LATE QUATERNARY VEGETATION HISTORY AND PALAEOENVIRONMENTS OF THE CEDERBERG MOUNTAINS, SOUTH AFRICA:
Evidence from hyrax (*Procavia capensis*) middens

Thesis Presented By:

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This dissertation is submitted as an academic requirement for the fulfilment of an MSc in the Department of Environmental and Geographical Science University of Cape Town

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Declaration

This work has not been previously submitted in whole, or in part, for the award of any degree. It is my own work, each significant contribution and quotation in this dissertation from the works of other people have been attributed, cited and referenced.

Yours Sincerely,

....

Abstract

Rock hyrax (*Procavia capensis*) middens have been identified as excellent sources of palaeoenvironmental information in arid and semi-arid areas, and have been successfully used in various parts of southern Africa. Hyrax middens from the De Rif site in the Cederberg Mountains of the south-western Cape have been collected and sampled.

Through the application of pollen analysis to the midden material, local plant communities were inferred and a palaeoenvironmental reconstruction of prevailing conditions over the period of accumulation was produced. An assessment of the overall pollen assemblages indicates that typical mountain fynbos were present at De Rif throughout the last 28 ka and that generally there were no major changes in vegetation communities throughout this period.

Stable carbon and nitrogen isotope analysis applied to the midden material registered palaeoenvironmental changes by identifying variations in water-use efficiencies and therefore provided information on changing water availabilities at the site. The two most significant periods of enrichment in the $\delta^{13}C$ and $\delta^{15}N$ records, whereby there were dramatic decreases in moisture availability, were from ~ 22 000 – 21 000 cal yr BP falling around the Last Glacial Maximum and ~ 12 700 – 11 500 cal yr BP coinciding with the Younger Dryas.

The multi-proxy record established at De Rif and presented in this thesis, casts new light on key climate change episodes and provides links to how changes in sea surface temperatures, variations in sea ice and shifts of the westerlies have modified regional climates over the last 28 ka.

Acknowledgements

This project is specifically dedicated to Cletus and Fransisco as well as hyraxes in general, as without them and their unique middens this project could not have existed.

As the man behind the middens, Dr Brian Chase was integral to this project. Thank you for your continuous involvement throughout the project, the constructive criticism and for always challenging me to do my best.

To Prof. Mike Meadows: thank you for supervising my work, for editing this thesis, for the funding and for all the advice and support that you have provided throughout my academic career.

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Many thanks go to Kathryn Vickery for the support she offered me throughout this project and for the large quantity of time she spent editing of my work. Thanks also go to all my other friends and most importantly, my family for their unconditional support and encouragement.

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List of Acronyms

ACR – Antarctic Cold Reversal

CAM – Crassulacean acid metabolism

CFR – Cape Floristic Region

DK1 – Die Kelders 1

DR – De Rif

EBC – Elands Bay Cave

ESR – Electron Spin Resonance

HA – Holocene Altithermal

OIS – Oxygen Isotope Stage

KB-1 – Katbakkies 1 (KB-1)

LGM – Last Glacial Maximum

LGIT – The last glacial – interglacial transition

MSA – Middle Stone Age

N – Nitrogen

PCA – Principal Component Analysis

SAHP – South Atlantic High Pressure

SRZ – Summer rainfall zone

SSTs – sea surface temperatures

SWC – southwestern Cape

TK-4 – Truitjes Kraal 4

WRZ – Winter rainfall zone

WUE – Water-use efficiency

YD – Younger Dryas

YRZ – Year round rainfall zone

1 Introduction

1.1 INTRODUCTION

The understanding of how environmental systems have responded to climate variability in the past is an essential means to uncover the nature of future climate change. The knowledge of past environmental dynamics should then make it more feasible and reliable to predict and mitigate for future changes (Lovejoy and Hannah, 2005). The Quaternary Period[1] is an important phase in Earth's geological history, within which climate changes have been extraordinary variable over many different spatial and temporal scales (Lowe and Walker, 1997). Therefore, as the Quaternary is the most recent time period, and is characterised by high climate variability, knowledge of the mechanisms for environmental change during this period is a prerequisite for modelling future change. To this extent, the northern hemisphere's Quaternary palaeoenvironmental history has been reasonably well-established due to the abundance of published studies. In contrast, palaeoenvironmental evidence for the arid and semi-arid regions of southern Africa remains frustratingly incomplete as palaeoclimatic proxy records are scarce and often discontinuous (Meadows and Baxter, 1999; Chase and Meadows, 2007). Within this region, the southwestern Cape is an important focus area as it is recognised as being the heart of the biodiversity hotspot known as the Cape Floristic Region (CFR). Due to its importance in terms of high levels of species richness and endemism (Cowling *et al.*, 1992) and its key location within the winter rainfall zone (WRZ) of southern Africa, the environmental history of this area needs to be further resolved (Chase and Meadows, 2007).

Despite the occasional successful application of traditional palaeoecological methods (e.g. the use of organic pollen-rich wetland deposits) in generating palaeoenvironmental evidence in the region (Meadows and Sugden, 1991; Baxter and Meadows, 1999), there are few wetland deposits in the region, and climates are characterised by marked rainfall gradients, and high seasonality. Therefore, in order to elucidate past environmental conditions during the late Quaternary within the southwestern Cape and synthesise existing palaeoenvironmental records, new forms of evidence are being sought.

[1] The Quaternary Period represents the last 2.6 million years (Pillans, 2004a; b). Although it should be noted that there has been much debate about the exact timing and status of the Quaternary within the geological time scale

This study uses hyrax (*Procavia capensis*) middens found in the Cederberg as an innovative palaeoecological archive. Hyrax middens have previously been used as a valuable palaeoecological tool in parts of southern Africa (Scott and Bousman, 1990; Scott, 1990; Scott, 1994; Scott *et al.*, 2004; Gil-Romera *et al.*, 2006; Scott and Woodborne, 2007a; Scott and Woodborne, 2007b; Gil-Romera *et al.*, 2007) Through the analysis of fossil pollen found within these middens, it is possible to reconstruct the vegetation history of the study area and make inferences about past climatic variability within the Cederberg. In addition, stable carbon and nitrogen isotope analyses of midden material may provide high resolution evidence of past variations in water availability.

The Cederberg is a unique mountain range in the southwestern Cape as it is a species-rich part of the CFR and represents a sharp transition zone between the vegetation and geology of the Cape and the Karoo (van Rooyen and Steyn, 2004). The Cederberg falls within the Greater Cederberg Biodiversity Corridor and is therefore marked as an important conservation area. Previous palaeoenvironmental studies have shown that relatively stable conditions have dominated this region during the later part of the Quaternary (Sugden, 1989; Meadows and Sugden, 1991, 1993; Seliane *et al.*, in review), whereas at Pakhuis Pass (hyrax midden site in the northern reaches of the Cederberg) greater variability within the Last Glacial Maximum (LGM)[2] has been inferred (Scott, 1994; Scott and Woodborne 2007a, b). These interpretations suggest the possibility that records with lower levels of temporal resolution may mask or seemingly subdue changes in vegetation communities and climate systems during this period (Chase and Meadows, 2007). This study details a previously unknown midden site in the Cederberg, and offers a stronger chronological framework and correspondingly higher resolution palaeoenvironmental evidence spanning much of the last 28 ka, which, it is hoped, may generate greater insight into the nature of environmental change in the Cederberg in particular, as well as the WRZ as a whole.

In summary, this project engages with the following key research questions:

- What ecological and environmental changes have occurred in the Cederberg during the last 28 ka and how have these changes been revealed through previously established palaeoecological records?

[2] LGM: time of maximum global ice volumes, 24 000 -18 000 cal yr BP (Mix *et al.*, 2001; Clark and Mix, 2002)

- How has climate changed in the region, and what has the impact been on vegetation communities?

- How does the vegetation history, as revealed by the analysis of midden samples, compare to previously and presently studied palaeoecological records in the Cederberg?

1.2 AIM

To use fossil hyrax middens as a palaeoenvironmental archive to investigate the vegetation dynamics and associated environmental conditions in the Cederberg over the last 28 ka, through the application of pollen analysis and stable isotope geochemistry.

1.3 SPECIFIC OBJECTIVES

This study is founded on the basis of the following specific objectives:

- Identify and sample suitable fossil hyrax middens in the Cederberg mountain region;
- Sub-sample midden sediments in order to establish:
    - an accurate high resolution chronology of accumulation for hyrax midden material,
    - a pollen record of vegetation community changes over the time,
    - stable isotope records reflecting changes in moisture availability at the study area;
- Reconstruct the general palaeoenvironmental conditions for the study area using the conclusions drawn from the above analyses.
- Evaluate the conclusions and interpretations drawn from the above analyses by assessing them against the backdrop of previous and presently studied palaeoenvironmental records for the area.

1.4 THESIS OUTLINE

The next chapter outlines the contemporary regional environment of the Cederberg as well as specifically detailing the local environment found at the study sites. Chapter 3 represents a review of the palaeoenvironmental history of the southwestern Cape as established by previous records in the region. The rationale behind and description of the methodological approach used in this study is provided in chapter 4. This is followed by the results chapter, presenting the chronology of the middens, the results of the pollen analysis in the form of pollen diagrams and the outcomes of the stable isotope analyses. Chapter 6 provides a summary of palaeoenvironmental change at the study area over the last 28 ka, and presents a comparison with other Cederberg palaeoenvironmental records, evaluating the results against the regional context outlined in chapter 2. Chapter 6 also includes an appraisal of the results against the broader backdrop of the southern hemisphere, displaying links between the isotopic results and global palaeoclimatic proxies. Finally, chapter 7 provides a synthesis of the overall outcomes of the project and concludes the thesis through a reflection on the original aims and objectives and the extent to which they have been met.

2 Contemporary Cederberg Environments

2.1 INTRODUCTION

An understanding of the contemporary environmental context of the study area is vital for investigating the link between the responses of vegetation communities and key indicator species to past climatic changes, as well as developing hypotheses of the possible impacts of future climate change on the region. This chapter describes the contemporary Cederberg environment and places the study within a regional context by outlining influencing factors such as climate, geology and vegetation. Details of the local environment within which the middens are situated are then provided.

2.2 THE CEDERBERG MOUNTAINS

The Cederberg forms the drier northernmost part of the Cape Fold Belt Mountains (Compton, 2004) of the southwestern Cape (SWC). This mountain range, which has an average elevation of between 1 200 to 1 500 m amsl, is situated approximately 250 km north of Cape Town and to the east of the towns of Clanwilliam and Citrusdal (figure 2.1). The range rises steeply from the Olifants River valley in the west and marks the boundary between the Fynbos and the Karoo biomes (Figure 2.1). The Cederberg Wilderness Area forms a major part of the Greater Cederberg Biodiversity Corridor as it is the central mountainous region in this biodiversity conservation initiative and encompasses a substantial area of 71 000 ha (Low *et al.*, 2004; CapeNature, 2007) (figure 2.1).

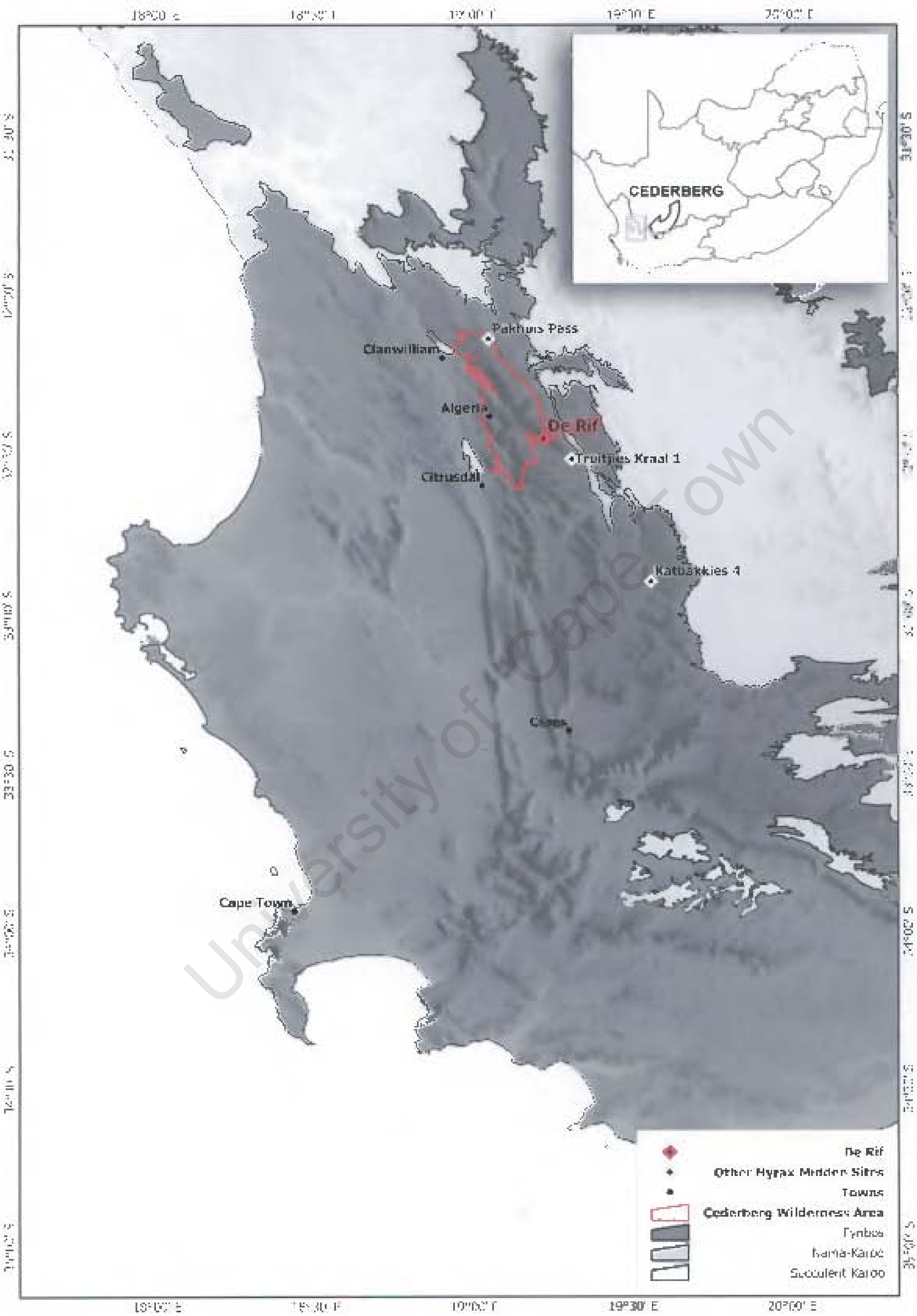


Figure 2.1: Regional map, showing location of the Cederberg and the study site, De Rif (data source: Appendix A)

2.3 GEOLOGY OF THE CEDERBERG

Geology is the fundamental component of any landscape as it represents the underlying structure of the physical environment, influencing other components including: climate, geomorphology, soils and vegetation.

The Cederberg is composed of predominantly sedimentary rocks of the Table Mountain Group within the Ordovician to Devonian Cape Supergroup (Compton, 2004). In the west, near the Olifants River, there are remnants of the older Malmesbury Group shales and sandstones and in the east there is a sharp transition to the younger Bokkeveld formations along the Moordenaarsgat River (Taylor *et al.*, 1996). The range is dominated by four major geologic formations of the Table Mountain Group of the Cape Supergroup, represented from oldest (bottom) to youngest (top) in Table 2.1:

Table 2.1: Cederberg Geologic Formations (Theron, 1984; Taylor *et al.*, 1996; Compton, 2004)

Geologic Formation	Description	Location
Nardouw Formation	Course grained orthoquartzites with some pebbles and lenses of vein quartz, distinctively redder than the Peninsula Formation	Plateau-like summits above the shale band e.g. Tafelberg, Sneeukop and Pakhuis Peak
Cederberg Formation (the shale band)	Shale and siltstone interbedded with fine-grained sandstone, can be identified in the landscape as a narrow green band strongly contrasted by the rocky surfaces above and below it	Band running below all major peaks
Pakhuis Formation	Thin layer of sandy tillite or glacial mudstones found immediately below the shale band. Contains random-sized pebbles with striations and facets made by the movement of ice	Remnants of the glacial pavement, examples can be found on Pakhuis Pass and at Groenberg
Peninsula Formation	Thick deposit of coarse-grained quartzitic sandstones interspersed with occasional white quartz pebbles and sand shale lenses	Characterises all regions of the Cederberg where the upper strata has been eroded away

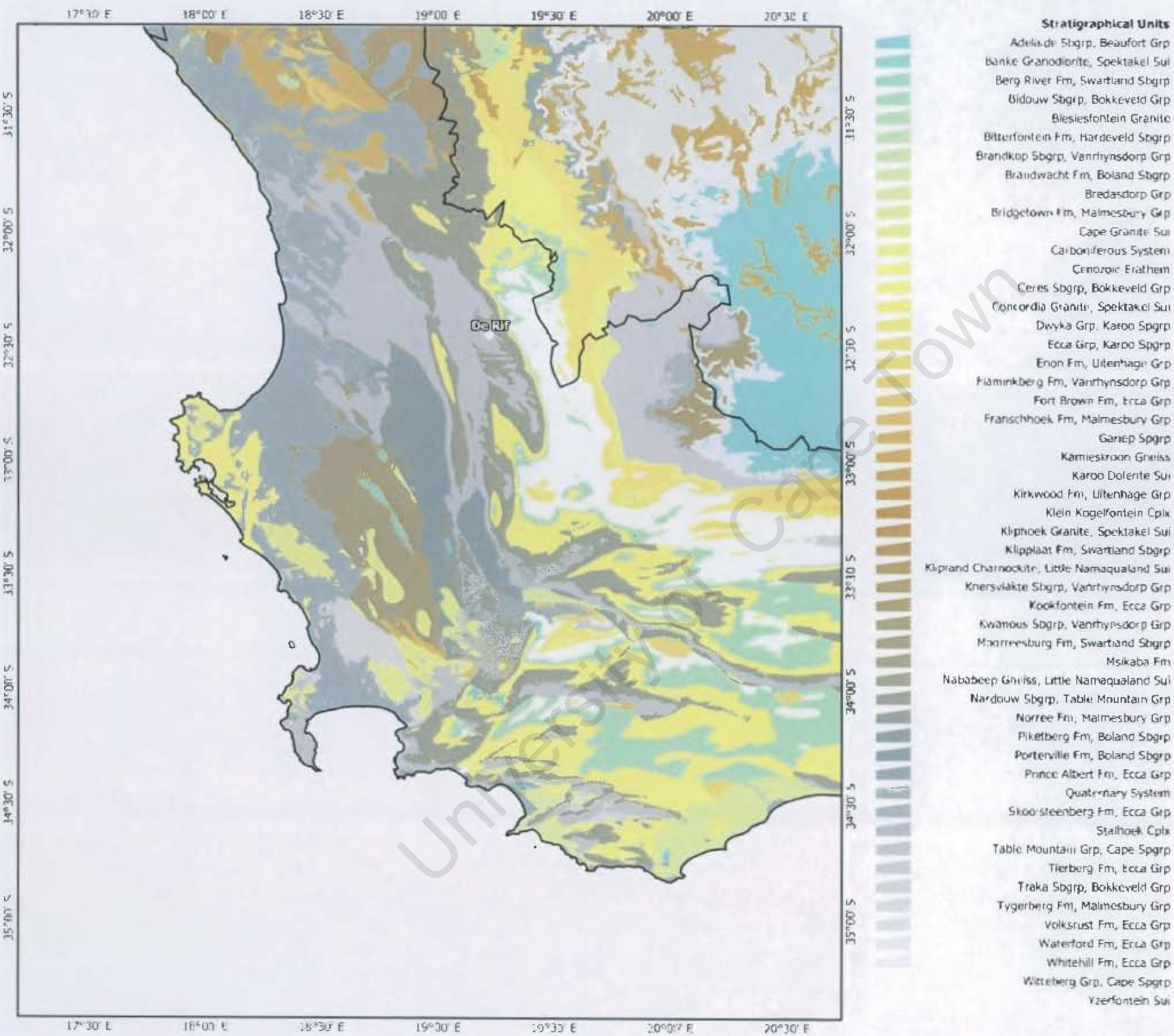
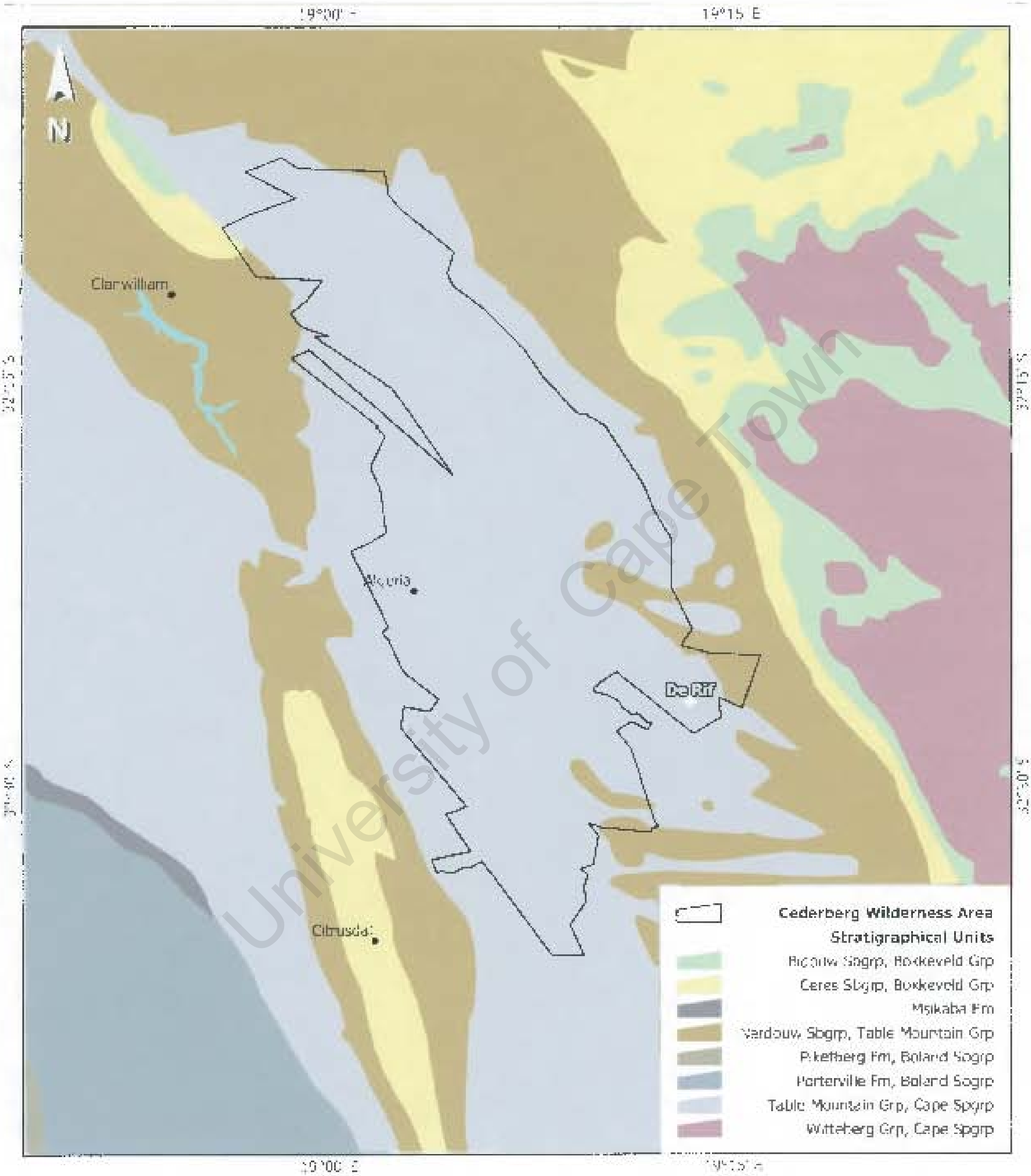


