	30.3	140.3	58.5	53.6	94.0	7	43	32
Bourkes Luck	1411	47.5	28.0	320.0	55.4	47.6	111.9	14	41	65
Serala	1600	50.8	32.8	154.0	55.3	59.3	84.6	8	44	45
Umtamvuma	1664	62.4	40.0	147.8	64.5	60.3	64.0	3	33	56
Correlation coefficient (R)		0.75	0.68	-0.73	0.72	0.85	-0.58			
R^2		0.57	0.46	0.53	0.52	0.73	0.34			
Probability (P)		**	**	**	**	***	*			

Multiple regression (Radv, Tangv, Numv) fresh wood $R^2 = 0.77$, **.
charcoaled wood $R^2 = 0.58$, *

standard error

Location	N	Charcoaled wood Radv	Tangv	Numv	Fresh wood Radv	Tangv	Numv
Suikerbosrand	5	2.1	1.8	18.1	2.4	2.2	22.0
Origstad dam	5	1.5	1.7	25.1	2.4	1.1	10.6
Mhlwazini	10	1.5	1.6	22.1	3.7	2.4	10.6
Itala	5	1.9	0.8	8.3	2.4	1.6	10.6
Sterkspruit	5	0.7	1.2	24.6	7.0	2.8	8.6
Kamberg	5	1.0	1.4	14.7	3.7	2.9	20.2
Cathedral Peak	5	1.4	1.8	33.7	1.6	4.5	22.1
Gillits	5	2.3	1.8	5.9	1.0	2.5	7.4
Ngome forst	5	3.8	2.3	2.2	0.8	1.9	8.9
Bourkes Luck	5	2.9	1.1	6.7	1.0	1.2	6.8
Serala	5	3.3	1.1	3.0	1.7	4.4	9.6
Umtamvuma	5	3.1	2.3	5.6	1.9	2.7	3.9

There are no statistically significant results for *C. apiculatum* although general trends do indicate that vessel sizes increase while vessel frequency decreases with increases in rainfall (Table 9). The lack of statistical significance for *C. apiculatum* is probably due to the fact that sample sizes for the charcoaled wood are substantially smaller than for fresh wood by at least 50%. As with the fresh wood comparative sample these correlations should become more significant as sample sizes increase. Results are, however, sufficient to indicate that the climatic significance of vessel size and frequency is maintained when wood is charcoaled. The results also indicate the necessity for large sample sizes in both an extant wood charcoal sample as well as archaeological charcoal sample in order to maintain statistical integrity. Sample sizes for the extant charcoal sample should be increased from five per location to a minimum of ten.

Table 11. Mean values and standard error for radial vessel diameter (Radv), tangential vessel diameter (Tangv) and number of vessels (Numv) for *Protea caffra* along a rainfall gradient within the research area. Values are both before and after carbonisation at 500°C. N = 5, NS denotes no significant difference between means.

Mean values

Location		Charcoaled wood			Fresh wood			% shrinkage		
	Rain	Radv	Tangv	Numv	Radv	Tangv	Numv	Radv	Tangv	Numv
	in mm	in μm	in μm	per mm^2	in μm	in μm	per mm^2	%	%	%
Suikerbosrand	765	61.1	33.4	166.2	67.0	60.6	76.1	8	44	54
Kamberg	1105	64.8	38.8	82.6	62.5	65.8	56.7	-3	41	31
Cathedral Peak	1153	57.0	30.4	161.5	59.6	58.7	57.9	4	48	64
Hluhluwe	1170	76.0	45.7	95.2	78.0	68.1	45.0	2	32	52
Umtamvuma	1664	77.7	47.6	94.3	74.3	70.9	53.9	-4	32	42
Correlation coefficient (R)		0.68	0.69	-0.56	0.40	0.72	-0.63			
R^2		0.46	0.48	0.32	0.16	0.52	0.40			
Probability (P)		NS	NS	NS	NS	NS	NS			

Multiple regression (Radv, Tangv, Numv) fresh wood R^2 = 0.63, NS.
charcoaled wood R^2 = 0.53, NS.

Standard error

Location	Charcoaled wood Radv	Tangv	Numv	Fresh wood Radv	Tangv	Numv
	in μm	in μm	per mm^2	in μm	in μm	per mm^2
Suikerbosrand	2.2	1.4	14.4	2.6	4.5	3.0
Kamberg	4.3	3.5	8.2	2.7	2.0	9.1
Cathedral Peak	3.6	2.4	31.1	2.5	3.6	3.3
Hluhluwe	3.3	1.2	7.0	1.7	3.1	2.0
Umtamvuma	4.7	1.6	14.4	3.0	2.4	5.4

Conclusions

In *C. apiculatum* vessel diameter is positively while vessel frequency is negatively, correlated to rainfall. These results are not statistically significant. Charcoaled samples of *P. roupelliae* and *P. caffra*, however, do show a significant correlation between rainfall and vessel diameter (Table 10). On the basis of these results a well identified archaeological charcoal sample may be analysed in order to reconstruct the rainfall history of the research area. The results for *P. roupelliae* may prove to be the most reliable. Further research on *C. apiculatum* is necessary before reliable results can be obtained from this species. This reliability can be verified with a comparison of the results for *C. apiculatum* and *P. roupelliae* from well-dated archaeological sites.

In the course of the analysis it has been determined that different species react to carbonization differently. These different responses in vessel morphology to carbonization mean that all archaeological charcoal samples have to be positively identified to species level before comparisons can be made between an extant wood sample and a prehistoric sample.