Figure 1.2: Geological detail of the Southwestern Cape (data source: Council of Geosciences, see Appendix A)



<u>Figure 2.3</u>: Geology of the study site, De Rif, and the wider Cederberg Wilderness Area (data source: Council of Geosciences, see Appendix A)

2.4 CLIMATE

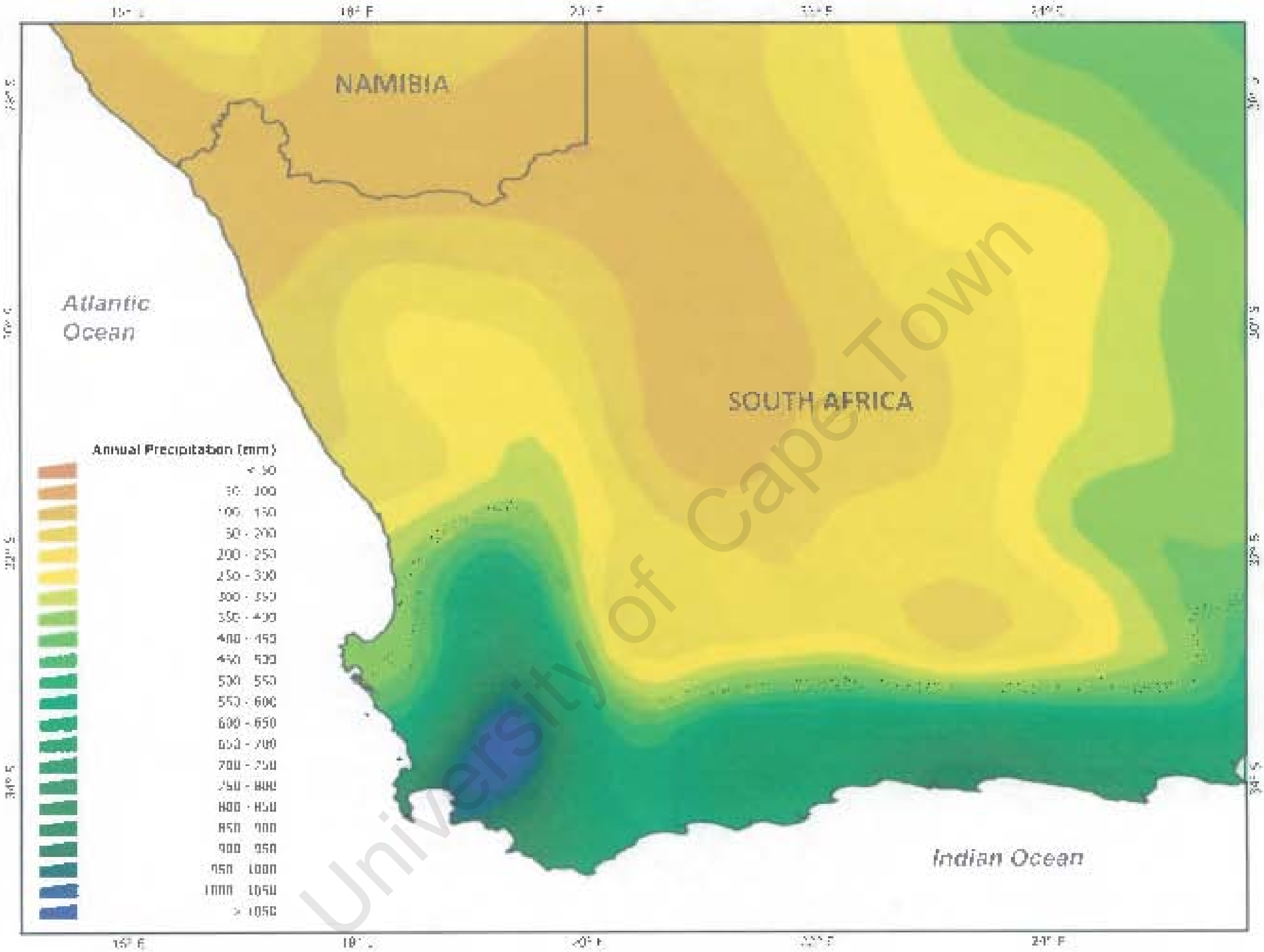
A Mediterranean-type climate dominates the SWC, with cool, wet winters and warm, dry summers (Tyson, 1986). The SWC falls within the winter rainfall zone (WRZ) which is defined as the region where more than 66% of the mean annual precipitation falls between April and September (*sensu* Chase and Meadows, 2007, figure 2.5). The intensification and northward expansion of the circumpolar westerly wave belt in winter causes frontal depressions embedded in this system to reach the southwestern Cape, resulting in cyclonic rainfall over the area (Tyson and Preston-Whyte, 2000).

By referring to the selected climographs displayed in figure 2.6, it is evident that winter rainfall is definitely more dominant towards the western margins of the SWC and that summer/autumn rainfall is more prevalent towards the interior. Due to its location, the Cederberg receives at least 80% of its rainfall in the winter months (Taylor *et al.*, 1996) and also receives relatively large amounts of precipitation (figures 2.4 and 2.6). However, the rainfall distribution to this area may have been different in the past: the seasonal distribution of rainfall in the Cederberg may well have differed at varying stages of the Quaternary (Scott and Woodborne, 2007b).

The topographic complexity of the Cederberg (section 2.5) leads to a high degree of spatial and temporal variability in rainfall, with steep precipitation gradients from valley bottoms to high peaks (e.g. the difference in the average rainfall amounts at Clanwilliam and Algeria-Bos stations in figure 2.6) and decreasing amounts from the coastal-facing slopes to the interior-facing sides. In general, precipitation decreases markedly from west to east and south to north, and ranges from 300 mm to 2 500 mm (Schultze, 1979 in Taylor *et al.*, 1996). While snow falls on the higher mountain peaks almost every winter, it rarely covers extensive areas or last for more than a few days.

In general, temperatures for the southwestern Cape are moderate, with smaller variations along the coast as a result of the ocean's moderating effect and greater extremes in the interior. In the Cederberg, however, summer temperatures are high, with typical daily maxima ranging from 25°C to 35°C and occasionally reaching over 40°C. Frost is also common in the Cederberg in winter.

South-easterly winds dominate the southwestern Cape region in general in summer and north-westerlies in winter (Tyson, 1986). In the Cederberg, these winds are, however, neither as strong nor as persistent as that experienced further south.



<u>Figure 2.4</u>: Annual precipitation for southern Africa (data source: UNEP-GRID 2001)

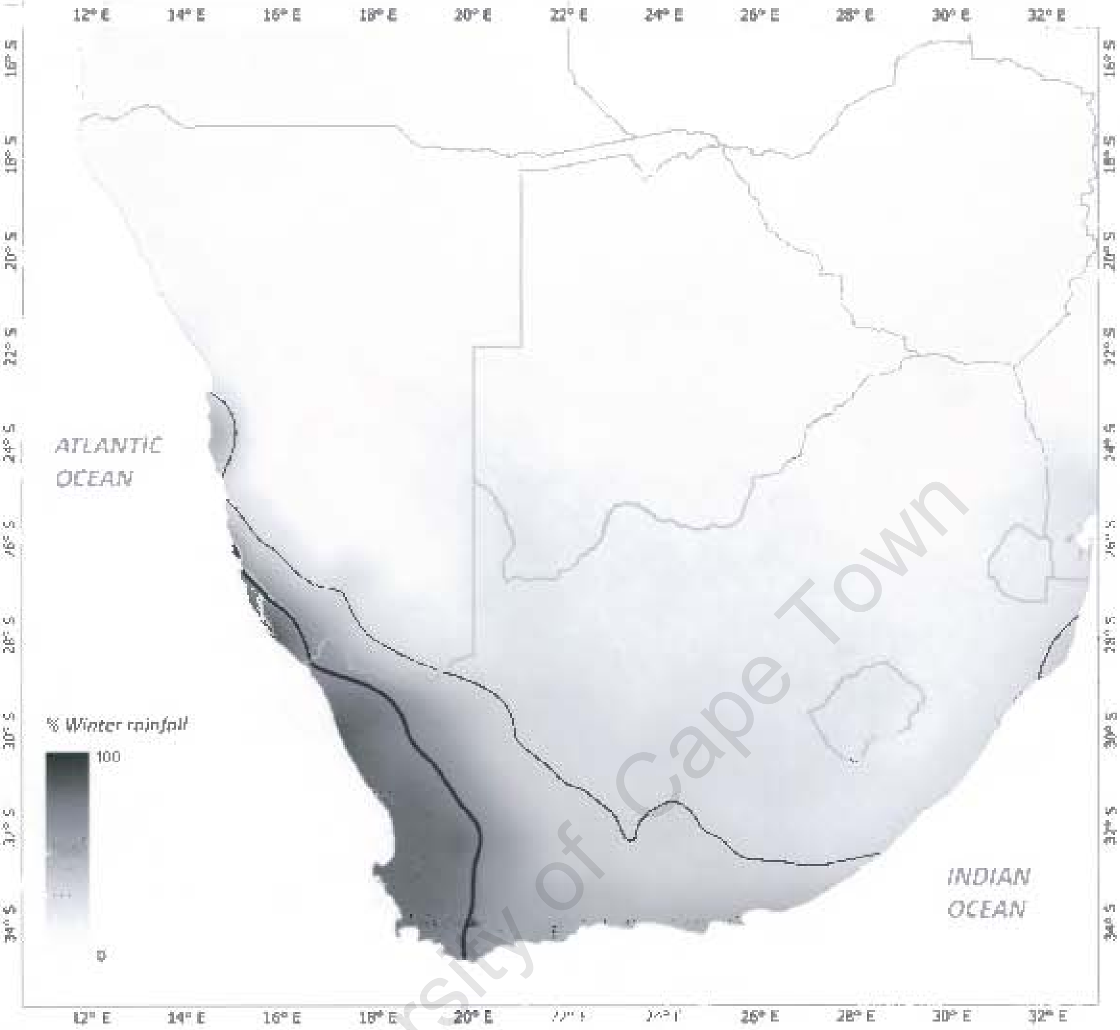


Figure 2.5: Rainfall seasonality in southern African:

WRZ – Winter rainfall zone, >66% winter rain – to the left of the thick black line

YRZ – Year round rainfall zone 66 – 33% winter rain – between the thick and thin lines

SRZ – Summer rainfall zone, <33% winter rain – to the right of the thin black line

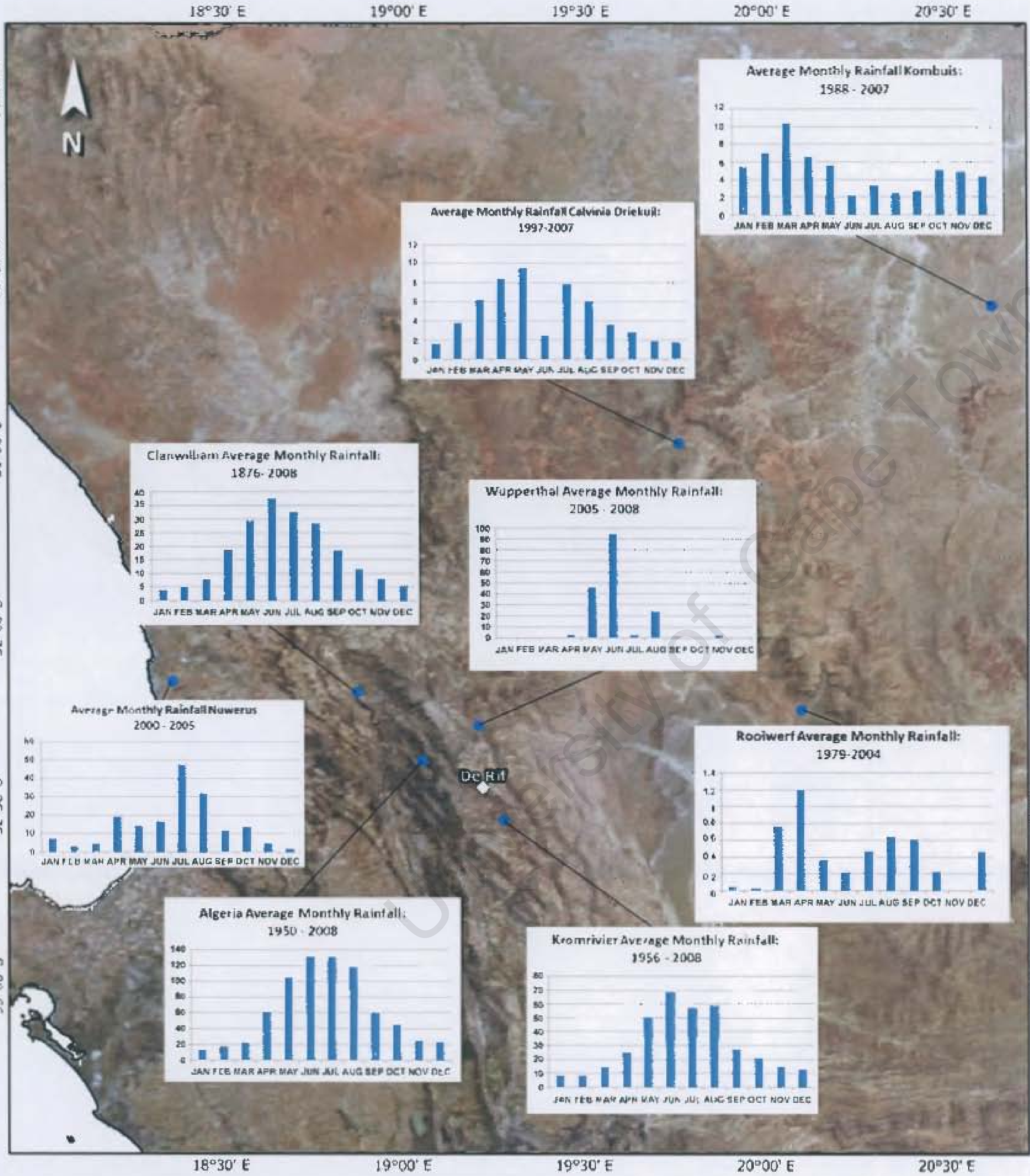


Figure 2.6: Selected rainfall stations (measured in mm) (data source: Climate Systems Analysis Group and South African Weather Service)

2.5 TOPOGRAPHY, GEOMORPHOLOGY AND SOILS

The topography of the entire Cederberg range trends north-south and was formed predominantly by upthrust and folding of sedimentary rocks followed by extensive faulting (Taylor *et al.*, 1996). The dominant rock form, quartzitic sandstone, is relatively resistant to weathering, whereas the 'shale bands' consisting of shales and mudstones are less resistant (Theron, 1984). The differential resistance and weathering of the underlying geological formations, (outlined in section 2.3) results in rugged topography characterised by a complex sequence of elevated ridges and peaks separated by broad linear valleys with the characteristic shelf of the shale band widely prevalent.

The major controlling factor over the topography, in addition to the underlying geology, is the semi-arid climate with associated pronounced seasonal differences in temperature and precipitation. The sandstone of the Table Mountain Group found in the Cederberg is not extremely folded or tilted and therefore the uplands often display nearly horizontal summits (Taylor *et al.*, 1996).

Cederberg soils are often yellow-brown to brown and not greyish like the soils typically associated with the Cape Fold Belt as they are derived from the underlying Pakhuis and Cederberg Formations (Theron, 1984; Taylor *et al.*, 1996). Most of the soils of the Cederberg are highly leached acid sands, coarse-grained, nutrient-poor and low in moisture-retaining capacity. With the exception of small pockets of sandy loam to clay loam soils derived from shales and mudstones of the Cederberg Formation. Soils on rocky slopes are skeletal and very porous.

2.6 VEGETATION

The Cederberg forms part of the CFR and falls within the Fynbos Biome[1] (Cowling *et al.*, 1997; Low and Rebelo, 1996) (Figure 2.7). Fynbos represents a broad complex floristic category of diverse evergreen sclerophyllous shrublands, characterised by high species richness (8 700 species) and high levels of endemism (68.8%) (Cowling *et al.*, 1992; Rebelo, 1996; Goldblatt and Manning, 2002; Mucina and Rutherford, 2006). The high species diversity is thought to be the product of explosive speciation since the late

[1] The Fynbos Biome encompasses only two major vegetation types: Fynbos and Renosterveld whereas the Cape Floristic Region refers to the general geographical area and includes other vegetation types

		Thamnochortus obtusus and *T. Punctatus*		
Renosterveld	North-western Mountain Renosterveld	Dominant species include: *Elytropappus rhinocerotis, Eriocephalus africanus, Euryops lateriflorus* and *Nylandtia spinosa*	Winter rainfall varying from 250 – 400 mm per year , with summer drought.	Granites and gneisses, deep sandy loamy soils
	Escarpment Mountain Renosterveld	Dominant species include: *Elytropappus rhinocerotis* and *Relhania genistifolia*	Dominantly winter rainfall, ranging from 200 – 300 mm per year.	Soils are mainly clays and silts derived from the Karoo Sequence shales
	Central Mountain Renosterveld	Open to medium-dense cupressoid and small-leaved, low to mid-high shrubland, high proportion of succulents are often present	Rainfall ranging from 250 – 400 mm per year, occurring mostly during winter	Soils derived from the Bokkeveld and Witteberg Groups
	West Coast Renosterveld	Mid-dense to closed cupressoid and small-leaved, mid-high evergreen shrubs with regular clumps of broad-leaved, tall shrubs as emergents. Overstorey dominated by *Elytropappus rhinocerotis*. The understorey is mainly annual and herbaceous with perennial (mainly C_3) grasses	Mainly winter rainfall, varying between 300 – 600 mm per year	Heavy clays and loamy soils derived from weathered Malmesbury Group, Cape Granite Suite and Klipheuwel shales
	South and South-west Coast Renosterveld	A very well developed grass component with mainly C_4 tropical species. The vegetation is open to mid-dense, cupressoid and small-leaved, low to mid-high shrubland	Rainfall mainly occurs in spring and autumn, with an increasing summer component in the east	Clays and silts derived from the Bokkeveld and Kango Group shales and Uitenhage Group conglomerates

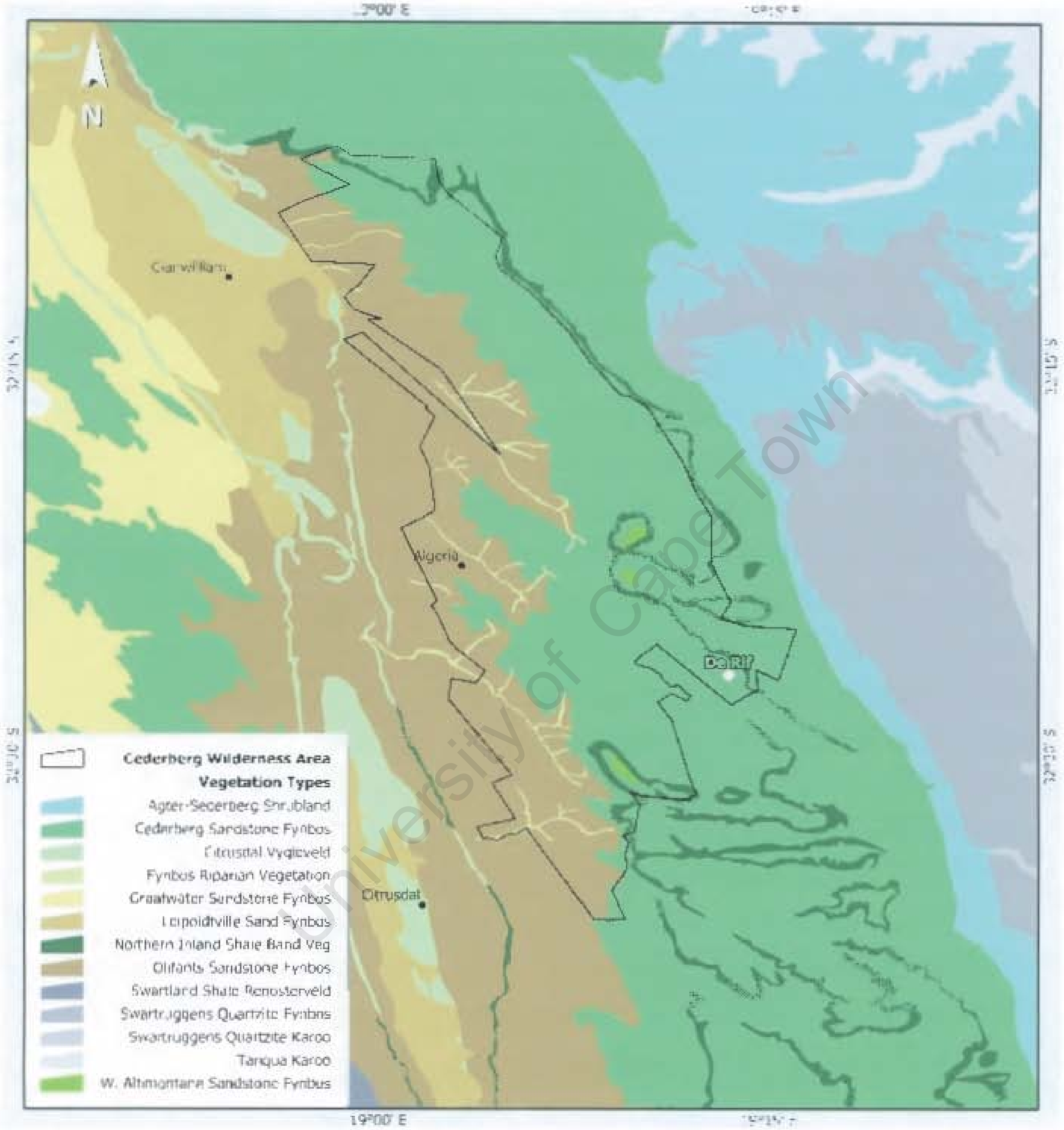


Figure 2.8: Vegetation of the Cederberg Wilderness Area and surrounding regions (data source: Mucina and Rutherford, 2006)

The particular community of fynbos found in the Cederberg is broadly classified as Mountain Fynbos (Taylor, 1996) (Table 2.2), but may be subdivided into the following units:

1. Restioid Fynbos. This unit has high restioid and sedge components and low amounts of shrubs.
2. Ericaceous Fynbos. Ericaceous Fynbos has a high cover of leptophyllous shrubs from the Ericaceae family and restioids. This unit also has large quantities of sedges and species from the Bruniaceae family. Ericaceous Fynbos can be found on nutrient-poor mesic soils, which often have a high silt content and can be waterlogged for long periods of time.
3. Proteoid Fynbos. This unit is characterised by the presence of a high percentage cover (greater than 10%) of medium to tall seed-regenerating proteoids.
4. Asteraceous Fynbos. A narrow band of this unit marks the transition between fynbos vegetation types and Karoo vegetation. It is a much more open vegetation type and occurs on the drier undulating eastern slopes of the Cederberg. The boundary between Asteraceous Fynbos unit and the Karoo vegetation types is precisely determined by the sharp contact between the Table Mountain Group and Bokkeveld Formation at the base of a fault valley. This unit is distinguished from the other units by a higher grass cover, greater numbers of succulents, higher non-ericaceous shrub cover (particularly species in the Thymelaeaceae, Asteraceae and Rhamnaceae families) and the presence of broad leptophylls, deciduous shrubs and microphyllous geophytes (Campbell, 1985 in Sugden, 1985).

Mountain fynbos has specifically adapted to fire and exhibits a wide range of fire-survival mechanisms and is resilient under many different fire regimes (Richardson and van Wilgen, 1992). Of considerable interest, botanically and biogeographically, is the presence on the Cederberg Mountains of the endemic *Widdringtonia cedarbergensis*, the so-called Clanwilliam Cedar from which the Cederberg derives its name (Manders, 1985). These trees can be found on rocky outcrops and summits between 1000 and 1500m (Manders, 1986; van Rooyen and Steyn, 2004). Cedar groves consist of individuals or small groups of trees; typically forming open woodlands which are normally associated with an ericaceous understorey. It has been purported that this species was much more common in the past and its decline is argued to be a result of anthropogenic exploitation coupled with changing climatic conditions (Manders, 1986; Sugden and Meadows, 1990).

There are also significant occurrences of karroid elements, more especially towards the drier eastern Cederberg, characterised by mainly xerophytic succulent dwarf shrubs including members of the following genera: *Crassula, Ruschia, Galenia, Euphorbia and Mesembryanthemum.* The presence of these elements is thought to be more likely controlled by the underlying geology and soils rather than rainfall or elevation (Mucina and Rutherford, 2006).

2.7 THE STUDY SITE: DE RIF

The two hyrax middens under consideration in this study are both located within the area known broadly as De Rif. De Rif can be accessed from the footpath starting at Driehoek farm, which leads up the side of the Driehoek valley, over a saddle and down into a large rocky ravine. This steeply contoured ravine represents the confluence of minor stream tributaries which end up flowing as one ephemeral river down through Groot-Hartbeeskloof, ultimately feeding into the Driehoek valley (Figure 2.9). The ruin of a former farmstead situated across the ravine from the midden sites gives the area its name. Directly above the ruins is a cedar plantation, above which lies Gabrielspaskloof which marks the watershed between De Rif's drainage basin and the other drainage basins further to the north.

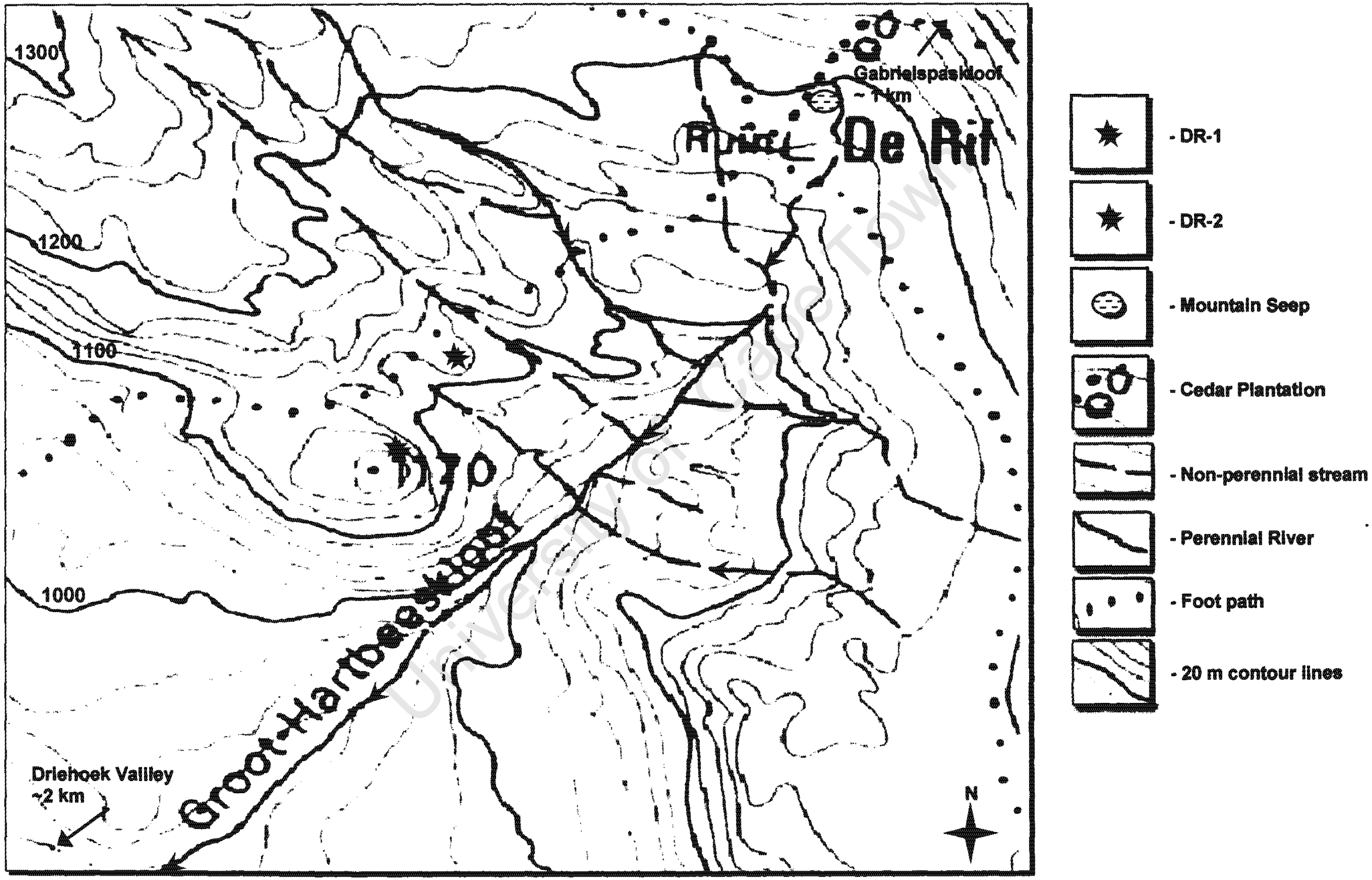


Figure 2.9: Map of De Rif, showing local geomorphological features, major landmarks and the locations of the midden sites DR-1 and DR-2 (Data source: 1:50 000 topographical map Chief Directorate Mapping and Surveys)

2.7.1 De Rif 1 (DR-1)

DR-1 (32 26.797 S; 19 13.429 E) is a hyrax midden found on the periphery of the major ravine at De Rif and lies about 150 m above the bottom of this ravine. The midden is situated on the western edge of a north-east facing crevice found between two large boulders within a free-standing stacked outcrop of sandstone blocks (Figure 2.10). At 1138 m above sea level, DR-1 is lower than the surrounding edge of the ravine. The midden site is encompassed by a grove of Clanwilliam cedar (which included six adult trees and 10 seedlings; however this count has subsequently been reduced substantially as a result of a fire in the region during July 2008).

The opening of the rock crevice within which the midden is situated, faces north to north-west. The horizontal stratigraphy of the midden is visible (Figure 2.11). The deepest section of the midden is 37 cm, with the section extracted for analysis being approximately 10 cm, there is a further 15 cm gap between the top of the midden and the roof of the crevice. The horizontal extent of the midden is approximately 120 cm.

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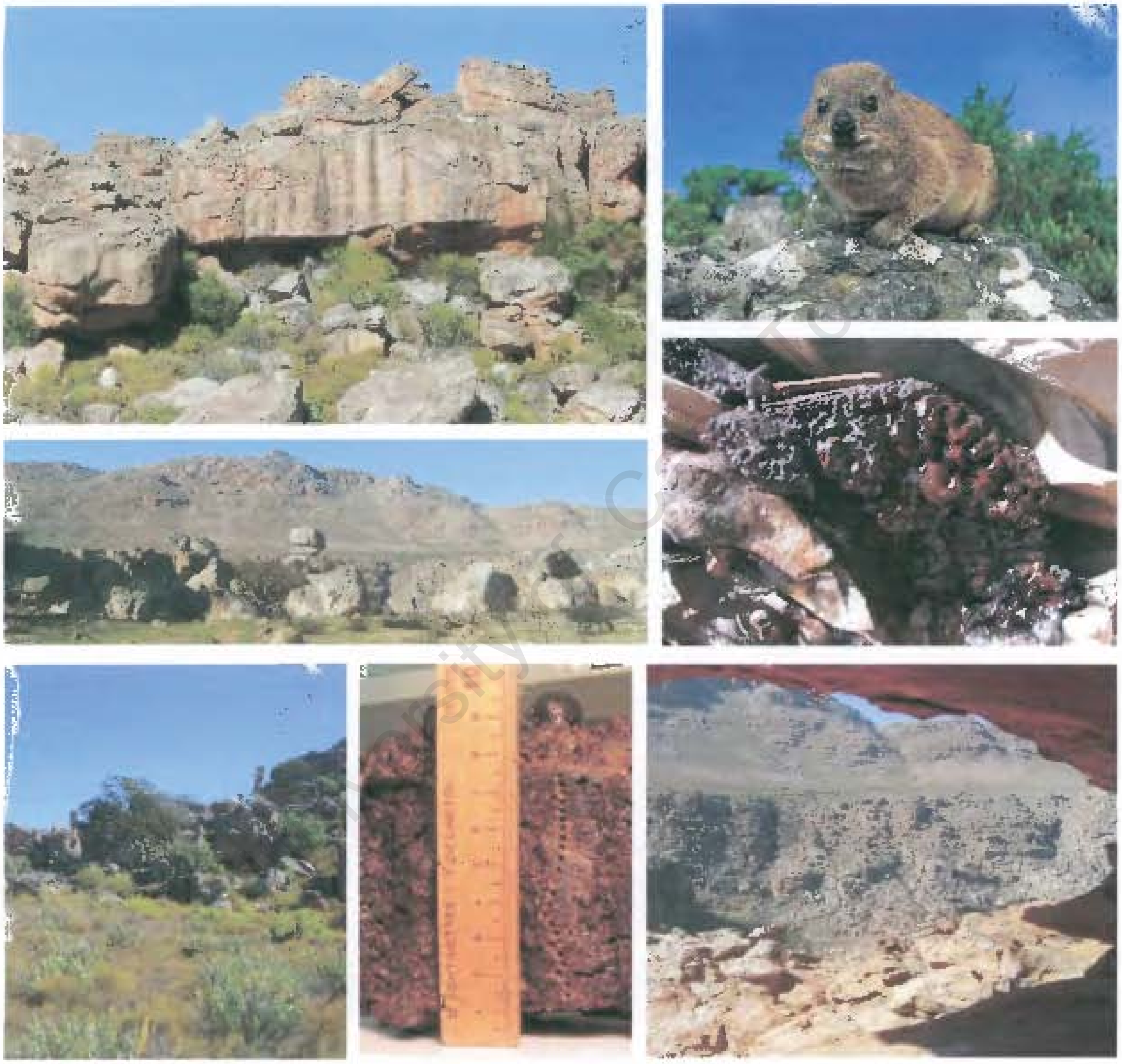

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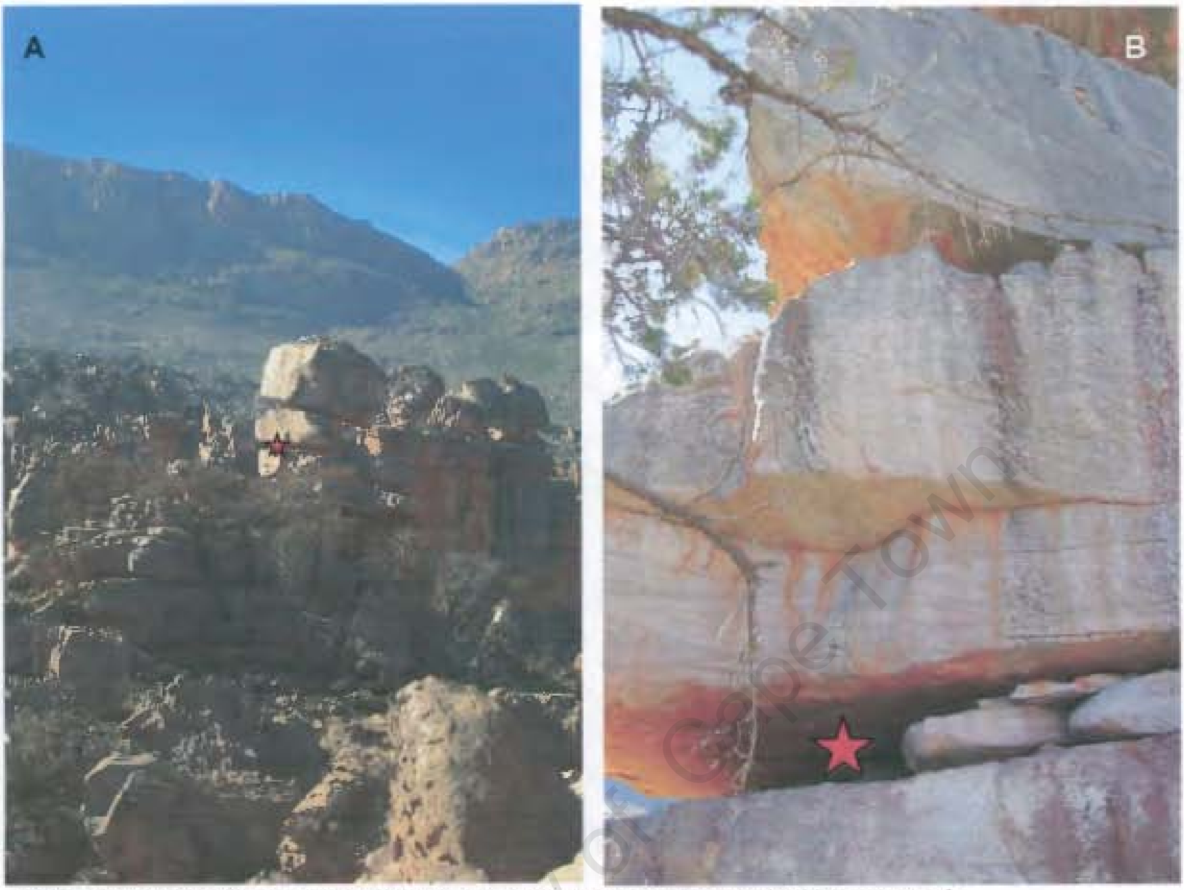


Figure 2.10 A: DR-1 taken from DR-2; B: DR-1 (midden location marked by red stars)

Figure 2.11: DR-1 (sample extracted from red demarcated area)

2.7.2 De Rif 2 (DR-2)

DR-2 (32 26.844 S; 19 13.406 E) is 143 m south-east of DR-1 and at an elevation of 1151 m above sea level (figure 2.9). It is located beneath a 2 m overhang which forms the roof of an extensive complex of sandstone slabs embedded in the upper mid-rock slope of the south wall of the ravine (Figure 2.12).