CHAPTER 6

IDENTIFICATION AND ANALYSIS OF ARCHAEOLOGICAL CHARCOAL

Introduction

The results from both treatments of the extant wood sample indicate that different species exhibit different responses in vessel size and frequency to increases in rainfall (Tables 6 - 11). *Buddleia saligna* does not increase vessel size, rather it is vessel frequency that increases (Table 8). Mean values for vessel diameter of *Protea caffra* are lower than those for *Protea roupelliae* (Tables 7, 10 & 11). These differences in vessel morphology between different species mean that all archaeological charcoal samples have to be positively identified prior to further analysis.

At Mhlwazini Cave and Collingham Shelter the major woody species identified in the archaeological charcoal sample is *Protea* sp. or spp. The genus *Protea* has a wide distribution range throughout Africa, with according to Rourke (1980) 13 species in the summer rainfall region of South Africa. Only two of these 13 species occur in the vicinity of Mhlwazini Cave today. On a collecting trip to the area only one specimen of *P. caffra* was found within two kilometres of the cave while a number of specimens of *P. roupelliae* were available. This situation may have changed at some point within the last 2000 years so both species were examined in this study. At Collingham Shelter there is absolutely no *Protea* growing in the vicinity of the site today even though more than 30% of the charcoal sample from this site can be identified as *Protea* sp. or spp. Both these archaeological sites are located at similar altitudes (Collingham shelter 1800 m & Mhlwazini cave 1860 m). According to Edwards (1967) and Mazel (1990 & 1992) these sites are located in the *Protea* Savanna belt of the Natal Drakensberg with a similar mean annual rainfall and temperature regime.

P. caffra and *P. roupelliae* are two of the largest and tallest *Protea* species in the summer rainfall area today. The wood anatomy of these *Protea* spp. has not been described at all, although Rourke (1980) has given a good systematic description of the genus *Protea* including both *P. caffra* and *P. roupelliae*. *P caffra* varies from an erect shrub or small tree 3 - 8 m in height, with a distinct main stem or trunk about 400 mm in diameter, to an erect shrub 500 mm to 2 m in height, with many branches and lacking a definite trunk. *P. roupelliae* forms a small many branched tree with a short main trunk about 200 to 400 mm in diameter (Rourke 1980).

Descriptions

In order to positively identify the *Protea* and *Combretum* species from the charcoal in archaeological sites the anatomical structure of the wood has to be recognized. The anatomy of *P. roupelliae* and *P. caffra* have not been previously described while *C. apiculatum* has been described by Kromhout (1975). The descriptions presented below are based on the examination of 169 *Combretum apiculatum*, 132 *Protea roupelliae* and 55 *Protea caffra* thin sections (Table 4). Sample preparation was the same as that described in Chapter 4. With no *Protea* growing at Collingham Shelter, it is impossible to compare the generalized anatomy of either *P. roupelliae* or *P. caffra* with that of corresponding specimens which could have grown in the vicinity of the shelter. Only *P. roupelliae* can be compared anatomically with samples from the vicinity of Mhlwazini Cave, where one growing specimen of *P. caffra* was encountered.

P. roupelliae

Growth rings indistinct to distinct. Diffuse porous to ring porous.

Vessels solitary and often tangentially arranged. Larger vessels between 40 and 65 μm in diameter. Between 65 and 165 vessels per mm^2. Vessel element length was not measured but perforation plates are simple. Intervessel pitting alternate, no spiral thickening.

Fibres are thick walled.

Axial parenchyma unilateral paratracheal.

Rays of two distinct size classes. Smaller rays 1 - 3 cells wide and larger rays 4 - 10 cells wide in tangential section. Ray height greater than 1 mm and seldom more than 3 mm. In transverse section larger rays often have a herring bone pattern as ray cells can be rhomboidal. Average ray area 20% of total area measured.

P. caffra

Growth rings indistinct. Vessels occasionally arranged tangentially.

Vessels solitary diffuse porous can be tangentially arranged. Larger vessels between 55 to 85 μm in diameter. Between 45 to 90 vessels per mm^2. Perforation plates simple. Intervessel pitting alternate, no spiral thickening. Vessel element length was not measured.

Fibres thick walled.

Axial parenchyma predominantly paratracheal. Can be unilaterally paratracheal.

Rays of two distinct size classes. Smaller rays 1 - 3 cells wide. Larger rays 4 - 10 cells wide. Ray height greater than 1 mm frequently being greater than 5 mm. In transverse section larger rays often have a herring bone pattern as ray cells can be rhomboidal. Average ray area 30% of total area measured.

Combretum apiculatum

Growth ring boundaries intermediate between distinct and indistinct.

Vessels solitary diffuse porous. Larger vessels between 80 and 100 μm in diameter. Between 15 and 35 vessels per mm^2. Perforation plates simple. Cambial variant, included phloem, tangentially arranged and diffuse. Vessel element length not measured.

Fibres thick walled.

Axial parenchyma aliform and aliform confluent.

Rays 1 cell wide occasionally 2 cells wide. Horizontal cells forming 'canals' prominent in radial section. These 'canals' often filled with crystals. The crystals are also prominent in the ray cells in tangential view. Even after the wood is charcoaled these white crystals are still very prominent.

Results of archaeological charcoal sample analysis

When charcoaled, differences between the two species of *Protea* are in tangential vessel diameter (mean values for *P. caffra* 38 μm and *P. roupelliae* 30 μm, see Tables 10 & 11) and in number of vessels (mean values for *P. caffra* 126 per mm^2 and *P. roupelliae* 300 per mm^2, see Tables 10 & 11). Within a normal distribution, however, the two ranges do unfortunately overlap making it extremely difficult to quantify the differences between *P. caffra* and *P. roupelliae* on anatomy alone.

Table 12. Mean values and standard error for radial vessel diameter (Radv) tangential vessel diameter (Tangv) and number of vessels (Numv) for *Protea roupelliae* from the archaeological sites Mhlwazini cave and Collingham shelter and *Combretum apiculatum* from the Iron Age village of Dzata (see Table 3 & Figure 2).

Protea roupelliae

Archaeological site	N	R.C. Date (BP)	Layer	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Mhlwazini	10	Modern	MOD	38.9	1.5	31.4	1.6	310.9	22.1
Mhlwazini	13	190±45	MBS	40.5	1.5	35.3	1.6	224.0	14.6
Mhlwazini	16	320±40	BS2	40.2	2.1	33.1	1.2	227.2	22.2
Mhlwazini	11	580±50	WMAC	40.3	2.5	33.5	1.5	208.9	29.0
Collingham	25	1260±50	TBS	42.7	1.7	32.0	1.0	249.9	14.2
Collingham	26	1800±50	BSV2	42.9	1.3	34.8	1.1	257.2	14.9
Collingham	26	1880±45	BSV3	44.6	1.6	35.2	1.0	314.6	19.5
Mhlwazini	12	2280±50	AOBS	43.1	1.5	36.1	1.9	152.7	15.5

Combretum apiculatum

Archaeological site	N	R.C. Date (BP)	Layer	Radv in μm	Std Error in μm	Tangv in μm	Std Error in μm	Numv per mm^2	Std Error per mm^2
Dzata	5	0	MOD	64.6	3.4	37.0	1.3	56.5	16.8
Dzata	5	260±70	T2/7b	61.1	1.4	43.6	0.6	57.4	4.9
Dzata	8	290±50	T2/2	66.0	1.5	47.2	0.7	76.8	9.4
Dzata	6	370±40	T2/5w	63.3	1.3	41.6	0.7	95.3	19.4

As ray height of *P. roupelliae* seldom exceeds 3 mm whereas that of *P. caffra* often does, ray height was considered a reasonable defining feature, although there is still some overlap between the two species. When sorting the archaeological sample from both Collingham Shelter and Mhlwazini Cave on the basis of ray height it was found that the majority of samples were probably *P. roupelliae*. Mean values for vessel size and frequency confirm this identification.

The results of analysis of fresh wood samples of *C. apiculatum, P. roupelliae* and *P. caffra* along a gradient in the summer rainfall area has shown that vessel size increases while vessel frequency decreases with increases in rainfall (Table 6 - 11). The highest correlations are achieved when correlating mean annual rainfall to tangential vessel diameter (Table 6 - 11). This correlation persists even when wood is charcoaled although a correlation coefficient analysis on the means for *P. roupelliae* (Table 10) has a higher statistical significance than for *C. apiculatum* (Table 9).

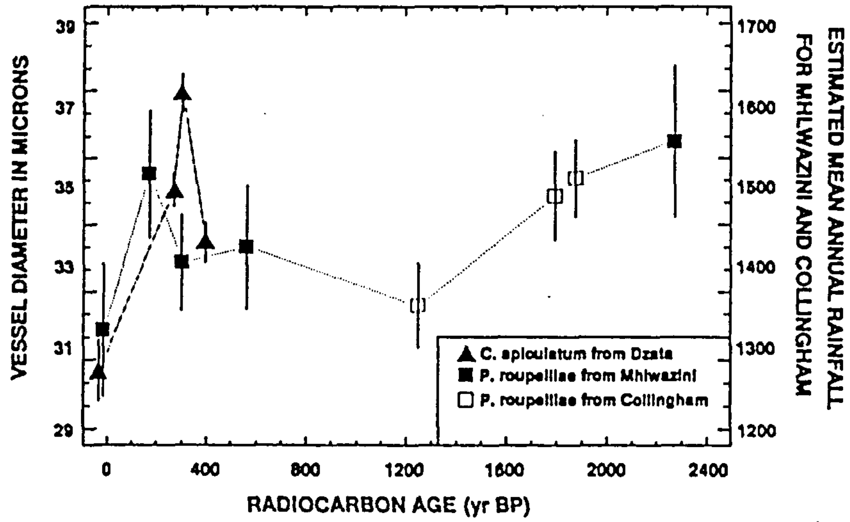

Figure 6. Means and standard error for tangential vessel diameter of an archaeological charcoal sample of *Protea roupelliae* from Mhlwazini Cave and Collingham Shelter in the northern Natal Drakensberg and *Combretum* from Dzata in Venda.

Results for tangential vessel diameter of the *Protea* spp. from Mhlwazini Cave and Collingham Shelter indicate that vessels were much larger at ± 2300 B.P. steadily decreasing in size to ± 1300 B.P. before increasing again somewhat to ± 200 B.P. before decreasing to the present sizes (Table 12, Fig 6). The suggestion is that there is a general decrease in rainfall from ± 2300 B.P. to the present. Indicated within this trend is a decrease in rainfall from 2300 B.P. to 1300 B.P. with low rainfall between ±1300 B.P. and ± 300 B.P. before an increase at 200 B.P prior to a decline to present levels (Table 12 Figure 6). Using a smaller sample (19 specimens from 3 layers) of *Combretum apiculatum* from the Iron Age village of Dzata. a similar pattern in rainfall for the last 400 years is indicated (Table 8, Figure 6).