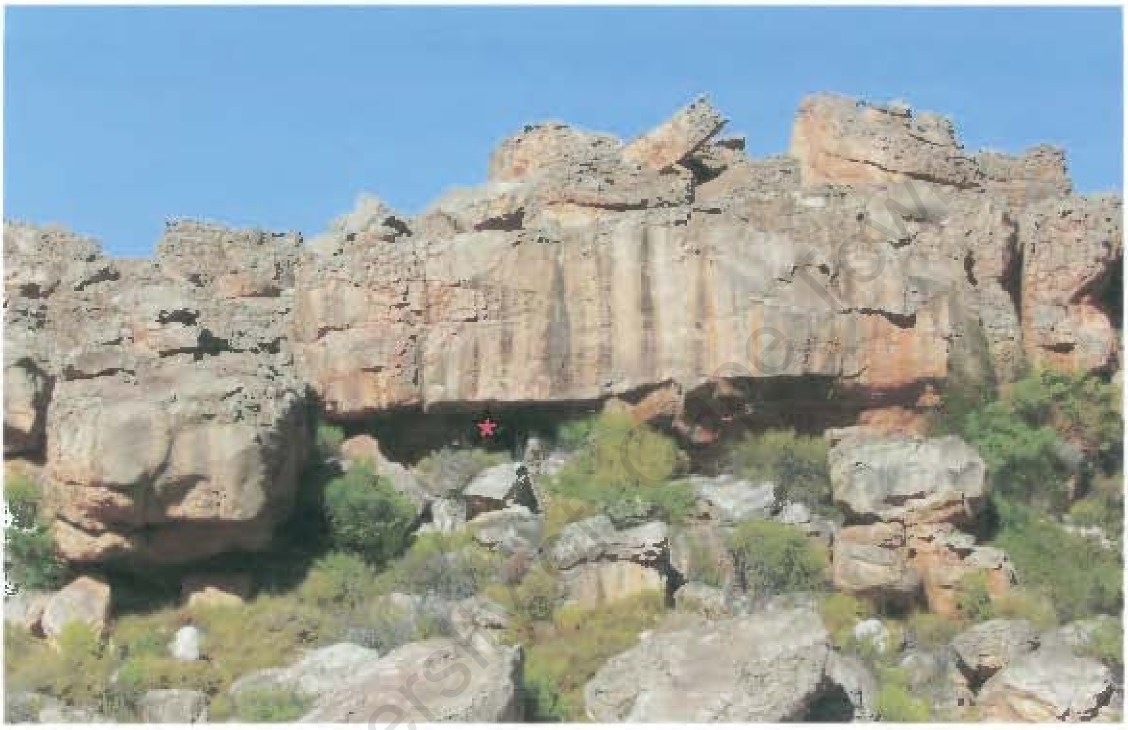


Figure 2.12: DR-2 (position marked by red star)

Figure 2.13: DR-2 before extraction

In contrast to DR-1, which represents a simple linear accumulation of material over time, DR-2 appears to have accumulated in a more complex fashion. The extensive midden complex (which has a horizontal extent of about 25 m) has mainly been formed through material filtering through rock crevices and over slabs, subsequently solidifying on rock faces at lower levels. Despite the complexity of the midden accumulation, the section extracted for analysis has been almost horizontally deposited.

2.7.3 Vegetation at De Rif

The vegetation at De Rif is consistent with the greater Cederberg vegetation type; Mountain Fynbos, and can be classified as belonging to Taylor's (1996) phytosociological vegetation community 11. De Rif's vegetation structure is defined as open woodland with mid-dense restioid understorey (Taylor, 1996). Generally there are three strata present within the overall vegetation structure:

There is a relatively high percentage cover of trees in the landscape especially on the upper slopes of the ravine. As mentioned above, a stand of six adult *Widdringtonia* *cedarbergensis* trees surround DR-1. Cedars are also scattered along the upper slopes of the northern section of the ravine. Medium to small trees found in direct proximity to both DR-1 and DR-2 are all typical of rocky mountain slope vegetation and include the following:

- *Euclea lineans*
- *Euclea tomentosa*
- *Diospyros glabra and D. austro-africana*
- *Olea europaea subsp. africana*
- *Maytenus oleoides*
- *Cassine peragua subsp. Affinis*
- Colpoon compressum

This overstorey layer also includes Proteoid elements such as *Protea nitida*, *P. laurifolia* and *P. glabra* and other species from the Proteaceae family.

The second stratum comprises of a wide variety of shrubs. This layer predominately consists of Asteraceous elements and small to mid-high shrubs commonly found in rocky mountain sandstone habitats. The following being the dominant species found within a 15 m radius of both midden sites:

- *Stoebe plumosa* and *S. aethiopica*
- *Cliffortia ruscifolia* and *C.triloba*
- *Passerina glomerata*
- *Gnidia deserticola*
- *Teedia lucida*
- *Heeria argentea*
- *Rhus rimosa*
- *Rhus undulate*
- *Holothrix aspera*
- Geophytes: *Oxalis obtuse* and *Watsonia vanderspuyiae*

The differential microclimatic conditions evident at DR-1 and DR-2 are manifested by the presence of xerophytic shrubs, specifically *Rhus scytophylla var. scytophylla* and

Lampranthus cedarbergensis, at DR-1 and ferns, *Mohria caffrorum* and *Pteridium aquilinum*, at DR-2.

The third stratum is represented by a restioid understorey, with a large proportion of restioid elements covering the slopes and the bottom of the ravine, particularly including; *Wildenovia incurvata*, *Ischirolepis virgea*, *I. ocreata* and *I. sieberi*. Poaceae can also be found interspersed among the restioid elements, although the grass component is substantially less prominent than that of the restios. In addition, the understorey contains Cyperaceae, for example; *Ficinia nigrescens* which was found approximately 10 m away from DR-1.

Figure 2.14: An example of the Mountain Fynbos vegetation landscape (taken from the saddle leading into the De Rif ravine)

2.8 CONCLUSION

An understanding of the contemporary environment of the midden sites at De Rif, a relatively high-altitude Mountain Fynbos location, is essential for the interpretation of the results of the pollen and isotope analyses discussed in subsequent chapters.

The mountains of the CFR are climatically and topographically complex, and as part of this system, the Cederberg is no exception. The major vegetation determinant of the Cederberg is that of the geology; with Table Mountain sandstones supporting mountain fynbos communities; and Bokkeveld shales, on the eastern boundary of the Cederberg, tending to support more karroid-type vegetation. A further factor that influences vegetation in the region is climate, specifically the distribution and timing of rainfall. Present day rainfall falls predominately in winter and therefore the Cederberg belongs to the WRZ but this might not always have been the case in the past.

On a local scale, factors such as aspect, altitude and topography play an important role in shaping the specific vegetation structure of the study area – De Rif.

The intricacies behind the origin, diversity and changing biogeographic distribution over time of fynbos have yet to be fully resolved (Pienaar and Mucina, 2007; Verboom *et al.*, 2008). This highlights the necessity for investigations into both present environmental and botanical conditions as well as past changes to the Fynbos Biome in the southwestern Cape. The following chapter reviews current understanding of the palaeoenvironmental history of the southwestern Cape.

3 Late Quaternary palaeoenvironments of the southwestern Cape

3.1 INTRODUCTION

"The contemporary uniqueness of the southwestern Cape environment suggests that its response to the environmental perturbations of the late Quaternary may have been correspondingly distinctive." (Meadows and Baxter 1999:193)

The aim of this chapter is to provide a review and synthesis of the evidence available from the southwestern Cape. The palaeoenvironmental history of the southwestern Cape has yet to be established, this is mainly due to the limited number of published records for this region (figure 3.1) and the discontinuous temporal nature of these records. The southwestern Cape, being part of the modern WRZ (figure 2.3b) and the Fynbos Biome (figure 2.4), represents a unique region especially in terms of its climatological, geographical and ecological characteristics. Therefore, the late Quaternary palaeoenvironmental history of the southwestern Cape was probably distinct and interpolations using evidence outside the boundaries of this region cannot always be directly applied.

3.2 DEFINITIONS:

3.2.1 Ages and time periods

Calibrated radiocarbon ages are cited using the suffix "cal yr BP", while uncalibrated ages are reported using the suffix "^{14}C yr BP". Ages reported using the suffix "ka" are ages generated from U-series, lumininescence and ^{18}O stratigraphies (Rose, 2007).

The key time periods of particular palaeoenvironmental significance which are discussed in this chapter include: the Last Glacial Maximum (LGM), the last glacial-interglacial transition, the Holocene and the Holocene Altithermal (HA). The LGM is the period within which global ice coverage reached its maximum and represents the time whereby glacial environmental conditions were the most developed. The 'Environmental Processes of the Ice-Age Land, Ocean, Glaciers Programme' (EPILOG) (Mix *et al.*, 2001; Clark and Mix, 2002) defines the LGM as the period from 24 000 cal yr BP to 18 000 cal yr BP. Even though the LGM is considered a global event; its regional expressions were varied, with maximum ice presence and extent peaking at different times in the northern and southern hemispheres (Dyke *et al.*, 2002; Gersonde and Zielinski, 2000; Crosta *et al.*, 2004; Stuut *et al.*, 2004). The last glacial – interglacial transition (LGIT) marks the boundary between the Late Pleistocene and the Holocene and encompasses the time during which glacial conditions ceased and post glacial warming began, roughly equivalent to 14 500 – 11 500 cal yr BP. The LGIT does not represent a smooth transition period between these two climatic phases but instead corresponds to dynamic climate phase. The Holocene is the interglacial period covering the last ~11 500 years (Mayewski *et al.*, 2004). The warmest part of the Holocene in southern Africa is represented by the HA, Chase and Meadows (2007) define this period as 8 000 – 4 000 cal yr BP.

3.2.2 Defining the boundaries of the southwestern Cape

There are no definitive boundaries for the region termed the southwestern Cape (SWC). This region is generally viewed as the part of the Fynbos Biome that falls within the winter rainfall zone (WRZ). Meadows and Baxter (1999: 194) state the following: "The term southwestern Cape is taken as broadly speaking synonymous with the area of winter rainfall as defined by Meadows (1997) and approximates 'region A' of Partridge *et al.* (1990) and also the area occupied by the fynbos biome (Cowling *et al.*, 1992)". Due to the presentation of a more precise delineation of the boundaries of the WRZ (figure 2.3b and Chase and Meadows, 2007), the area covered by the WRZ is distinctly different from the rainfall area used in Meadows and Baxter (1999) and the limits of the Fynbos Biome. The implications of conflating climatic and biogeographical information as done in Partridge (1990), is that that review includes sites from outside the WRZ and SWC. For example: Boomplaas Cave (Deacon et al 1984) which is situated in the year-round rainfall zone (YRZ) within the southern Cape. Therefore for the purposes of this review, the SWC is taken to represent the area displayed in figure 3.1. Sites that are situated beyond the boundaries of figure 3.1 but provide additional insight into the palaeoenvironmental dynamics of the region are discussed in section 3.3.3. In addition, it should be noted that climate boundaries are dynamic and therefore precipitation boundaries may have had changed over the time period relevant to this study.

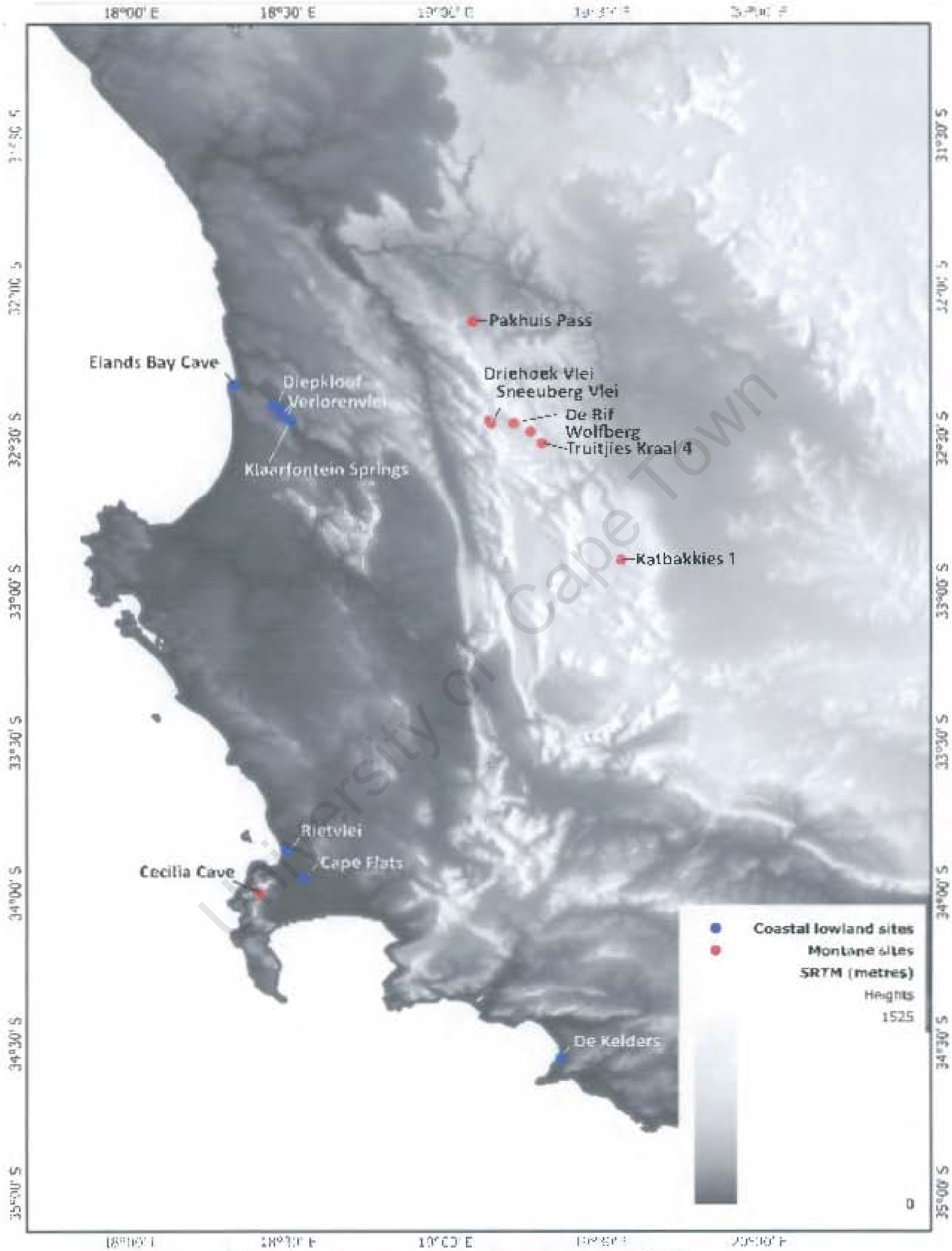


Figure 3.1: Location of the major palaeoenvironmental sites within the SWC

3.3 THE PALAEOENVIRONMENTAL RECORD OF THE SOUTHWESTERN CAPE

The SWC can be broadly divided into two zones according to topographical affinities: coastal lowlands vs. mountainous regions. The distinctiveness of these zones is reflected in the differing palaeoenvironmental information obtained from sites within these zones. Consequently, this review is structured by the various palaeoenvironmental sites with the SWC that fall within these two zones.

3.3.1 Coastal lowland sites

3.3.1.1 Elands Bay

Most of the significant palaeoenvironmental and archaeological studies situated in this zone are concentrated along the west coast. The greatest source of information for this zone has been found at Elands Bay Cave (EBC), which is a northwesterly-facing cave situated on Baboon Point headland on the west coast about 250 km north of Cape Town (figure 3.1). The area is presently subject to a semi-arid climate and experiences winter rainfall between 200 - 250 mm/yr [1] (Cowling *et al.*, 1999). The contemporary vegetation is described as being part of the 'strandveld' (Boucher and Moll, 1980) which is a form of xeric thicket. Through various analyses of sediments that have preserved the evidence of human occupation in EBC for periods within the late Quaternary, a multiproxy record of environmental change has been established. However the deposit does not represent a continuous sequence but rather a 'pulsed' record due to the episodic nature of human habitation (Cartwright and Parkington, 1997).

Macrofaunal evidence was examined by Klein and Cruz-Uribe (1987) and Klein (1991). Despite the small assemblage size, the taxa identified in the Pleistocene levels showed marked differences to those found in Holocene levels. The assemblage for the LGM period included several grazing fauna including two equids and springbok (*Antidorcas marsupialis*) (Klein and Cruz-Uribe, 1987). This type of assemblage usually indicates drier conditions but the associated presence of the hedgehog (*Erinaceus frontalis*, which inhabit areas with annual precipitation between 300 – 800 mm (Smithers 1983: 21)) possibly suggests greater moisture availability together with increased grass cover (Klein and Cruz-Uribe, 1987).

In addition, the relatively large size of dune molerat (*Bathyergus suillus*) distal humeri indicates that relatively humid conditions most probably prevailed during the early Holocene (Klein and

Cruz-Uribe, 1987; Klein, 1991). The increased size of the molerat signifies that rainfall values were at least 400 mm/yr[1] (Klein, 1991), an amount which is approximately double what is presently received.

An extensive wood charcoal record has been established for EBC (Cartwright and Parkington, 1997; Cowling *et al.*, 1999; Parkington *et al.*, 2000) (figure 3.2). The section of the record dating to >40 000 ^{14}C yr BP is dominated by afromontane forest taxa (such as *Kiggelaria africana*, *Podocarpus elongata* and *Myrsine africana*) indicating that conditions during the late Pleistocene were most probably several degrees cooler and somewhat wetter than today (Parkington *et al.*, 2000). After the >40 000 ^{14}C yr BP section there is a reduction in afromontane taxa, with the complete replacement of these forest elements by mesic thicket at 21 700 cal yr BP followed by a hiatus in the record (figure 3.2). From 16 800 – 12 300 cal yr BP the sequence is dominated by mesic thicket taxa (such as *Diospyros glabra*, and *Olea europaea ssp. africana*) and Proteoid fynbos elements including *Protea glabra*, *Leucodendron pubescens* and *Erica* spp. A drying trend can be associated with the period between ~12 300 cal yr BP to the about ~8 000 cal yr BP with increases in asteraceous shrubland elements (e.g. *Eriocephalus aromata*, *Aspalathus* sp. and *Passerina glomerata*) and xeric thicket. By ~4 000 cal yr BP asteraceous shrubland and xeric thicket taxa (such as *Euclea racemosa*, *Rhus undulata* and *Ruschia maxima*) dominate the assemblage indicating that the late Holocene was characterized by warm and dry conditions within which the modern vegetation, the 'strandveld' was established.

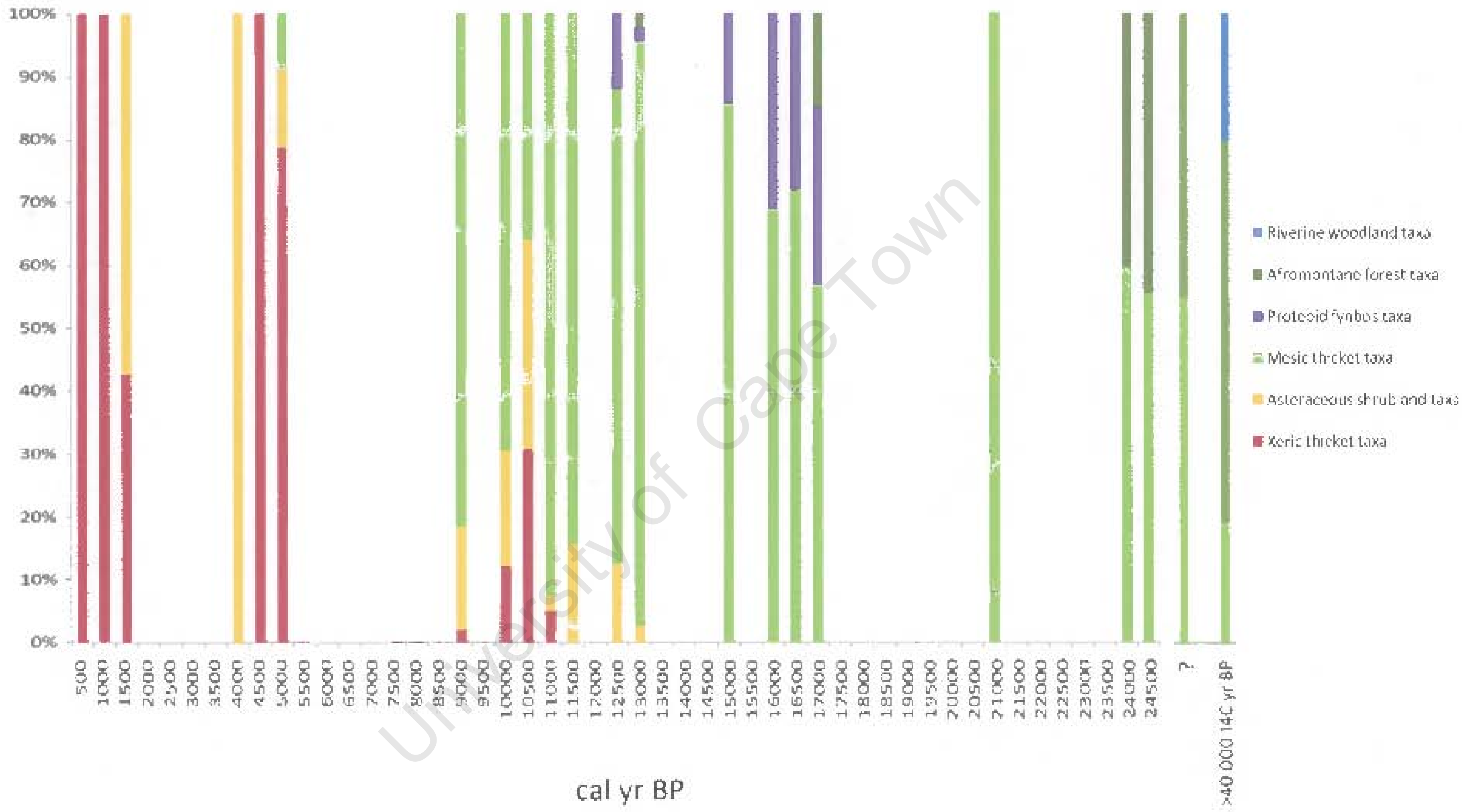


Figure 3.2: Elands Bay Cave charcoal taxa percentages (Parkington *et al.*, 2000)

In addition to the charcoal record, twelve sedimentary units were suitable for pollen analysis and dated from >40 000 ^{14}C yr BP to 12 500 cal yr BP (Baxter, 1996). The pollen assemblage exhibits many similarities to the charcoal results (Parkington *et al.*, 2000). Pollen assemblage zone EBC-B (refer to figure 3.3) is taken to represent the LGM period and is marked by maximum values in afromontane taxa, with *Kiggelaria*, *Ficus* and *Podocarpus* occurring only in this zone (figure 3.3). This zone is also characterised by low frequencies of xeric karroid and strandveld pollen types and relatively high percentages of grass pollen (Baxter, 1996). Consequently, significantly moister and cooler conditions have been inferred from this zone (Baxter, 1996; Meadows and Baxter, 1999; Parkington *et al.*, 2000). However, due to the fact that uncalibrated ages were used for the pollen assemblage diagram, zone EBC-B does not represent the LGM very well as indicated by the calibrated chronology in figure 3.2.