The remarkable similarity for Collingham Shelter, Mhlwazini Cave and Dzata reinforces the integrity of the results. These results also fit what little evidence there is from South Africa documenting climate change over the last two thousand years. It would appear from the work of Butzer *et al.* (1978 & 1984), Klein (1980), Cooke and Verstappen (1984) and others, that at about 3000 B.P. conditions in the summer rainfall region of South Africa were generally much wetter than at present (Tyson 1986). In addition, Smith (1992) has tentatively suggested a single flood event of the Orange river dated to ±2400 B.P. which is the exact radiocarbon age of the charcoal from Mhlwazini Cave identified from this study as being from a wetter period.

The period from about 1100 B.P. (900 A.D.) to 300 B.P.(1700 A.D.) has been called the Little Ice Age, a world wide phenomenon which is not as extensively documented in the southern Hemisphere as it has been in the northern. What evidence there is does, however, suggest that the Little Ice Age in South Africa was the coolest and driest period within the last 10 000 years (Tyson & Lindesay 1992). A reinterpretation of the tree ring data of Hall (1976) and Dunwiddie and Le Marche (1980) by Tyson (1986) shows below normal tree growth from at least the fourteenth century to the mid sixteenth century in response to the cooler drier conditions prevalent at the time. With climatic amelioration at about 1700 A.D. (300 B.P.) warming occurred and summer rainfall increased. The Karkloof tree ring sequence (Hall, 1976) shows an increase in growth at about 1760 which may be associated with this amelioration (Tyson 1976).

Rainfall trends through the nineteenth century data are rather more ambiguous and there are two schools of thought. Acocks (1955) may have been the first to record the expansion of the Karoo veld into grassland. Early research intimated that any expansion of the Karoo into grassland was the result of bad farm management coupled with a general decrease in mean annual rainfall. More recently Tyson (1986), Vogel (1989) and Avery (1991) have shown that the case for progressive desiccation is unjustifiable. Rather, they propose that the situation has been very much more dynamic with fluctuations in rainfall around a mean with wetter and drier cycles. The results of the analysis of the archaeological charcoal from Dzata, Collingham and Mhlwazini does show conditions to be much drier at present than at any other time within the last ±200 years.

CHAPTER SEVEN

CONCLUSIONS AND RECOMMENDATIONS

Introduction

This report discusses the procedures used in the development of a new method for climate reconstruction using wood charcoal excavated from archaeological sites. A result of this work has been a contribution to the reconstruction of the rainfall history of the last 2000 years in the summer rainfall region.

Previous studies have indicated a link between vessel diameter, vessel frequency and climate (Carlquist 1977 a & b, Baas 1982, Baas *et al.* 1983, Zhang *et al.* 1988). These researchers have pointed out that the diameter of xylem vessels decreases, while the vessel frequency increases with increasing drought. Scholtz (1986) was the first to realize the potential for using the variation in anatomy of wood charcoal from archaeological sites to infer palaeoclimatic change. Scholtz (1986) developed a computer based technique for measuring a wide range of potentially ecoclimatically significant variables observable in a cross section of wood. The present study was a systematic application of Scholtz's approach to palaeoclimatic reconstruction in order to test its applicability and precision.

The three questions that are important here are:

(1) What is the relationship between vessel size, vessel frequency and rainfall?
(2) If there is a good correlation between these variables, then does this correlation still hold even when wood is charcoaled?
(3) In a reconstruction of climate change using xylem analysis of wood charcoal what is the precision with which we can reconstruct rainfall from the archaeological record?

The project will now be viewed in the light of these three questions.

<u>Results and recommendations for future research</u>

<u>**Question 1**</u>: What is the relationship between vessel size, vessel frequency and rainfall?

As has been stated previously a number of studies have shown the relationship between vessel size, vessel frequency and climate. In the present study the wood anatomy of a number of trees and shrubs were analysed across a rainfall gradient in order to determine the exact relationship between vessel size, vessel frequency and rainfall for a number of woody species endemic to the summer rainfall region of South Africa. In this analysis the cross sectional xylem anatomy of *Acacia tortillis, Acacia karoo, Acacia nilotica, Combretum apiculatum, Protea roupelliae, Protea caffra* and *Buddleia saligna* are related to rainfall.

The results for the *Acacia karoo* and *Acacia nilotica* sample indicate a general tendency for vessel size to increase and vessel frequency to decrease with increases in rainfall (Table 5). Sample sizes are however, too small to obtain statistically significant results. Results for the much larger sample of *Acacia tortillis* do not however, show any statistically significant trends between vessel diameter, vessel number and rainfall (Table 5).

For *Combretum apiculatum, Protea roupelliae* and *Protea caffra* the relationship between xylem morphology and rainfall indicates that xylem vessel size is positively, and vessel frequency negatively, correlated with rainfall (Tables 6 & 7). Vessel diameter of *Buddleia saligna* does not show any correlation with rainfall but vessel frequency is positively correlated (Table 8).

From the above it was concluded that with increasing rainfall, vessel size increases while vessel frequency decreases in *C. apiculatum, P. roupelliae and P. caffra* (Tables 6 & 7). This cannot be taken as a general premise, however, since it was found, for example, that *Buddleia saligna* does not show any change in vessel size, yet vessel frequency is positively related to rainfall (Table 8). More research is needed to establish the ecological component in vessel size and frequency variations of *Acacia* spp.

The difference in responses of the various species to rainfall enforces the need to positively identify all archaeological samples to species level before comparisons can be made between an extant wood sample and a prehistoric sample.

Question 2. If there is a good correlation between vessel frequency, vessel diameter and rainfall, then does this correlation still hold even when wood is charcoaled?

In an attempt to ascertain the relationship between rainfall, vessel size and vessel frequency in charcoaled wood along a climate gradient, five samples of *C. apiculatum*, *P. roupelliae*, and *P. caffra* per collecting site were charcoaled and re-analyzed (Tables 9 - 11). The results of this experiment indicate that in the *Protea* samples there is a strong correlation between vessel size vessel frequency and rainfall, even when wood is charcoaled. The results of a correlation coefficient analysis on the relationship between rainfall and vessel diameter for charcoaled samples of *C. apiculatum* are not statistically significant although the general trends still hold true (Table 9). It is felt that the statistical significance of the *Combretum* sample should improve with an increase in sample size.

Question 3: In a reconstruction of climate change using xylem analysis of wood charcoal what is the precision with which we can reconstruct rainfall from the archaeological record?

If it is possible to obtain statistically significant correlations between rainfall, vessel size and vessel frequency for charcoaled wood, then the same should hold true for archaeological charcoal. Wood charcoal from three archaeological sites identified as *P. roupelliae* and *C. apiculatum* show that there is a general decrease in rainfall from a peak 2500 years ago to about 800 A.D. after which followed a dry period for about 900 years to 1700 A.D., when rainfall increased briefly before declining to present levels. There is a good regional fit between the results of this study and other evidence documenting climate change in southern Africa (Butzer *et al.*, 1978 & 1984, Klein 1980, Cooke & Verstappen 1984, Tyson 1976, Avery 1991, Smith 1992).

Apparent time discrepancies can probably be explained by geographic variations, lag times and dating problems. The resolution of the time series is, however, insufficient to allow detailed interpretation of rainfall conditions over the last 2000 years. Some generalized patterns of wetter and drier periods can be postulated, however, which suggest that it should be possible to use wood charcoal from archaeological sites to determine patterns in rainfall through time more comprehensively. As there are abundant assemblages of charcoal from archaeological sites, the only limitations on this method of obtaining proxy rainfall data are the resolution of the radiocarbon dates and a suitable distribution of sites in time.

Concluding remarks

As the methods have now been established, future research efforts should focus on expanding the archaeological database both spatially and temporally so that a more detailed reconstruction of the climatic history of the last 2000 years can be made. These methods should work efficiently on *Protea* spp. A priority for future research should be to establish whether a significant relationship can be found between rainfall and vessel diameter for the present sample of charcoaled *C. apiculatum*.

The results are site specific and there are large gaps in the dating, but encouraging correlations with other lines of evidence suggest that the methods used in this study are useful at providing rainfall estimates. A larger sample of well-dated charcoal should be analysed in order to obtain a more cohesive picture of rainfall change through time.

A major emphasis in any future research should be to determine the range in rainfall over the last 300-400 years. From the evidence presented in this study it is suggested that when colonial farmers first moved into the summer rainfall region mean annual rainfall was much higher than at present.

Stable carbon isotope ratios of wood across a rainfall gradient exhibit some interesting results (Appendix 1). In view of these results the use of stable carbon isotope values of wood charcoal from archaeological sites, as an adjunct to xylem analysis, may prove to a valuable means of determining changes in rainfall patterns through time.

APPENDIX 1

STABLE CARBON ISOTOPE ANALYSIS OF *COMBRETUM APICULATUM* ALONG A RAINFALL GRADIENT

Introduction

Recent studies suggest that plant $^{12}C/^{13}C$ ratios not only react to atmospheric CO_2 levels but are also good indicators of water available to plants (Freyer & Belacy 1983, Leavitt & Long 1986). When CO_2 is absorbed by plants the heavier ^{13}C isotope is discriminated against relative to the much lighter ^{12}C isotope due to the diffusion effect of the stomates and the kinetic effect of the chemical reactions. With increased water stress stomatal closure results in reduced CO_2 uptake and therefore more positive $\partial^{13}C$ values. Ehleringer and Cooper (1988) sampled various species along a moisture gradient in California and identified a change in $\partial^{13}C$ values from $-24^{\circ}/_{\infty}$ in the driest habitats to $-26^{\circ}/_{\infty}$ in the wetter habitats. It is this relationship between $\partial^{13}C$ values and the amount of water available to the plant that was investigated using a sample of *Combretum apiculatum* from the research area.

Methods

All stable carbon isotope analysis was carried out in the Archaeometry Laboratory at the University of Cape Town. Sections of whole wood weighing approximately 0.02 grams from close to the outer margin of the wood, but not including the phloem, were analysed. Sample combustion was in sealed quartz tubes as described by Sofer (1980). The sample, copper oxide and a piece of silver foil were loaded into quartz tubes, the tubes evacuated to less than 10^{-2} Torr, sealed off with an oxy-butane torch and heated for a minimum of 4 hours at 800°C. The CO_2 produced was separated from any nitrogen and water vapour on a gas separating line (see Sealy 1986 for a full description of the methodology). $\partial^{13}C$ measurements were carried out on a 90° sector, double collector Micromass 602E spectrometer with a dual inlet system. The references were made against a laboratory reference gas related to the Chicago PDB marine carbonate standard by calibration against 6 NBS reference standards (see Van der Merwe 1982 and Sealy 1986).

Table 13. $\partial^{13}C$ values for whole wood samples of *Combretum apiculatum* along a rainfall gradient in the north eastern Transvaal.