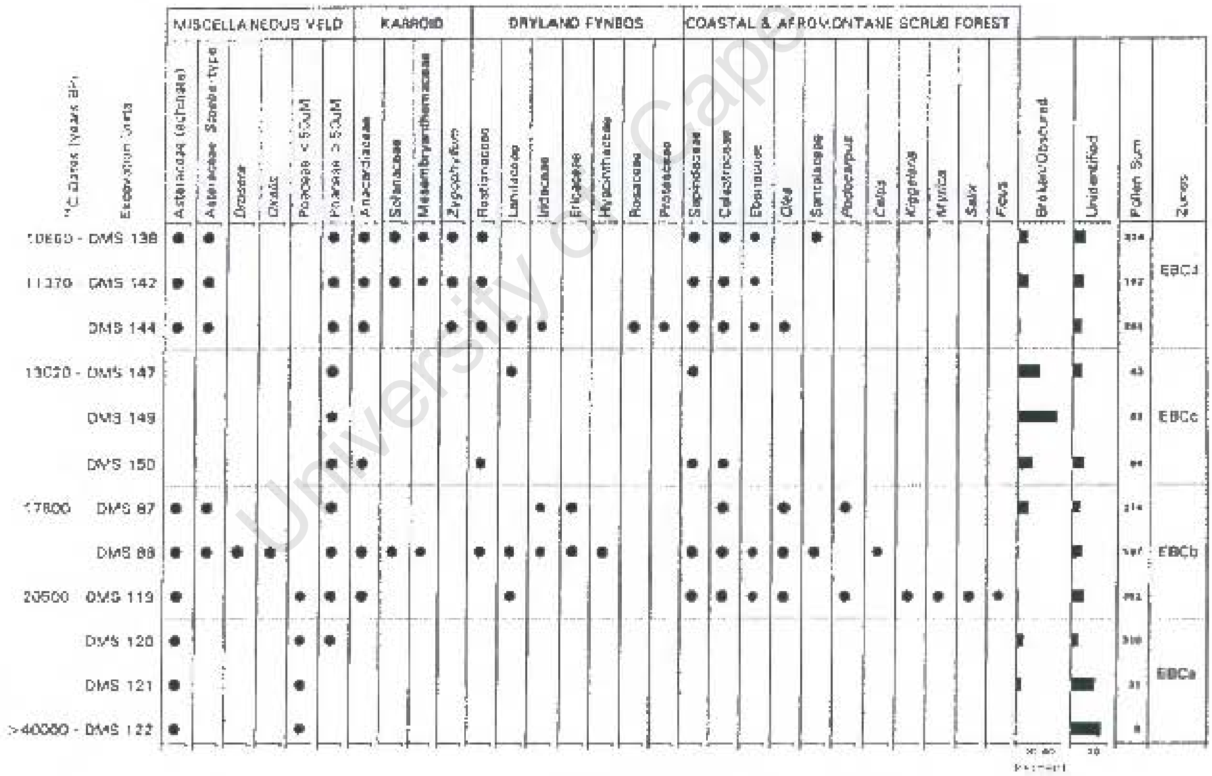


Figure 3.3: Elands Bay Cave pollen presence diagram (Baxter 1996 in Meadows and Baxter, 1999)

The EBC deposits have also yielded a record associated with changes in the adjacent marine environment. A sea-surface temperature (SST) record of the southern Benguela upwelling system was reconstructed using mollusc (*Patella granatina* and *P. granularis*) shells from midden deposits using oxygen isotopes and aragonite-calcite ratios (Cohen *et al.*, 1992). Three significant deviations from the modern $\delta^{18}O$ and aragonite values occurred: 13 000 to 11 000 cal yr BP, 3 000 to 2 000 cal yr BP and 300 to 100 cal yr BP (Cohen et al., 1992) (figure 3.4). These excursions represent periods of decreased SSTs and correspond to periods of global cooling. Of particular interest is the cooling period between 13 000 – 11 000 cal yr BP as this coincides to within the LGIT and more specifically the Younger Dryas episode (12 900 – 11 500 cal yr BP; Alley, 2000).

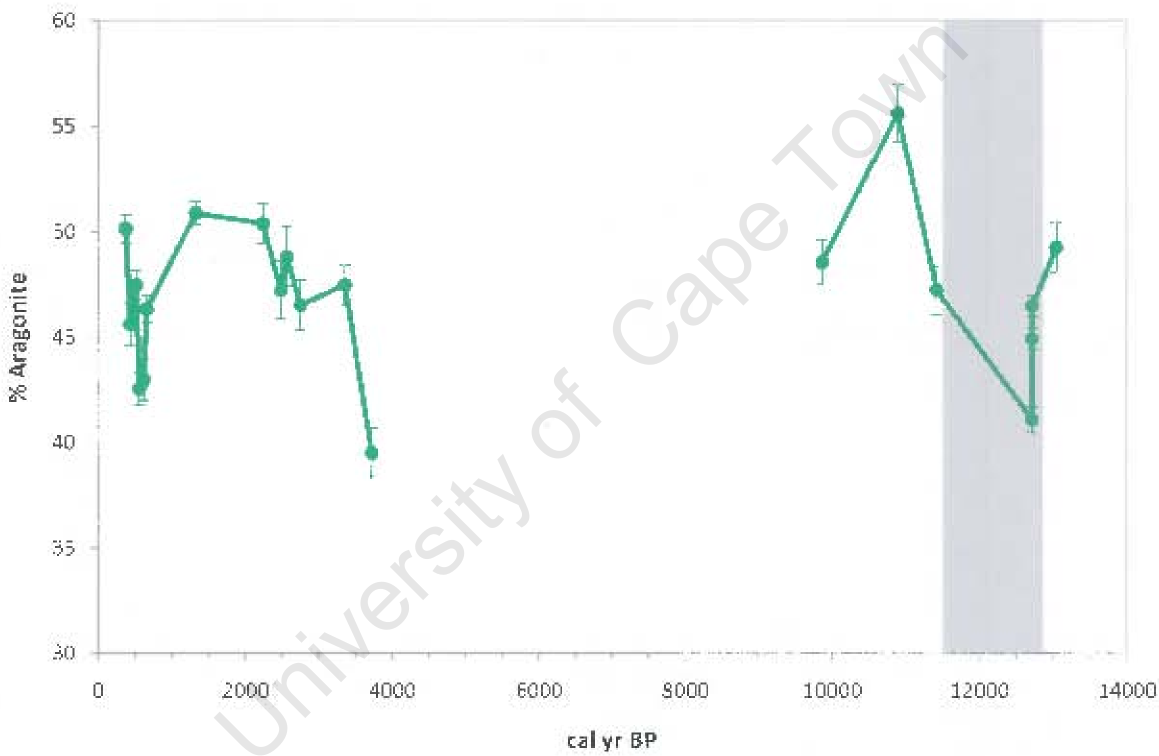


Figure 3.4: % Aragonite from *Patella granularis* shells found at EBC (Cohen *et al.*, 1992). Grey bar representing the Younger Dryas.

3.3.1.2 Diepkloof Cave

Diepkoof Cave is situated about 10 km inland from the town of Elands Bay and overlooks the Verlorenvlei coastal wetland (see 3.3.1.3). Butzer (1979) uses roof spall to infer cooler conditions during portions of the Middle Stone Age (MSA, ~200 – 40 ka). In addition, the presence of afromontane forest taxa at Diepkloof during the period ~65 000 to 50 000 ka implies more humid conditions during glacial times than today (Cedric Poggenpoel, *pers. comm.* in Chase and Meadows, 2007).

3.3.1.3 Verlorenvlei and Klaarfontein Springs

Near Elands Bay, within the coastal estuarine/lacustrine wetland known as Verlorenvlei, sediment cores have been analysed providing a multiproxy record of climatic, hydrological and sea level changes for the area (Baxter, 1996). The pollen record extracted from the Grootdrift site provides evidence for an arid HA. This is inferred from the increased percentages of xeric taxa (such as Asteraceae and Chenopodiaceae) at the base of the core at 6 300 cal yr BP, indicating that the wider environment most probably experienced more arid conditions than that of today (Meadows *et al.*, 1996; Meadows and Baxter, 1999). The Grootdrift pollen record indicates greater moisture availability was associated with the late Holocene (Meadows and Baxter, 1999).

The most significant influence on both the Grootdrift sediments and the pollen assemblage appears to have been sea level change (Meadows *et al.*, 1996). A composite sea-level curve was created from the work conducted at Grootdrift. Evident in this curve, as well as others constructed for the West Coast (figure 3.4), is the mid-Holocene sea level transgression that is generally dated to ~5 000 – 4 000 yr BP which falls within the HA.

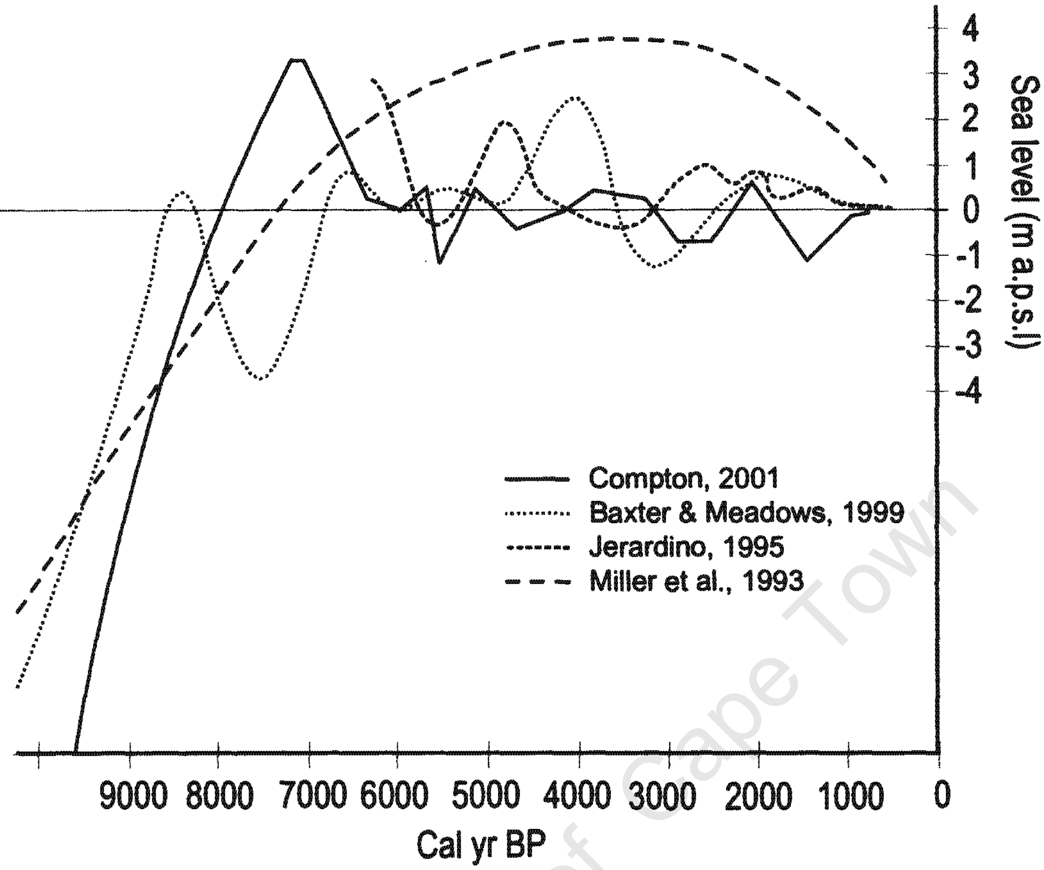


Figure 3.4: Composite of Holocene sea level variations (Chase, 2005)

A 6 metre core was extracted from Klaarfontein Springs, an artesian spring site about 18 km inland of Elands Bay town (Meadows and Baxter, 2001). Pollen from this site further supports the idea of arid conditions prevailing at the HA, with the section covering the period: 7 500 – 4 000 cal yr BP dominated by Poaceae, Asteraceae and Chenopodiaceae pollen (Meadows and Baxter, 2001). In accordance with inferences made from the Grootdrift record, moister conditions are evident at Klaarfontein from 4 000 – 2 000 cal yr BP (Meadows and Baxter, 2001).

3.3.1.4 Cape Flats and Rietvlei

Further south on the Cape Peninsula, Schalke (1973) analysed pollen from several sediment cores extracted from the Cape Flats and Rietvlei basin (figure 3.1). As a result of sea level fluctuations, variable aeolian activity, changes in the regional hydrology and drainage patterns; these deposits have produced discontinuous palaeoenvironmental sequences (Schalke, 1973). Despite these complexities, marked differences exist between the pollen assemblages for the

Holocene and those dated to >40 000 – 37 000 cal yr BP (some of Schalke (1973) ages are deemed infinite as they fall beyond the limits of radiocarbon dating abilities) (Schalke, 1973; Chase and Meadows, 2007). The Holocene regions of Schalke's (1973) pollen diagrams show a complete absence of forest taxa, whereas the sequences for the period roughly equivalent to 38 000 cal yr BP are dominated by afromontane forest taxa (for example: *Podocarpus*). The latter assemblages are very similar to the modern vegetation communities found in the Knysna area within the year-round rainfall region. This suggests that the Cape Peninsula received significantly more effective year-round precipitation during this period than what is experienced today (Chase and Meadows, 2007).

3.3.1.5 Die Kelders

The major archaeological site of Die Kelders is a sea cave complex about 120 km southeast of Cape Town. Dating the archaeological deposits found at Die Kelders 1 (DK1) has proved difficult and contentious (Butzer, 2004). The sediments were deposited beyond the range of radiocarbon dating (approximately 40 ka) and therefore luminescence (Feathers and Bush, 2000) and electron-spin resonance (ESR) (Schwarcz and Rink, 2000) dating techniques have been employed to provide a chronology. Differing assumptions with regard to moisture content and stratigraphical inconsistencies mean that the best age estimate for the MSA late Pleistocene sequence at DK1 is: 70 – 60 ka (Feathers and Bush, 2000; Klein, 2000; Schwarcz and Rink, 2000).

The macrofaunal evidence from DK1 strongly indicates cooler and wetter conditions for the estimated period 70 – 60 ka. Greater humidity is inferred from the large mean size of the Cape dune molerat, while the large size of the gray mongoose (*Galerella pulverulenta*) implies decreased temperatures (Klein and Cruz-Uribe, 2000). In addition, the presence of extralimital ungulates point to relatively moist and grassier environments (Klein and Cruz-Uribe, 2000). The scenario of cooler and wetter phases in the MSA is corroborated by both the micromammalian evidence, in the form of higher percentages of *Myosorex varius* and *Otomys saundersae* (Avery, 1982), and the presence of frost shattered roof spall (Butzer, 1984).

3.3.2 Montane Sites

3.3.2.1 Driehoek and Sneeuberg Vleis, Cederberg

The Cederberg Mountain range, extensively discussed in terms of its contemporary environment in the previous chapter, is the location for the majority of the upland palaeoenvironmental archives of the SWC.

In the central Cederberg, in one of the highest parts of the range, sediment cores were extracted from wetlands and their pollen contents were analysed (Sugden, 1989; Meadows and Sugden 1990; 1991). The base of the Sneeuberg Vlei core was dated to 10 980 cal yr BP while the record from Driehoek Vlei, at a slightly lower altitude, covers the last 17 600 cal yr BP. From the examination of the pollen assemblages it can be concluded that the overall palaeoenvironmental record, obtained from these Cederberg wetland sites, is one of stability and that fynbos was the dominant vegetation type throughout the period of sedimentation (Sugden, 1989; Meadows and Baxter, 1999).

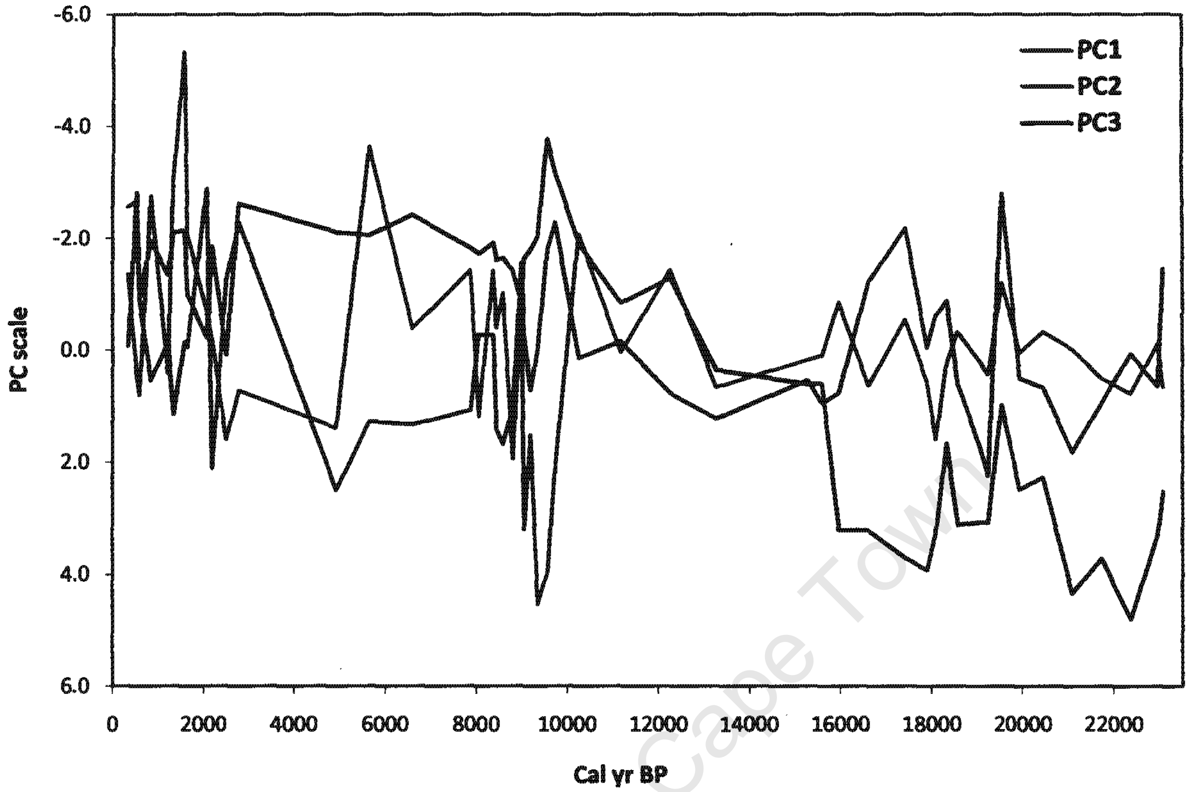
Despite the fact that the LGM period is not encompassed in the Driehoek record, the steady decline in the abundance of the Clanwilliam cedar (*Widdringtonia cederbergensis*) from the base of the record, has been used to suggest that the climate of the last glacial period may have been more favourable to this endemic tree, therefore indicating that cooler and wetter conditions prevailed during the LGM (Sugden and Meadows, 1991, Meadows and Baxter, 1999).

3.3.2.2 Pakhuis Pass

Towards the northwestern, more xeric, side of the Cederberg, pollen from hyrax midden deposits at Pakhuis Pass were examined (Scott, 1994; Scott and Woodborne, 2007a, b). In contrast to the limited variation in the pollen found in the high altitude vlei records, the lower altitude Pakhuis Pass record, covering the last 23 000 cal yr BP, indicates significant variations between glacial and interglacial environments. The vegetation at the LGM is characterised by *Stoebe* and/or *Elytopappus*-type pollen and typical fynbos elements such as Ericaceae, Proteaceae, *Passerina* and *Cliffortia*, as well as elevated levels of Cyperaceae. Holocene vegetation generally consisted of a mosaic of fynbos, thicket and succulent vegetation. The shift from glacial to Holocene vegetation is marked by a sharp increase in *Dodonaea* at ~16 000 cal yr BP (figure 3.5). Scott and Woodborne (2007a,b) attributed this shift to a reduction in soil moisture associated with an increase in temperatures and a decrease in precipitation during the last glacial-interglacial transition.

Statistical analyses of the pollen data from Pakhuis Pass has yielded mean temperature and moisture indices derived from Principal Component Analysis (PCA) (Scott and Woodborne, 2007b) (figure 3.5). Based on the loadings and components scores of a selected group of indicator taxa, Scott and Woodborne (2007b) relate PC1 with temperature, PC2 with seasonality of temperature and precipitation and PC3 with general moisture availability. From these more generalised climatic indices it can be concluded that cold and relatively dry conditions prevailed from 23 000 cal yr BP to 16 000 cal yr BP; the exception being a warmer and wetter period between 21 000 – 19 000 cal yr BP followed by a cool dry event at about 19 000 cal yr BP. It has been suggested that this moisture peak could be due to an increased influence of summer rainfall to the region (Scott and Woodborne, 2007b). The effect of an increased contribution of summer rainfall would have been enhanced due to the simultaneous decrease in winter rainfall as a result of a southward displacement of the westerly wave belt (Scott and Woodborne, 2007b; Gasse *et al.*, 2008).

Moisture peaked again at ~ 17 500 cal yr BP, followed by a warming trend associated with generally increasing moisture from 16 000 – 9 500 cal yr BP. The poor resolution of this period means that it is not possible to accurately define the LGIT or identify the Younger Dryas. The Holocene sequence indicates that generally warm conditions prevailed with increased temperature and moisture variability occurring from ~2 500 cal yr BP to the present.



<u>Figure 3.5</u>: **Pakhuis Pass PCA scores with the principal components indicating the following: PC1 - temperature variability, PC2 - seasonality of temperature and rainfall and PC3 - general moisture availability (Scott and Woodborne, 2007b)**

Despite the differences that exist between the glacial and interglacial environments as indicated in the pollen record and the PCA scores, there is a high degree of variability within the Pakhuis Pass record, especially within the LGM period and the LGIT.

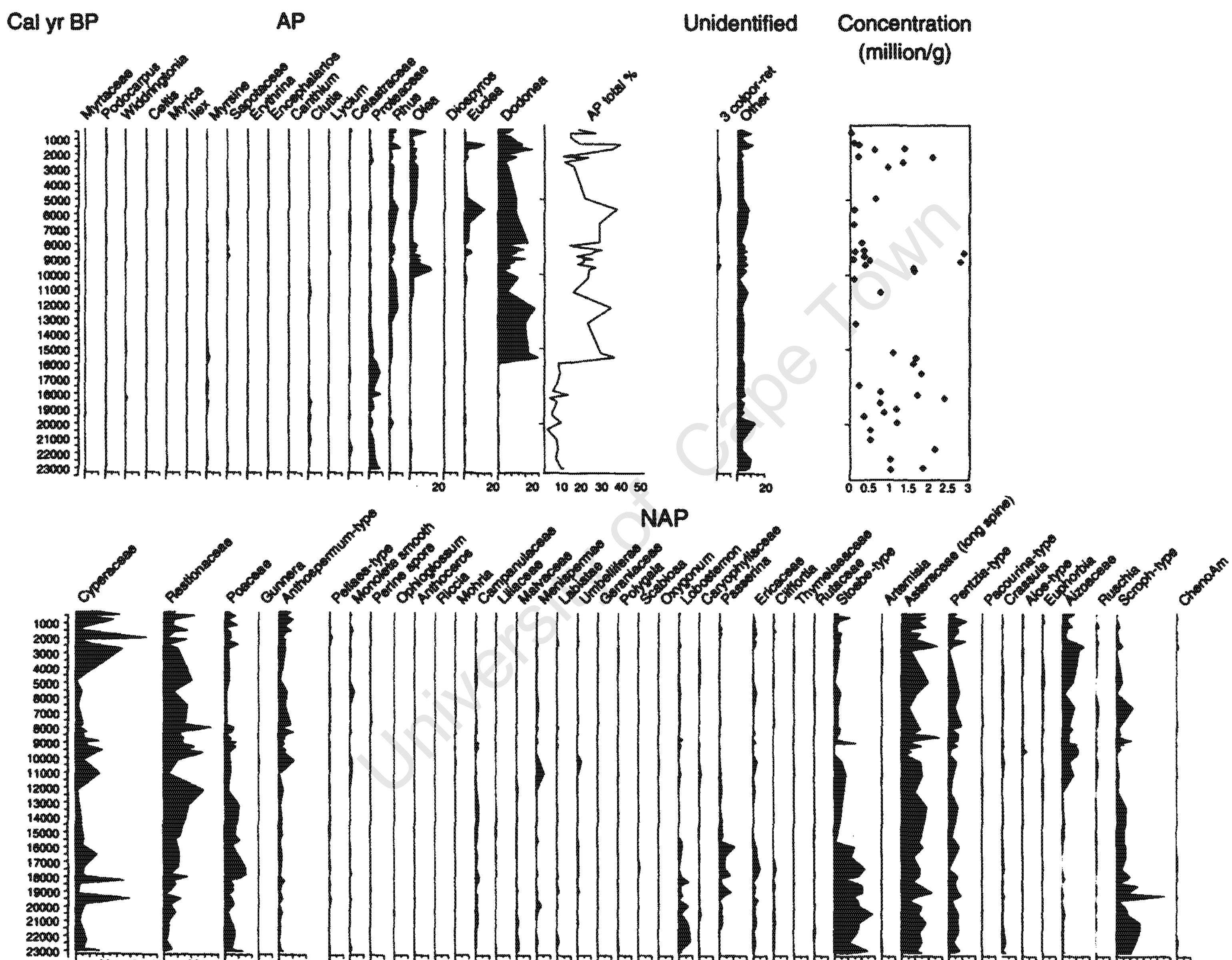


Figure 3.6: Pakhuis Pass relative percentages pollen diagram (from Scott and Woodborne, 2007a)

3.3.2.3 Truitjes Kraal 4 (TK-4) and Katbakkies 1 (KB-1)

Truitjes Kraal is a hyrax midden site situated in the southern reaches of the Cederberg, about 17 km southeast of Driehoek. TK-4 is an 11 cm section of the deposit which has formed within the Holocene over the period 9 500 to 1 300 cal yr BP (Seliane *et al.*, in review). Pollen and stable carbon and nitrogen analyses were carried out on TK-4, with the results from these analyses concurring that, in general, very little environmental change occurred in the region over the Holocene (Seliane *et al.*, in review). In spite of the overall conclusion of environmental stability, subtle changes in the pollen frequencies were evident. Slightly greater moisture availability was inferred for the section representing the earlier Holocene as it contained higher frequencies of Poaceae, Ericaceae and arboreal elements as well as relatively depleted $\delta^{13}C$ and $\delta^{15}N$ values (Seliane *et al.*, in review). The HA and late Holocene are characterised by a minor increase in asteraceous and succulent pollen together with enrichments in $\delta^{13}C$ and $\delta^{15}N$ values, indicating a trend towards more arid conditions (Seliane *et al.*, in review).

Katbakkies Pass in the Swatruggens Mountains, part of the Cape Fold Belt but further south than the Cederberg, is the location of an additional hyrax midden (KB1) examined by Seliane *et al.* (in review). This midden has accumulated over a shorter period during the late Holocene from 3 700 cal yr BP to 600 cal yr BP, (Seliane *et al.*, in review). Only very subtle changes in the pollen assemblage for this site are apparent, however, the earlier section (~ 3 700 – 2 400 cal yr BP) did contain relatively higher frequencies of Crassulaceae and Euphorbiaceae. Together with slightly elevated $\delta^{13}C$ and $\delta^{15}N$ values, this may indicate warmer and drier conditions during this period (Seliane *et al.*, in review). A drying trend is also apparent in the stable isotope record from 1 300 cal yr BP with increased $\delta^{13}C$ and $\delta^{15}N$ values (figure 3.7).

Collectively the pollen and stable isotope records from TK-4 and KB-1 indicate very minimal changes in the vegetation and climatic conditions within the Holocene. The reliability of the pollen records for TK-4 and KB-1 are somewhat questionable as a result of their low taxonomic resolution as a result of pollen identification difficulties as well as conflation of information due to the sampling intervals being to large which led to sections containing both warmer/drier and cooler/wetter indicators. However, the concordance between the pollen and the isotope records provide some validation for these records.

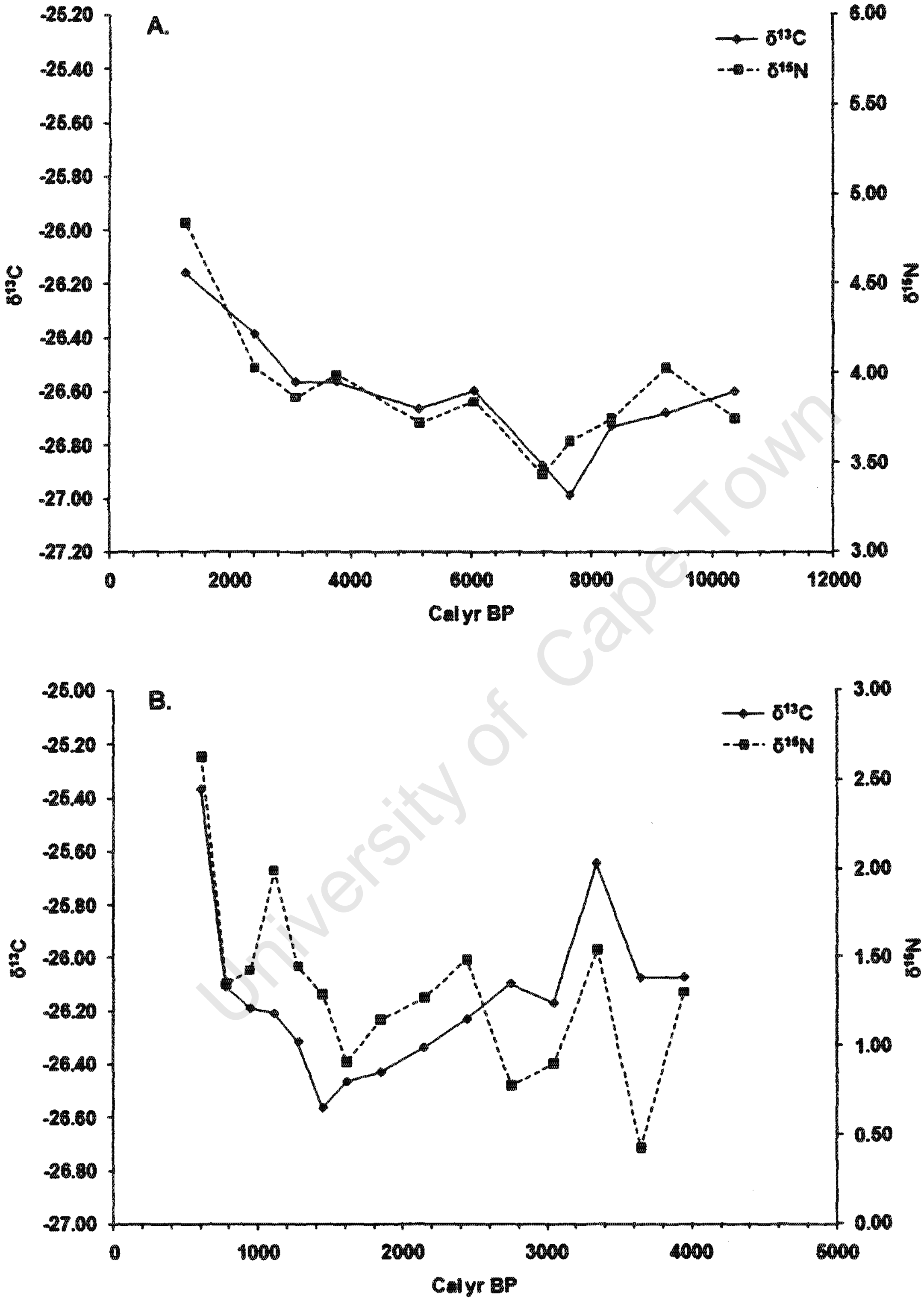


Figure 3.7: Truitjes Kraal 4 (A) and Katbakkies 1 (B) stable isotope data (Selaine *et al.*, in review)

3.3.2.5 Cecilia Cave, Table Mountain

Baxter (1989) examined pollen from sediments taken from Cecilia Cave, situated at an altitude of approximately 550 m on the eastern side of Table Mountain, on the Cape Peninsula. The sediment deposit found at the rear of the cave accumulated intermittently within part of the Holocene (Meadows and Baxter, 1999). Despite the absence of overarching changes in the pollen frequencies, possible under-representations of arboreal taxa and over-representations of anemophilous pollen, the pollen record obtained from this mountainous site does provide some significant palaeoenvironmental information:

The dominance of Asteraceae pollen together with low absolute pollen concentrations at the base of the pollen record, dated to 8 300 cal yr BP, implies that drier conditions most likely prevailed at the site during the HA (Baxter, 1989; Chase and Meadows, 2007). Slightly moister and possibly cooler conditions were inferred from the pollen sequence for the period 4 000 – 2 000 cal yr BP due to the presence of Ericaceae combined with an increase in Restionaceae and Iridaceae, and a decrease in Poaceae pollen (Baxter, 1989).

3.3.3 Evidence derived from sites beyond the boundaries of the SWC

3.3.3.1 The western margin of southern Africa

Sites inland and off the coast of Namibia and Angola represent a significant body of palaeoenvironmental information which validate and support the evidence derived from within the SWC.

Boegoeberg 1 is a hyena den located on the west coast of South Africa approximately 450 km north of EBC. The large size of hyena bones together with the presence of two extralimital ungulates; the blue wildebeest (*Connochaetes taurinus*) and the southern reedbuck (*Redunca arundinum*) have been interpreted as being indicative of cooler temperatures and increased rainfall during the period roughly equivalent to late Oxygen Isotope Stage 5 (128 – 71 ka) and ~41 000 cal yr BP (Klein *et al.*, 1999).

The results of pollen analysis carried out on a hyrax midden deposit taken from the Brandberg Massif in northern Namibia indicated that the vegetation during the late Pleistocene differed markedly from the current arid vegetation (Scott *et al.*, 2004). *Olea*, *Artemisia*, *Stoebe-type* pollen as well as fern spores were identified in samples dating to 35 000 cal yr BP and 21 000 cal yr BP, therefore providing further evidence of increased humidity during this period (Scott et al., 2004; Chase and Meadows, 2007). In addition, geomorphological data derived from a variety of studies within the Namib Desert (e.g. Vogel and Visser, 1981; Beaumont, 1986; Teller and Lancaster, 1986) also point to increased humidity during the last glacial period (Chase and Meadows, 2007).

Marine cores off the Namibian coast have provided important evidence of long term climate change for the region (e.g. Little *et al.*, 1997; Shi *et al.*, 2000, 2001; Stuut *et al.*, 2002). Of particular significance are the pollen results from two marine cores, GeoB1023-5 (Shi *et al.*, 2000) and GeoB1711-4 (Shi *et al.*, 2001), showing maximum frequencies in Restionaceae pollen from 32 000 – 23 000 cal yr BP (figures 3.8 and 3.9) indicating greater moisture availability than present. Increased humidity during the LGM is also inferred from increases in the quantity of fluvial sediments as well as a peak in the trade wind proxy from marine core MD962094 (Stuut *et al.*, 2002).

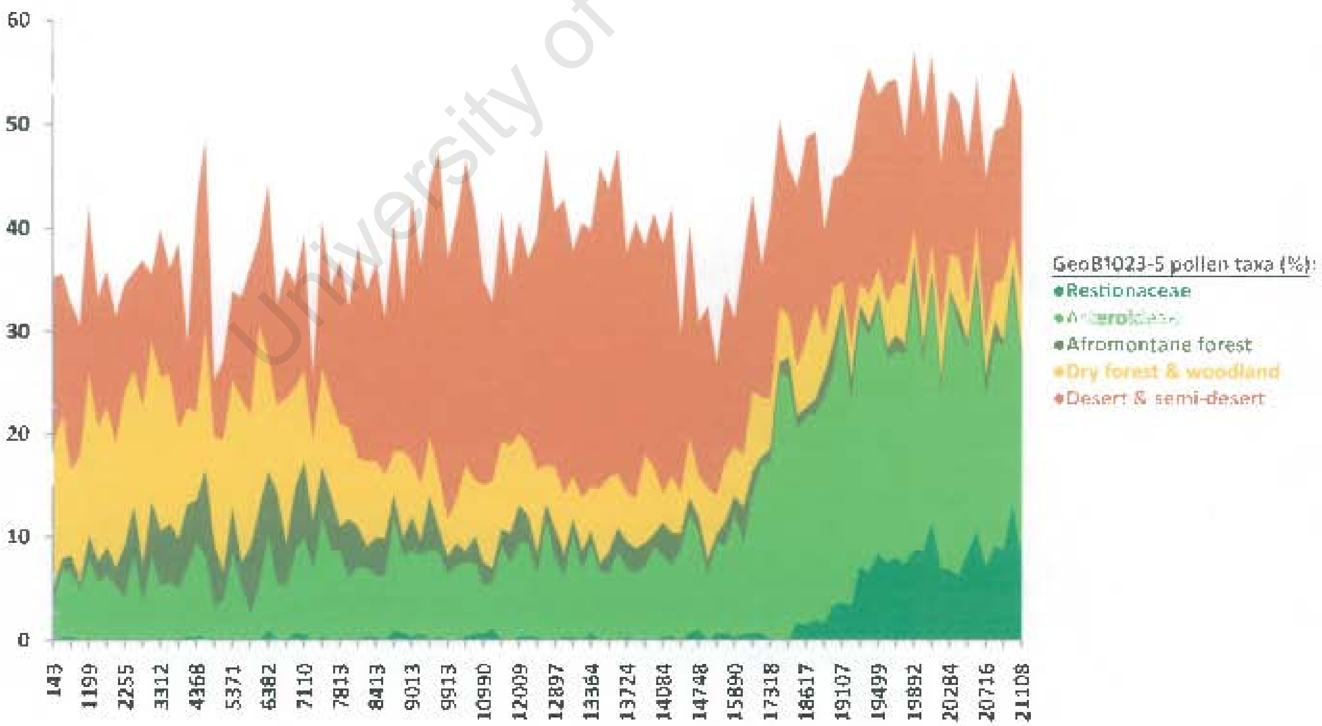


Figure 3.8: Pollen taxa percentages for marine cores GeoB1023-5 (Shi *et al.*, 2000)

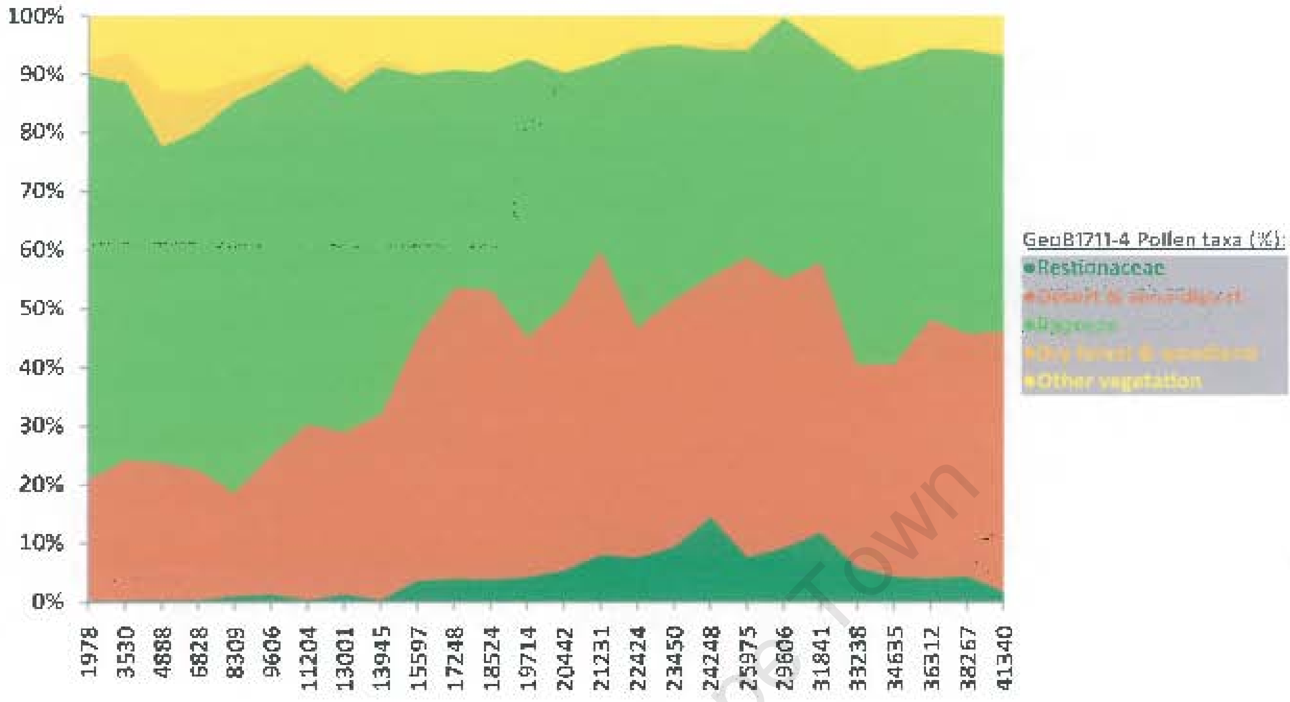


Figure 3.9: Pollen taxa percentages for marine cores GeoB1711-4 (Shi et al., 2001)

The peaks in Restionaceae pollen in the GeoB cores are followed by gradual declines until ~ 19 000 cal yr BP for GeoB1023-5 and 15 000 cal yr BP for GeoB1711-4, after which the frequencies drop off rapidly to negligible values (Shi *et al.*, 2000; 2001) (figures 3.8 and 3.9). Increases in desert, semi-desert and temperate pollen taxa in GeoB 1023-5 (Shi *et al.*, 2000) from 21 000 – 17 500 cal yr BP correspond to lowered SSTs in association with enhanced upwelling (Kim *et al.*, 2000).