Location	N	$\partial^{13}C$	Std	Precip mean
Messina	4	-23.24	0.7	281
Letaba	4	-25.36	0.38	385
Bourkes Luck	3	-24.64	0.84	401
Pafuri	3	-24.72	0.66	434
Punda Maria	3	-25.2	0.55	493
Itala	3	-26.57	0.89	942

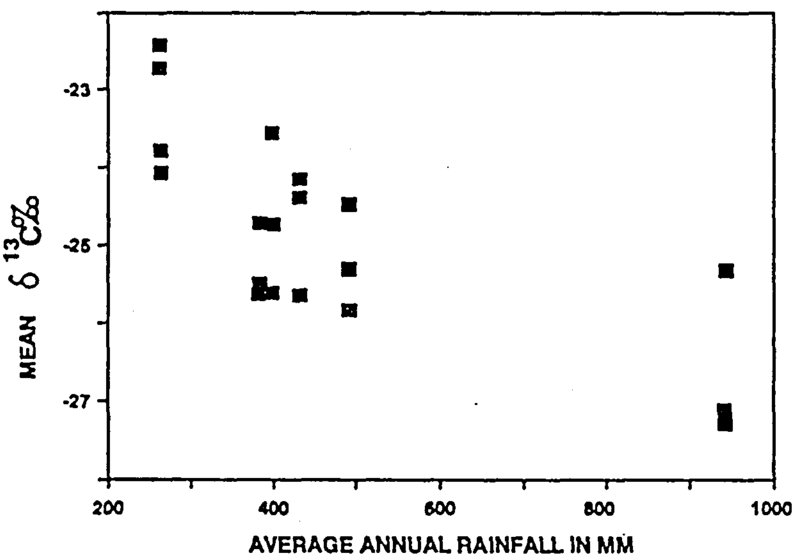

Figure 7. Stable carbon isotope ratios of *Combretum apiculatum* along a rainfall gradient in the research area.

Results and discussion

The results (Table 13 & Fig. 7) are entirely consistent with those of Ehleringer and Cooper (1988). There is a clear relationship between $\partial^{13}C$ values of a *Combretum apiculatum* sample and rainfall in the research area ($N = 6$, $R = 0.83$). This relationship between $\partial^{13}C$ values and rainfall was established on whole wood. Most previous studies use the cellulose extract from wood. In order to identify changes in $\partial^{13}C$ values through time using wood charcoal the same relationships have to be established on a charcoaled wood sample across a rainfall gradient. Within the research objectives of a follow up project is an assessment of the potential for using stable carbon isotope ratios of wood charcoal as a climate indicator. It may be possible to pinpoint oscillations in precipitation through changes in $\partial^{13}C$ values of the charcoal from archaeological sites through time (February & van der Merwe 1992).

Conclusion

The use of $\partial^{13}C$ values of wood charcoal from archaeological sites as an adjunct to xylem analysis may prove to be a valuable means for determining changes in rainfall patterns through time. $\partial^{13}C$ values of the two species of *Protea* represented in the Drakensberg material may also prove to be a factor in determining the differences between the two species.

APPENDIX 2

ARCHIVING OF DATA GENERATED FROM THIS STUDY

At its conclusion the raw data generated by the project should be appropriately stored for future retrieval. At present data is stored on computer in custom written files. This will be amended over the next year to storage within the computerised database presently being developed by the South African Museum. This will provide greater security and a more general knowledge of the computer storage system. All computer generated data will also be stored on 720 k 3 inch computer disks and housed in the library of the S.A. Museum along with all 35 mm slides, black and white photographs and a copy of this report.

The wet and dry wood collections as well as the microscope slides should be transferred on a long-term loan basis to the Botany Department of the University of the Western Cape. This should be on the understanding that the South African Museum will have access thereto, and remains the owner thereof. The transfer of material to the University of the Western Cape should only take place once all Water Research Commission related projects of this nature at the South African Museum have been completed.

All archaeological charcoal samples will be returned to the various institutes from which they were obtained. In most cases these have been loaned to the project and should be returned as soon as all WRC related projects have been completed.

REFERENCES

Avery, D.M. 1991. Micromammals, owls and vegetation change in the Eastern Cape Midlands, South Africa, during the last millennium. *Journal of Arid Environments* **20**: 357-369.

Baas, P. 1982. Systematic, phylogenetic and ecological wood anatomy - history and perspectives. *In* Baas, P. *ed.*, *New perspectives in wood anatomy*, 23-58. The Hague: Martinus Nijhoff.

Baas, P., Esser, P.M., van der Westen, M.E.T. & Zandee, M. 1988. Wood anatomy of the *Oleaceae*. *IAWA Bulletin* n.s. **9**(2): 103-182.

Baas, P., Werker, E. & Fahn, A. 1983. Some ecological trends in vessel characters. *IAWA Bulletin* n.s. **4**: 141-159.

Baas, P. & Schweingruber, F.H. 1987. Ecological trends in the wood anatomy of trees, shrubs and climbers from Europe. *IAWA Bulletin* n.s. **8**(3): 245-274.

Barefoot, A.C. & Hankins F.W. 1982. *Identification of modern and Tertiary woods.* Oxford: Clarendon Press.

Beall, F.C., Blankenhorn, P.R. & Moore, G.R. 1974. Carbonized wood - physical properties and use as an SEM preparation. *Wood Science* **6**: 212.

Box, E.O. 1981. *Macroclimate and plant forms: An introduction to predictive modeling in phytogeography.* The Hague, Boston, London: Dr W. Junk Publishers.