It should be noted that the authors' interpretations of the pollen data derived from the above marine cores have been brought under question (Chase and Meadows, 2007). The changes to the pollen assemblages from these cores were most probably a response to variations in windiness as well as pollen transport regimes rather than a function of temperature and precipitation changes at the core sites. An increase in windiness would have resulted in more remote (often more mesic) taxa being brought to the sites whereas a decrease in windiness would have resulted in greater proportions of local xeric taxa being incorporated into these offshore assemblages. In addition, there are many taphonomical biases affecting pollen transport regimes over the continent with changing wind directions bringing different types of pollen from different parts of the continent to the core sites. Consequently, the overall pollen sequences are a result of a complex combination of these factors together with actually vegetation changes and therefore this data is susceptible to multiple interpretations until further evidence can be supplied.

3.3.3.2 Southern Cape palaeoenvironments

Sites situated along the southern Cape coast do not form part of the SWC or the modern WRZ but fall within the contemporary year-round rainfall zone (YRZ) as delineated in figure 2b. The palaeoenvironmental history of this region seems to have been influenced by changes in both the WRZ and the SRZ.

During the glacial period summer rainfall would have been reduced due to less effective monsoonal influences together with a variety of further climatic factors (outlined in Chase and Meadows, 2007). Evidence from Cape Agulhas (Carr *et al*., 2006), Boomplaas (Scholtz, 1986) and Vankersvelvlei (Irving, 1998) suggest that the WRZ extended its influence to the southern Cape during the late Pleistocene. Data from Boomplaas and Nelsons Bay Cave appear to support this theory with cooler and drier conditions prevailing during the period 21 500 – 17 000 cal yr (Avery, 1982, 1983; Klein, 1980, 1983, 1984; Butzer, 1984; Chase and Meadows, 2007).

From ~17 000 – 14 000 cal yr BP Scholtz (1986) claims that the southern Cape would have probably received maximum effective precipitation. This would have been most likely due to the region receiving enhanced winter rainfall together with increasing amounts of summer rainfall which would have led to a greatly reduced and less intense dry season (Chase and Meadows, 2007). From 14 000 cal yr BP a general drying trend is evident with the HA appearing to have been associated with reduced winter rainfall and warmer temperatures. This is inferred from the changing size of dune molerat remains from Byneskranskop, with molerat remains being greater in size during the period 14 500 – 11 000 cal yr BP in comparison to 7 300 cal yr BP (Klein, 1984). Warm, dry conditions at the HA are inferred from charcoal recovered from Boomplaas Cave dating to 7 300 cal yr BP (Scholtz, 1986). Greater moisture availability from increased winter rainfall together with decreased temperatures meant that after ~ 4 500 cal yr BP there was an expansion of forests towards the contemporary distribution.

3.4 SYNTHESIS OF SWC PALAEOENVIRONMENTS

As subsection 3.3.1 and 3.3.2 illustrates, the palaeoenvironmental evidence for the SWC is both spatially and temporally discontinuous. Despite the sparse evidence presently available, in conjunction with evidence outlined in subsection 3.3.3, it is possible to conclude the following:

The coastal lowland region of the SWC seems to have been subject to cool conditions with increased moisture availability during the late Pleistocene (Schalke, 1973; Klein and Cruz-Uribe, 2000; Parkington *et al.*, 2000).

Information obtained from the marine cores GeoB 1023-5, GeoB 1711-4 and MD962094 (Stuut *et al.*, 2002), together with evidence from Boegoeberg 1 (Klein *et al.*, 1999), the Brandberg (Scott *et al.*, 2004) and the Namib desert (Lancaster, 2002) provides further support for greater moisture availability along the western margin of southern Africa during the last glacial period. It should be noted that from the marine core data it is also evident that the LGM period was a transitional phase and therefore should not be considered the best representation of southern African glacial conditions.

A possible reason for increased moisture during the glacial period is related to the expansion of Antarctic sea ice. This would have led to the intensification and/ or expansion of the westerly wave belt resulting in more frequent or intense frontal systems which would have produced increased rainfall along the coastal areas within the SWC and further north (Stuut *et al.*, 2002; Chase and Meadows, 2007). The occurrence of the peaks in Restionaceae (a typical fynbos element) within cores GeoB 1023-5 and GeoB 1711-4 (Shi *et al.*, 2000, 2001) is consistent with the hypothesis of a northward extension of the WRZ during this period, although increases in trade winds and long-distance transport of pollen cannot yet be eliminated as a possible alternative explanation.

With few sites, the majority of which only cover parts of the Holocene, the overall palaeoenvironmental record for the mountainous region of the SWC is limited, the exception being the Pakhuis Pass sequence which extends beyond the LGM. This record suggests that the climate during the LGM in the Cederberg region was complex with the palynological evidence indicating that from 22 000 – 21 000 cal yr BP it was cold and relatively dry, while from 21 000 – 19 000 cal yr BP there was greater moisture and temperatures were possibly higher;

followed by a return to cool and dry conditions from 19 000 cal yr BP to 17 500 cal yr BP (Scott and Woodborne, 2007b)..

For the coastal lowland assembly of sites, inferences from Elands Bay point to an increase in temperatures towards the LGIT period with the early Holocene characterised by warm and humid conditions (Klein and Cruz-Uribe, 1987). The presence of a Younger Dryas event is not apparent in the low resolution terrestrial records but there is some indication from the marine record from Elands Bay of a lowering of SSTs during the period around 13 000 – 11 000 cal yr BP (Cohen *et al.*, 1992). Further north, the decline in Restionaceae within GeoB1023-5 and GeoB1711-4 in conjunction with an increase in xeric taxa from ~ 15 000 cal yr BP indicates a drying trend during the last glacial – interglacial period. A decrease in moisture along the western coastline moving out of the glacial period is most probably as a result of the reduced influence of the westerlies and a contraction in the extent of the WRZ (Chase and Meadows, 2007).

Pakhuis Pass, representing the only record from the montane region that covers the last glacial period, generally supports the idea that this period represents a transition phase to drier and warmer climates (Scott and Woodborne, 2007a,b). However the Pakhuis Pass sequence suggests that warmer and drier conditions only set in from 16 000 cal yr BP indicated by a sharp increase in *Dodonaea* (Scott and Woodborne, 2007a,b). The LGIT was a period of great variability within the Pakhuis Pass record, with fluctuations continuing into the early Holocene. Despite this variability, the record does indicate that the climate during the early Holocene in the Cederberg was similar to the coastal lowland's climate with warm and humid conditions prevailing until ~ 9 500 cal yr BP (Scott and Woodborne, 2007b).

The HA, like the LGM, is not well represented in the lowland records but Meadows and Baxter (1996, 2001) infer from the Verlorenvlei cores that conditions were warmer and drier than that of today. Evidence from all the montane sites support this inference made by Meadows and Baxter (1996, 2001) of a warm, dry HA (Baxter, 1989; Meadows and Sugden, 1990, 1991; Meadows and Baxter, 1999; Scott and Woodborne, 2007a,b; Selaine *et al.*, in review). This reduction in moisture availability at the HA was most probably associated with a decrease in the amount and/ or the intensity of frontal systems associated with a contraction of the westerly wave belt (Chase and Meadows, 2007).

For the lowland region, temperatures during the late Holocene were similar to present day but have been interpreted to be associated with greater moisture potential (Meadows and Baxter, 1999). This climatic phase was most likely the result of a relative increase in the influence of the westerlies after the HA. Evidence from the montane sites, particularly Pakhuis Pass, suggest that the late Holocene was generally warm and dry but included periods whereby greater amounts of moisture was available (Scott and Woodborne, 2007a,b; Selaine *et al.*, in review).

3.5 CONCLUSION

The palaeoenvironmental evidence presented in this chapter illustrates the discontinuous and often poorly-dated nature of the overall record and indicates that the entire region has not responded uniformly to climate changes during the late Quaternary. The lack of coherence among the records may reflect differences in the temporal and spatial resolution; but perhaps also changes in the seasonality of rainfall (e.g. southern Cape versus SWC palaeoenvironments), marked geographical variations within the region (e.g. lowland versus montane sites) and responses of individual ecosystems to climatic changes. Furthermore, due to the discontinuous nature of many of these archives as well as the insufficient resolution and length of them, previous interpretations have been formulated using information that is potentially equivocal. For example, many inferences have previously been made about the climate during the LGM period despite the fact that this period has been being poorly represented and inaccurately dated in many of the published records for this region. Therefore, a re-assessment of many of these records is required. This, together new palaeoenvironmental evidence for this region such as the data from De Rif, presented and discussed in this study, will provide new insight into the palaeoenvironmental history of the SWC.

4 Methods

4.1 INTRODUCTION

This chapter discusses the unique potential for the use of hyrax middens in the reconstruction of palaeoenvironments. The rationales behind the application of the selected analyses as well as the specific techniques used within these analyses are detailed within this chapter. The diagram below provides a summary of the overall methodological approach that is presented in the subsequent sub-sections.

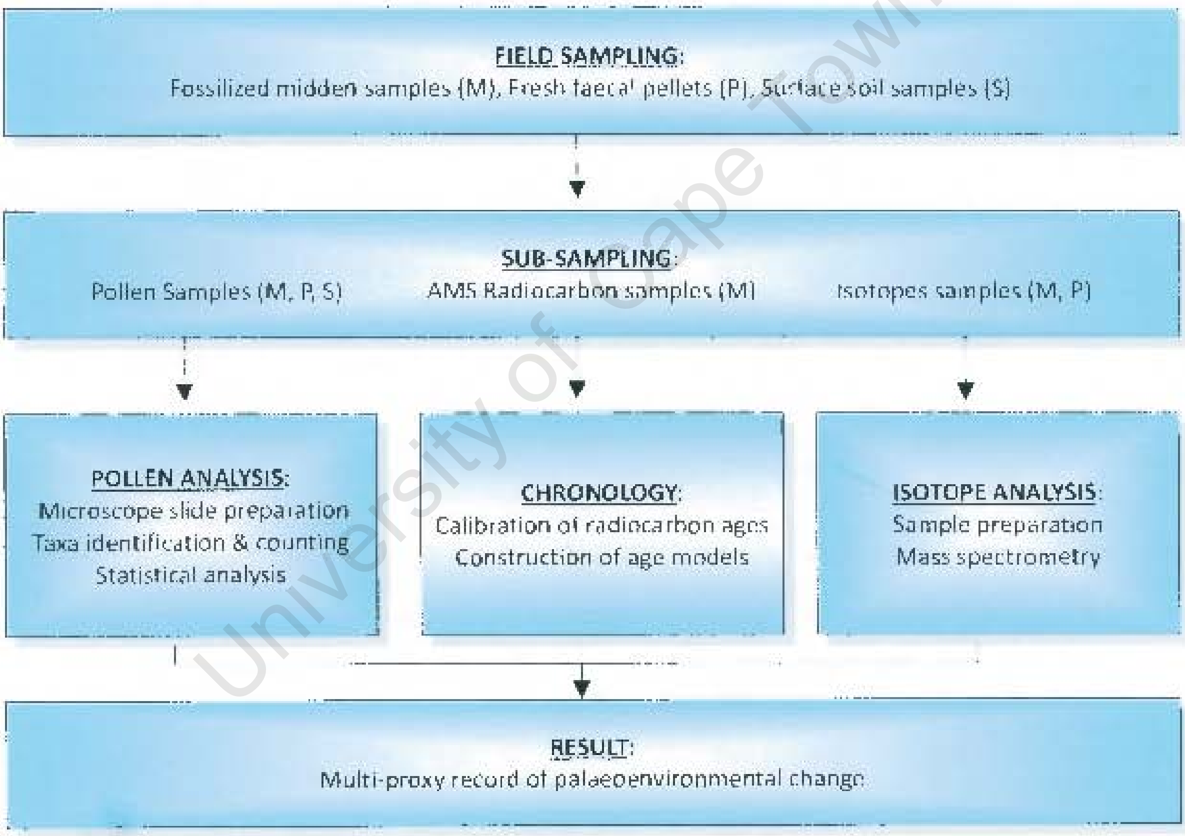


Figure 4.1: Summary of methodological approach

4.2 MIDDENS AS A KEY TO PAST ENVIRONMENTS

***"Middens have been a windfall to biogeographers [...], for whom the answers to many problems rest on knowing what species* [of plants] *used to live where and when"* (Diamond, 1991: 26).**

Palaeoenvironmental studies of arid and semi-arid regions are constrained by a dearth of suitable environments for the preservation of fossil plant material and pollen needed for the reconstruction of past vegetation histories in these areas (Fall *et al.*, 1990). However, herbivore middens[1] located in caves and rock shelters in these types of environments represent an important key to unlocking the nature and complexity of past vegetation change.

Middens act as time capsules, containing well-preserved datable fossil plant material and pollen grains that can be analysed in order to provide a reconstruction of the vegetation growing near the midden at the time that it accumulated. Inferences can then be made about the broader vegetation dynamics of the area and can provide extremely useful insight into the nature of regional climate variability (Betancourt *et al.*, 1990).

Palaeoenvironmental studies have been successfully carried out in North America using middens constructed by packrats (*Neotoma* spp.) and have resulted in an exceptionally detailed picture of environmental changes over the last 40 000 years for the region of the south-western United States (Betancourt *et al.*, 1990; Pearson and Betancourt, 2002). These studies have paved the way for the extension of midden research to dryland regions of several continents through the study of middens made by analogous species (e.g. Australia: Pearson and Dobson, 1993; Pearson, 1999. Peru: Holmgren, 2001. The Middle East, Jordan: Fall *et al.*, 1990).

4.2.1 Hyrax middens in southern Africa

In southwestern Africa, existing palaeoecological proxies are scarce and often discontinuous (Meadows and Baxter, 1999; Chase and Meadows, 2007) due to the lack of traditionally suitable palaeoenvironmental environments, such as peat bogs, lakes and wetlands for the preservation of palaeoecological proxy data sources, for example pollen

[1] Midden: originally an archaeological term, describing deposits formed by humans through the long term accumulation of waste and debris, applied in this context to animal deposits/nests consisting of waste material and debris accumulated over long time periods potentially forming stratified layers.

grains. Therefore, the potential use of middens as palaeoecological archives in southern Africa is considerable.

The potential of rock hyrax middens in palaeoenvironmental studies in southern Africa has previously been demonstrated by Scott and others through a range of studies carried out over the last two decades (Scott, 1994; Scott and Bousman, 1990; Scott and Cooremans, 1992; Scott *et al.*, 2004; Scott and Vogel, 2000; Scott and Woodbourne, 2007a,b). In South Africa rock hyrax populations (including *Procavia capensis*) are abundant at elevations from sea level to approximately 2 500 m (Scott, 1990b) and can be found throughout the Cederberg (figure 4.1). Their faeces accumulate in large piles in rock shelters that are occupied continuously for generations. Faecal pellets, together with hair, dust and pollen become cemented together by the hyraxes' highly concentrated urine (Maloiy and Eley, 1992) known as 'amberat' or 'hyraceum'; this process may form extensive middens (Scott, 1990a) under particular circumstances. The specific mechanisms by which pollen is trapped in these deposits is described in detail in section 4.2. Pollen sealed within these middens is protected from microbial decay and can be preserved for many thousands of years (Scott, 1996, Scott and Woodbourne, 2007a).

The key difference between similar middens found in other parts of the world and southern African hyrax middens is that, rather than being nests, hyrax middens are primarily urino-faecal deposits (Scott, 1990a). Studies by Scott (1994, 1996) have shown that, whereas packrat middens (nests) contain abundant macro-botanical remains, the processes of mastication and digestion generally result in hyrax middens containing very little identifiable macro-plant material (table 4.1). Thus whereas packrat middens are constructed relatively quickly and then indurated with urine, hyrax middens are deposited in successive layers over time, creating a stratigraphic proxy record of environmental change. More complex midden formations that are not just simple stratigraphic accumulations can, however also be found. For example middens formed laterally through leaching and filtration through rock and sand (Scott, 1990a); or when urine has flowed over the edge of a midden and has solidified, deposits form horizontally creating overhanging platforms (Scott, 1990b). These more complex formations highlight the fact that the style of midden accumulation is an important aspect that needs to be considered before sampling and interpretations can be made.

Figure 4.2: The distribution of hyraxes (Chase *et al.*, 2008). The present distribution refers to the areas within which hyraxes have been directly observed to inhabit; whereas the possible distribution represents areas that encompass habitats that are known to be favourable to hyraxes.

Table 4.1: Principal differences between hyrax middens and similar animals' middens (Betancourt *et al.*, 1990; Scott, 1990a,b; Scott and Bousman, 1990)

Hyrax Middens	Other middens (e.g. dassierat, packrats, stick nest rats)
Primarily urino-faecal deposits	Nests containing various forms of debris and waste
Consists predominately of micro plant material (e.g. pollen)	Dominated by macro plant remains
Not vulnerable to microbial decay as formed in semi-arid to arid environments and are sealed by hyraceum	Vulnerable to microbial decay especially in moist environments
No bioturbation (mixing by insects etc) occurs within middens as the hyraceum acts as a sealant and a repellent	Mixing of deposit by the midden builder itself as well as termites, beetles and ants
Is stratigraphically deposited	Little or no stratigraphy
High temporal resolution: can be preserved over long time periods	Low temporal resolution: represent single points in time

4.2.2 The sampling of hyrax middens

4.2.2.1 Field sampling

The location of potential hyrax middens within the Cederberg has been investigated and many possible sites have been identified. Although the location of midden sites within a region is a relatively random process, crevices and narrow caves within rocky outcrops on northerly-facing slopes are preferred (Scott and Cooremans, 1992). Hyraxes occupy these slopes to obtain maximum sunlight as they are poor thermoregulators (Maloiy and Eley, 1992). Knowing this specific biophysical trait as well as their preferred habitat, the identification of sites in the field can be simplified. The specific collection technique for sampling these midden deposits is determined by the nature and location of individual middens. As hyraceum often adheres strongly to the rock faces surrounding the midden, the removal of samples can be difficult and requires tools such as a hammer, large chisel and drill (figure 4.3). In some instances a portable generator and angle grinder have been used to remove larger samples (Chase *pers comm.*).

There are two general types of hyrax midden deposits classified on the basis of the degree of consistency within a midden – either highly urine-indurated cohesive middens or loosely cemented deposits (Scott, 1996). The usefulness and reliability of these two types as palaeoenvironmental tools may differ as a result of differential pollen content found within these middens. The consistency of the midden deposit also plays a role in the ease of extraction: if deposits contain predominantly pellets and smaller amounts of hyraceum, the midden tends to be very brittle and attempts at removing samples may result in crumbling. If middens are too large to successfully remove and transport in their entirety, representative, more manageable portions of the midden are then extracted and labelled.

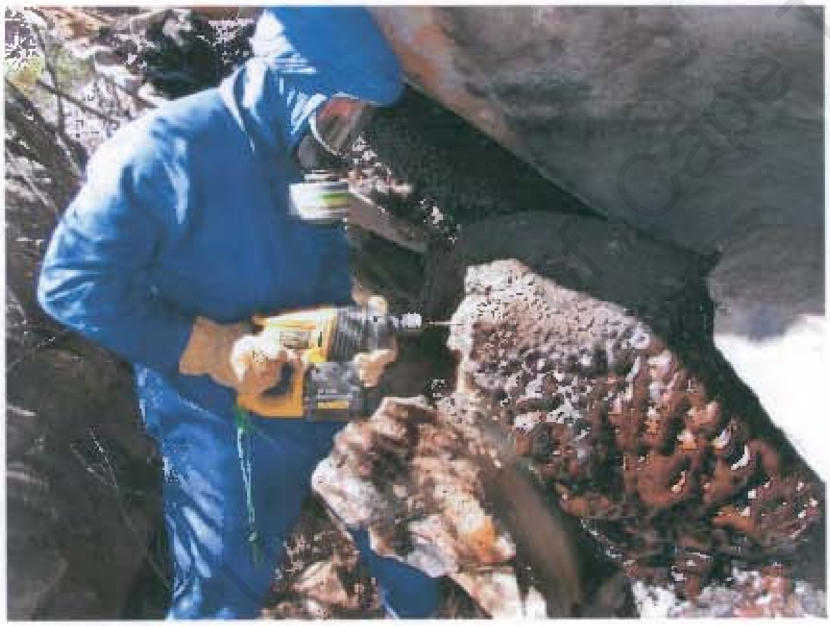


Figure 4.3: Removing DR2 from its rock crevice

In addition to the extraction and collection of the fossilized midden deposit, fresh hyrax faecal pellets were collected from the midden area to obtain and study modern pollen spectra for the site. Surface soil samples were also taken for pollen analysis

4.2.2.2 Sub-sampling

As hyrax middens accumulate over long periods of time it is possible to obtain high resolution records through precise sequential sub-sampling for both pollen and isotope analyses. To avoid contamination that may affect the subsequent analyses sub-sampling ideally takes place under controlled laboratory conditions. The exact temporal resolution achievable is different for pollen and isotope samples respectively and is described in the subsequent sections.