Butzer, K.W. 1984. Late Quaternary environments in South Africa. *In* Vogel, J.C. *ed.*, *Late Cainozoic palaeoclimates of the southern hemisphere*, 235-264. Rotterdam: A.A. Balkema.

Butzer, K.W., Stuckenrath, R., Bruzewicz, A. & Helgren, D.M. 1978. Late Cenozoic palaeoclimates of the Gaap Escarpment, Kalahari margin, South Africa. *Quaternary Research* **10**: 210-339.

Carlquist, S. 1966. Wood anatomy of Compositae: a summary, with comments on factors controlling wood evolution. *Aliso* **6**: 25-44.

Carlquist, S. 1975. *Ecological strategies of xylem evolution.* Berkeley: University of California Press.

Carlquist, S. 1977(a). Ecological factors in wood evolution: a floristic approach. *American Journal of Botany* **64**: 887-896.

Carlquist, S. 1977(b). Wood anatomy of Peneaceae (Myrtales): comparative, phylogenetic and ecological implications. *Botanical Journal of the Linnaean Society* **75**: 211-227.

Carlquist, S. 1980. Further concepts in ecological wood anatomy with comments on recent work in wood anatomy and evolution. *Aliso* **9**: 499-553.

Clark, R.L. 1982. Point count estimation of charcoal in pollen preparations and thin sections of sediments. *Pollen et spores* **24**(3-4): 523-530.

Cooke, H.J. & Verstappen, H.T., 1984. The landforms of the western Makgadgadi basin in northern Botswana, with a consideration of the chronology of the evolution of Lake Palaeo-Makgadigadi. *Zeitschrift für Geomorphologie* **28**: 1-19.

Cousins, W.J. 1975. Optical microscopy of charcoal. *Journal of Microscopy* **105**: 15-18.

Deacon, H.J., Scholtz, A. & Daitz, L.D. 1983. Fossil charcoals as a source of palaeoecological information in the fynbos region. *In* Deacon, H.J., Hendey, Q.B. & Lambrechts, J.J.N. *eds.*, Fynbos palaeoecology a preliminary synthesis. *South African National Scientific Programmes Report* **75**: 174-182.

Dunwiddie, P.W. & LaMarche Jr, V.C., 1980. A climatically responsive tree-ring record from *Widdringtonia cedarbergensis*, Cape Province, South Africa. *Nature* **286**: 796-797.

Eberhard, A.A. & Poynton, R.J. 1987. Fuelwood calorific values and preferences as criteria for the choice of tree species for planting in South Africa. *Proceedings of conference on renewable energy potential in Southern Africa, University of Cape Town, 1986.*

Edwards, D. 1967. A plant ecology survey of the Tugela River basin. *Botanical Survey of South Africa Memoir* **36**.

Ehleringer, J.R. & Cooper, T.A. 1988. Correlations between carbon isotope ratio and microhabitat in desert plants. *Oecologia* **76**: 562-566.

February, E.C. 1990. Climatic reconstruction using wood charcoal from archaeological sites. University of Cape Town: Unpublished M.A. thesis.

February, E.C. 1992. Archaeological charcoals as indicators of vegetation change and human fuel choice in the late Holocene at Elands Bay, western Cape Province, South Africa. *Journal of Archaeological Science* **19**: 347-354.

February, E.C. & Van der Merwe, N.J. 1992. Stable carbon isotope ratios of wood charcoal during the past 4000 years: anthropogenic and climatic influences. *South African Journal of Science* **88**: 291-292.

Freyer, H.D. & Belacy N. 1983. $^{12}C/^{13}C$ records in northern hemisphere trees during the past 500 years—Anthropogenic impact and climatic superpositions. *Journal of Geophysical Research* **88**(C11): 6844-6852.

Gandar, M. 1982. Some social and environmental aspects of the use of fuelwood in Kwazulu. *In* Bromberger, N. & Lea, J.D. *eds., Rural studies in KwaZulu,* 147-152. Pietermaritzburg: University of Natal.

Godwin, H. & Tansley, A.G. 1941. Prehistoric charcoals as evidence of former vegetation, soil and climate. *Journal of Ecology* **29**: 117-126.

Hall, M. 1976. Dendroclimatology, rainfall and human adaptation in the Late Iron Age of Natal and Zululand. *Annals of the Natal Museum* **23**(3): 693-703.

Klein, R. G. 1980. Environmental and ecological implications of large mammals from Upper Pleistocene and Holocene sites in southern Africa. *Annals of the South African Museum* **81**: 223-283.

Krauss-Marguet, I. 1980. *Contribution a l'histoire de la végétation postglaciaire des Grands Causses d'après l'analyse anthracologique du gisement préhistorique de* *la Poujade (Commune de Millau- Aveyron).* Académie de Montpellier, Université des Sciences et Techniques de Lanquedoc.

Kromhout, C.P. 1975. 'n Sleutel vir die mikroskopiese uitkenning van die vernaamste houtsoorte van Suid-Afrika. *Departement van Bosbou Bulletin* **50**: 547-557.

Leavitt, S.W. & Long, A. 1986. Trends of $^{12}C/^{13}C$ ratios in Pinyon tree rings of the American Southwest and the global carbon cycle. *Radiocarbon* **28**(2A): 376-382.

Liegme, C.A. 1983. A review of ethno-botanical research in southern Africa. *Bothalia.* **14** (3-4).

Lilly, M.A. 1977. An assessment of the dendrochronological potential of indigenous tree species in South Africa. *Dept. of Geographical and Environmental Studies, University of the Witwatersrand Occasional Paper* **18**.

Loubser, J.H.N. 1991. The ethnoarchaeology of Venda - speakers in southern Africa. *Navorsinge van die Nasionale Museum Bloemfontein* **7** (8): 147-464.

Maggs. T. 1984. Ndondondwane: a preliminary report on an Early Iron Age site on the lower Tugela River. *Annals of the Natal Museum* **26**(1): 71-93.

Maggs, T. & Michael, M. 1976. Ntshekane: an Early Iron Age site in the Tugela Basin, Natal. *Annals of the Natal Museum* **22**(3): 705-740.

Mazel, A.D. 1990. Mhlwazini Cave: the excavation of Late Holocene deposits in the northern Natal Drakensberg, Natal, South Africa. *Natal Museum Journal of Humanities* **2**: 95-133.

Mazel, A.D. 1992. Collingham Shelter: the excavation of late Holocene deposits, Natal, South Africa. *Natal Museum Journal of Humanities* **4**: 1-51.

McGinnes, Jr, E.A. 1971. Some structural changes observed in the transformation of wood into charcoal. *Wood and Fibre. Journal of the Society of Wood Science and Technology* **3**(2): 77-83.

Milton, S.J. & Bond, C. 1986. Thorn trees and the quality of life in Msinga. *Social Dynamics* **12**(**2**): 64-76.

Prior, J. & Price Williams, D. 1985. An investigation of climatic change in the Holocene epoch using archaeological charcoal from Swaziland, southern Africa. *Journal of Archaeological Science* **12**: 457-475.

Rendle, B.J. & Clarke, S.H. 1934. The diagnostic value of measurements in wood anatomy. *Tropical Woods* **40**: 27-37.

Rourke, J.P. 1980. *The proteas of southern Africa.* Cape Town: Purnell & Sons.

Salisbury, E.J. & Jane, F.W. 1940. Charcoals from Maiden Castle and their significance in relation to the vegetation and climatic conditions in prehistoric times. *Journal of Ecology* **28**: 310-325.

Scholtz, A. 1986. Palynological and palaeobotanical studies in the southern Cape. University of Stellenbosch: Unpublished M.A. thesis.

Sealy, J.C. 1986. Stable carbon isotopes and prehistoric diets in the south-western Cape Province, South Africa. *Cambridge Monographs in African Archaeology* **15**, *BAR International Series* **293**.

Slavikova-Vesela, J. 1950. Reconstruction of the succession of forest trees in Czechoslovakia on the basis of an analysis of charcoals from prehistoric settlements. *Studia Botanica Cechoslovaca* **11**: 198-224.

Smith, A.M. 1992. Holocene palaeoclimatic trends from palaeoflood analysis. *Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section)* **97**: 235-240.

Sofer, Z. 1980. Preparation of carbon dioxide for stable carbon isotope analysis of petroleum fractions. *Annals of Chemistry* **52**(8): 1389-1391.

Tusenius, M. 1986. Charcoal analytical studies in the north-eastern Cape. University of Stellenbosch: Unpublished M.A. thesis.

Tusenius, M. 1989. Charcoal analytical studies in the north-eastern Cape, South Africa. *South African Archaeological Society Goodwin Series* **6**: 77-83.

Tyson, P.D. 1986. *Climatic change and variability in southern Africa.* Cape Town: Oxford University Press.

Tyson, P.D. & Lindsay, J.A. 1992. The climate of the last 2000 years in southern Africa. *Holocene* **2**(3): 271-278.

Van der Merwe, N.J. 1982. Carbon isotopes, photosynthesis and archaeology. *American Scientist* **70**: 596-606.

Van der Walt, J.J.A., Werker, E. & Fahn, A. 1988. Wood anatomy of *Pelargonium* (Geraniaceae) *IAWA Bulletin.* n.s. **8**(2): 95-108.

Vernet, J.L. 1973. Etudes sur l'histoire de la végétation du sud-est de la France au Quaternaire, d'après les charbons de bois principalement. *Paléobiologie Continentale* **IV**: 1-90.

Vogel, C.H. 1989. A documentary-derived climatic chronology for Southern Africa, 1820-1900. *Climatic Change* **14**: 291-307.

Wheeler. E.A., Baas. P. & Gasson, P.E. (eds.) 1989. IAWA list of microscopic features for hardwood identification. *IAWA Bulletin* n.s. **10**(3): 219-332.

Wilkins, A.P. & Papassotiriou, S. 1989. Wood anatomical variation of *Acacia melanoxylon* in relation to latitude. *IAWA Bulletin* n.s. **10**(2): 201-207.

Zhang Xinying, Deng Liang & Pieter Baas. 1988. The ecological wood anatomy of the lilacs (*Syringa oblata var. giraldii*) on Mount Taibei in northwestern China. *IAWA Bulletin* n.s. **9**(1): 24-30.

Zimmerman, M.H. 1978. Structural requirements for optimal conduction in tree stems. *In* Tomlinson, P.B. & Zimmerman, M.H. *eds.*, *Tropical trees as living systems*, 517-532. London, New York & Melbourne: Cambridge University Press.

Zimmerman, M.H. 1982. Functional xylem anatomy of angiosperm trees. *In* Baas P. ed., *New perspectives in wood anatomy*. The Hague: Nijhoff/Junk.

Zimmerman, M.H. 1983. *Xylem structure and the ascent of sap.* Berlin: Springer-Verlag.