4.3 POLLEN ANALYSIS

4.3.1 Palynology as a palaeoenvironmental tool

Pollen analysis, also referred to as palynology, is one of the most widely used techniques for the reconstruction of Quaternary environments (Faegri and Iversen, 1989 Moore *et al.*, 1991; Lowe and Walker, 1997; Williams *et al.*, 1998, Chambers, 2002).

Palynology is the study of the structure and formation of pollen grains and spores as well as their dispersal and their preservation under certain environmental conditions (Moore *et al.*, 1991). Palynology has been used in a wide range of scientific studies including: taxonomy, genetic and evolutionary studies, forensic science, allergy studies and in palaeoenvironmental science (Moore *et al.*, 1991). One aspect of pollen analysis involves the study of fossil pollen grains. These types of studies are possible because of the extraordinary preservation of the outer layer of the pollen grain, the extine. The extine consists of a waxy coating called sporopollenin, which is resistant to microbial decay. This outer layer preserves pollen grains in ancient deposits and sediments when almost all other organic materials are reduced to unrecognisable components (Lowe and Walker, 1997). A second important trait of pollen grains is the distinct identifiable variations in the sculpting of the extine (Moore *et al.*, 1991). These two characteristics of pollen grains *viz.* the preservation and sculpting of the extine, make it possible to use palynology as a powerful empirical tool to reconstruct vegetation histories.

The reliability of palynology as a palaeoenvironmental tool is a function of:

- the robust preservation of pollen grains and their resistance to decay (Moore *et al.*, 1991),
- the wide dispersal of pollen grains and their presence in a broad range of environments such as lakes, peat deposits, soils, colluvium, alluvium, estuarine deposits and faecal material (Moore *et al.*, 1991),
- the relative ease of identification as a result of the distinctive structural patterning of the extine (Faegri and Iverson, 1989),
- the direct link between the identification of pollen grains and the parent plant.

Pollen grains are viewed under the light microscope and their correct identification hinges on discriminating between various structural types and sculpting types of the extine and, less reliable but sometimes indicative, features such as shape and size (Chambers, 2002). Preparation of samples for mounting on microscope slides is performed in the laboratory.

4.3.2 Application to hyrax midden material

As mentioned in section 4.2, hyrax middens contain micro plant material including pollen which is sealed and embedded in the midden by hyraceum (Scott, 1990; Scott and Bousman, 1990). Pollen becomes incorporated in the midden through a number of pathways (figure 4.5).

Midden samples have a distinct advantage over wetland deposits in that their pollen content is not masked by high proportions of environmentally undiagnostic hygric (aquatic) elements and provide direct insights in plant communities on rocky slopes, and thus is perhaps more representative of the broader environment (Scott, 1990b). This is because, while both wetland deposits and middens receive regional pollen inputs via long distance aeolian transport, wetland deposits have larger inputs from hygric elements (such as sedges). This could mask the signal of non-aquatics, which possibly could result in the deposit's record not relating to broader environmental change patterns. Whereas wetland deposits contain almost exclusively anemophilous (wind-dispersed) pollen, middens contain local pollen brought in on the hyraxes' fur and through their diet (figure 4.5). The preservation of this zoophilous (animal-dispersed) pollen in middens is a further advantage of middens over wetland deposits as these types of pollen may be an important element of the local vegetation.

An important caveat of palynological studies using hyrax midden samples is that it may be difficult to determine the relative contributions of pollen derived from these different sources within the midden deposits (Scott, 1990b). Scott and Bousman (1990) and Scott and Cooremans (1992), however conclude that pollen in hyrax middens presents a relatively accurate representation of regional pollen composition, but some work from the Cederberg (Seliane, 2006) suggests that significant differences may exist between the pollen found in pellets and the overall pollen rain. The extent to which dietary preference may bias the pollen spectra recovered from faecal pellets has yet to be completely resolved. For this study the focus is on analysing the pollen content of the hyraceum, which should be more representative of environmental conditions. In addition, the regional nature of the pollen composition suggests that, despite the input of some zoophilous pollen from the hyraxes' fur, anemorphilous types still represent the dominant component of the pollen spectra in hyrax middens (Scott and Woodbourne, 2007a). Therefore this factor should be taken into account when reconstructing vegetation histories and making ecological inferences.

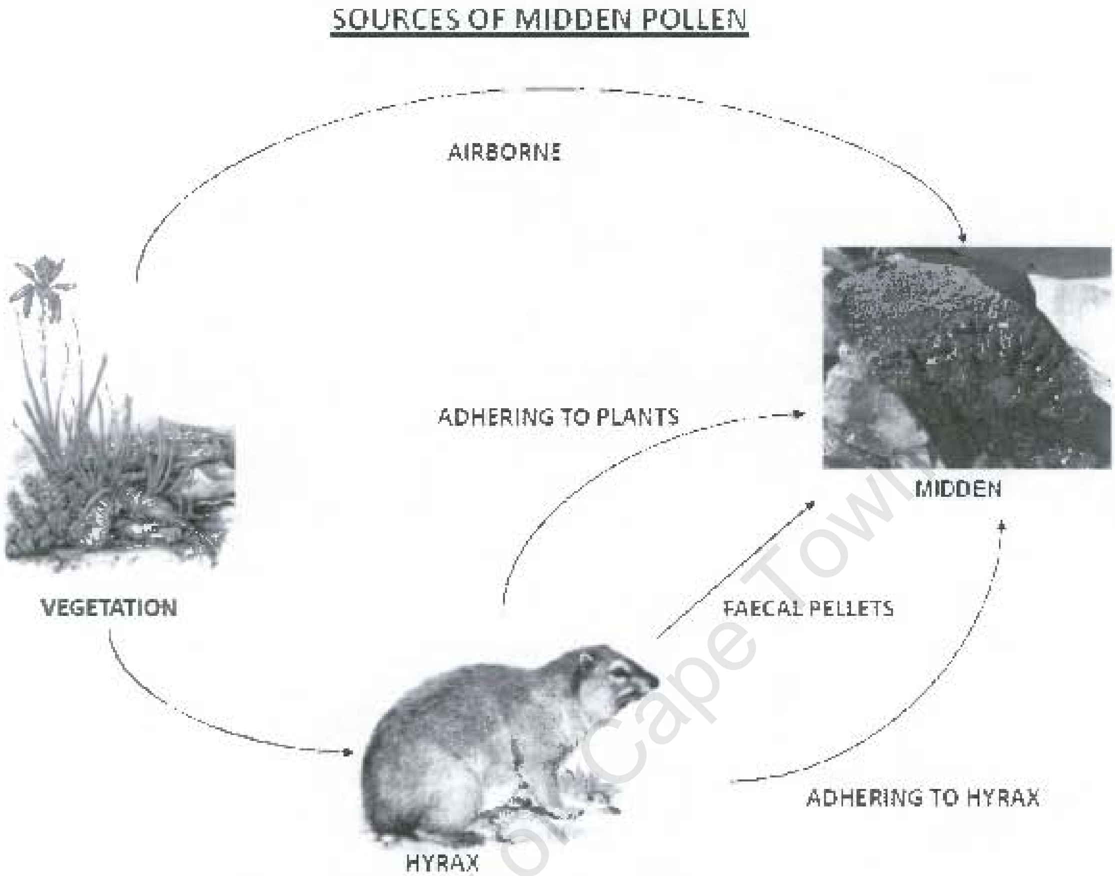


Figure 4.4: Pollen deposition and transport into middens

4.3.3 Sample preparation, laboratory procedures and chemical treatment

To ensure minimum contamination surfaces of the middens which were previously exposed, are cut and polished to create new sampling sections. Thorough investigation of the nature of the middens' accumulation needs to be conducted before creating a new surface, as once a surface has been cut it becomes difficult to observe the laminations that are evident when the midden is fractured along natural weaknesses

Figure 4.5: Pollen sampling using dental saw

Pollen sampling employed a dental saw to remove 5-10 mm thick blocks of material, each weighing between 1-2 g. The extraction of pollen from midden samples follows a similar methodological approach to the standard pollen analysis methods applied to wetland deposits (Scott and Woodborne, 2007a). Pollen is extracted from samples firstly through 10% KOH digestion followed by a heavy liquid mineral separation using $ZnCl_2$ at a specific gravity of 2.0 to separate the pollen grains from the mineral fraction (Faegri and Iversen, 1989; Scott and Bousman, 1990; Scott and Woodborne, 2007a) (See Appendix B).

To determine absolute counts and pollen concentrations, exotic pollen - *Lycopodium* spores are added (Stockmarr, 1973). The samples are also stained using *Safrinine* then mounted in glycerine jelly. Pollen counts of at least 250 grains per sample are carried out under the microscope at a magnification of 400x. Identification of pollen taxa is made possible using the University of Cape Town's pollen reference slide and photograph collection housed in the department of Environmental and Geographical Science.

4.3.4 Data representation

The results of the pollen analyses are presented graphically in the form of standard pollen diagrams using the *Tilia* software package, within which the data can be plotted against stratigraphic layer/depth and calibrated radiocarbon ages.

4.3.5 Data analysis

Various multivariate techniques to ordinate the pollen data have been used in the past (Birks, 1986; Prentice, 1986; Meadows and Sugden, 1991). The two primary statistical methods applied to pollen records extracted from hyrax middens include detrended correspondence analysis – DCA (Scott and Woodborne, 2007a; Gil-Romera *et al.*, 2007) and principal component analysis – PCA (Scott and Woodborne, 2007b). PCA has proven to be the most appropriate technique as it reduces multidimensional data sets to lower dimensions, reveals the underlying structure within the data and is comparable to other PCA data (Scott and Woodborne, 2007a). Therefore this project uses PCA (programme STATISTICA 8) for the statistical analysis of De Rif's pollen data.

4.3.6 Limitations of pollen analysis

Despite the input of some zoophilous pollen incorporated into the midden by the hyrax; as in most pollen records, the identified taxa are most probably those that have high pollen production and are well dispersed by wind (Scott and Woodbourne, 2007a). Therefore the inherent differential production and dispersal, as well as differences in accumulation and preservation of pollen types, are taken into account when interpreting results (Chambers, 2002).

General palynological shortcomings that are considered include; the presence of pollen taxa in the record for which no modern analogue exists, as well as unidentifiable taxa which have been damaged. A further limitation of pollen analysis is the difficulty of identifying pollen to the species level. However, through studying surface pollen surveys, it can be seen that a combination of a few prominent taxa can be characteristic of certain vegetation types and environmental conditions (Meadows and Sugden, 1991; Scott and

Cooremans, 1992). In addition, any shortcomings in the pollen analysis are supported by the results of the following analyses.

4.4 CHARCOAL ANALYSIS

The quantification of the accumulation of charcoal fragments preserved in lake sediments and other palaeoecological reserves are commonly used to investigate the occurrence and nature of past fires (Tinner and Hu, 2003; Sadori and Giardini, 2007). Microscopic charcoal particles are incorporated into middens in a similar manner to pollen grains *viz.* aeolian transport and saltation. The laboratory preparation used in pollen extraction from midden material (section 4.3.3) also preserves charcoal, making it possible to count charcoal particles and pollen grains simultaneously. The combination of charcoal and pollen analyses can establish relationships between fire regimes, vegetation changes and climate.

Charcoal particles were identified and counted on all pollen microscope slides analysed. Only fragments that were black, opaque and angular were counted. Tinner and Hu (2003) investigate two methods of quantifying charcoal presence and concluded that both methods (area measurements and particle counts) produced similar trends. Therefore counts of charcoal fragments >75 μm^2 (or ~ 10 µm long) were carried out as it represented the fastest and most reliable method (Tinner and Hu, 2003).

4.5 STABLE ISOTOPE GEOCHEMISTRY

4.5.1 Principles of stable isotope analysis

Isotopes are naturally occurring forms of the same element that differ in the number of neutrons in their nucleus. Stable isotopes are isotopes that do not undergo radioactive decay. Stable isotopes of the same element have the same chemical characteristics. The mass differences (due to the difference in the number of neutrons in the nucleus) of isotopes affect reaction kinetics and bond energies. These differences result in partial separation of the light isotopes from the heavy ones during chemical reactions. This is known as isotope fractionation (or isotopic discrimination). As a consequence of the fractionation process, substances often develop unique isotopic compositions (ratios of heavy to light isotopes) that may be indicative of the nature and source of the substance or of the processes that formed them (Dawson and Brooks, 2001). The applications of stable isotope analyses have been successfully used as a sound quantitative method in botanical, plant physiological, archaeological and ecological studies for many years (West, 2006).

Stable isotopes are expressed as "delta" (δ) values in parts per mil, also known as parts per thousand, (‰) enrichments or depletions relative to a standard of known composition (the PDB marine limestone for carbon and atmospheric (AIR) N, for nitrogen) (Fry, 2006). δ values are calculated by the following generalized equation:

$$(\text{in ‰}) = (R_{sample}/R_{standard} - 1)/1000$$

where "R" is the ratio of the heavy to light isotope in the sample or standard.

A positive δ value means that the sample contains more of the heavy isotope compared to the standard, known as an 'enriched' signal, while a negative δ value means that the sample contains less of the heavy isotope than the standard, therefore a 'depleted' signal (Dawson and Brooks, 2001).

The isotopic ratio of an element in a system not only reflects the source ratio of the element, but also any fractionation that may occur within the system or across its boundaries. These stable isotope ratios act as recorders or tracers in biotic and abiotic molecules, as δ values provide specific isotopic signatures that can be used to; "...trace the movements of nutrients, particles and organisms across landscapes and between components of the biosphere, and to reconstruct aspects of dietary, ecological and environmental histories" (West 2006: 408).

4.5.2 Stable carbon isotopes

The stable carbon isotopes ^{12}C and ^{13}C are unevenly distributed among and within different components of ecosystems. The distribution of these isotopes can reveal information about the physical, chemical and metabolic processes involved in carbon fractionations (Farquhar *et al.*, 1989a,b).

4.5.2.1 Stable carbon isotopic signatures of vegetation

Stable carbon fractionation is well documented in plants (Smith, 1972) and is a result of the photosynthetic process, which is dictated by the pattern of photosynthesis in which the plant species is engaging (O'Leary 1981; Farquhar *et al.*; 1989b; Cerling *et al.*, 1991; Dawson and Brooks, 2001). C_3 (Calvin), C_4 (Hatch-Slack), and CAM (Crassulacean acid metabolism) photosynthetic pathways all have different mechanisms of processing atmospheric CO_2 and consequently have different $\delta^{13}C$ values (Smith and Epstein, 1971) (table 4.2).

During photosynthesis, C_3 plants form a three carbon molecule, while C_4 and CAM plants form a four carbon molecule (Smith, 1972). In high temperature or strong sunlight conditions, C_4 and CAM plants are photosynthetically more efficient than C_3, confirmed by Ambrose and DeNiro (1986b) who show that in colder, shaded, high latitude or altitude regions, C_3 plants are shown to be more dominant. C_3 plants include trees, shrubs and temperate grasses whereas tropical grasses are C_4 species. CAM plants are mostly succulents. In southern Africa, C_3 plants are more abundant in the winter rainfall areas and include fynbos, while C_4 grasses are more common in the summer rainfall areas (Stock *et al.*, 2004).

Marine and terrestrial plants are depleted in ^{13}C relative to their carbon source, the atmosphere and the $\delta^{13}C$ standard - PBD (Park and Epstein, 1961). During photosynthesis, plants discriminate against ^{13}C and preferentially fix more ^{12}C CO_2 (Park and Epstein, 1961). The average $\delta^{13}C$ value of C_3 plants is approximately -27 ‰ and the average $\delta\ ^{13}C$ value of C_4 plants is about -13 ‰ (Sternberg and DeNiro, 1983; Ambrose, 1986a, b; Heaton *et al.*, 1986; O' Leary, 1981; Ehleringer *et al.*, 1997) (table 4.2). CAM plants have $\delta^{13}C$ values varying between C_3 to C_4 values: 'Obligate' CAM plants, which operate by fixing CO_2 at night, have $\delta^{13}C$ values similar to C_4 plants (Pate, 2001). Whereas, 'facultative' CAM plants – species that can shift between C_3 and CAM type photosynthesis depending on the conditions – have $\delta^{13}C$ values similar to C_3 plants when under well-watered conditions but under dry or saline environments they have values resembling C_4 plants (Pate, 2001; Ehleringer, 1989).

Carbon isotope signatures in plants are also influenced by water-use efficiency[2] (WUE) (Farquhar and Richards, 1984). Farquhar *et al.* (1989a) identified a broad relationship between $\delta^{13}C$ values of plants and their WUE. In general, the more negative the $\delta^{13}C$ value of a plant, the poorer the WUE is for that plant. Conversely, plants with high WUE should be enriched in ^{13}C relative to those with lower WUE (Farquhar and Richards, 1984, Farquhar *et al.*, 1989a).

Table 4.2: Summary of principal differences in carbon isotope discrimination and water-use efficiency (after Pate, 2001).

PLANT TYPE	$\delta^{13}C$ (‰)	WUE (mL H_2O transpired per g dry matter gain)	Characteristics
C_3 (e.g. fynbos)	-20‰ to -28‰	400 – 600	Use Calvin Cycle with Rubisco to fix CO_2 in leaf. Perform best at moderate temperatures and light intensities.
C_4 (e.g. tropical grasses)	-9‰ to -14‰	200 – 300	Use PEP carboxylase to fix CO_2 in leaf. More efficient water users than C_3 plants especially at high temperatures.
CAM/C_3 (e.g. succulents)	Same as C_4 plants when operating in CAM mode and close to C_3 plants when in C_3 mode	50 (when in CAM mode)	Fix CO_2 at night using PEP carboxylase. Succulent and very slow growing in CAM mode. Can convert to C_3 when water is available and/ salinity is reduced.

Carbon isotopic composition of C_3 vegetation has been shown to correlate negatively with rainfall over continental and landscape gradients (Ehleringer and Cooper, 1988; Ehleringer, 1992; Stewart *et al.*, 1995; Schultze *et al.* 1998; Miller *et al.*, 2001). This relationship is principally due to the effect of water availability on ^{13}C discrimination in leaves of C_3 plants (Farquhar *et al.*, 1989b) which then translates to community and landscape scales (Kaplan *et al.*, 2002). However the relationship between $\delta^{13}C$ and

[2] WUE: the efficiency with which plant dry matter is laid down relative to amounts of water which the plant transpires – measured in terms of water transpired per unit dry matter gain (Pate, 2001)

precipitation (or any other measure of water availability) is not constant at the community level (Schnyder *et al.*, 2006). Therefore the $\delta^{13}C$ values from plants have not been found to reliably show any significant direct relationship with environmental factors such as temperature (Smith, 1972) or precipitation (Swap *et al.*, 2004).

4.5.2.2 Carbon isotopic variation in animals: application to hyrax middens

Stable carbon isotope signatures within animals' tissues reflect those of their diet (DeNiro and Epstein, 1978a and b; Vogel, 1978; Schoeringer and DeNiro, 1983). The $\delta^{13}C$ values from animal's tissues can provide an integrated measure of the $\delta^{13}C$ discrimination within a plant community or for a certain landscape (Vogel and van der Merwe, 1977; Cerling and Harris, 1999). Animal tissue $\delta^{13}C$ therefore represents a better measure of $\delta^{13}C$ variations within plant communities than the specific $\delta^{13}C$ of individual plants. This is because small-scale variations affecting the $\delta^{13}C$ of individual plants are integrated within animal $\delta^{13}C$ signatures resulting in averaged, more representative values.

Stable carbon analysis using variations of $\delta^{13}C$ values in animal tissues is commonly used to examine dietary shifts and feeding behaviour of animals and humans and can indicate environmental changes through recording changes in habitat utilisation by herbivores (e.g. herbivore tooth collagen (Vogel, 1983) and tooth enamel (Lee-Thorp and Beaumont, 1995; Cerling *et al.*, 1997; Sponheimer and Lee-Thorp, 1999; Balasse *et al.*, 2002)). Researchers have also used carbon isotope analysis to discriminate between grazers and browsers (Ambrose and DeNiro 1986a), forest and savanna species (Smith and Epstein 1971; Ambrose and DeNiro, 1986a), forest floor and canopy species (Ambrose and DeNiro 1986a), terrestrial and marine food sources (Smith and Epstein, 1971; Heaton *et al.* 1986).

This analysis hinges on the distinct differences in $\delta^{13}C$ values of C_3, C_4 and CAM plants (table 4.2). The dominance of these vegetation types in the landscape varies as a function of temperature, precipitation and seasonality, and atmospheric CO_2 concentrations (Ehleringer *et al.*, 1997). Therefore the differences in the ecological tolerances between C_3 and C_4 plants can be determined from their carbon isotope signals: "Since the two groups of plant are isotopically distinct these differences are passed along the food chain to animal eating the various plants, with some further fractionation" (Sillen and Lee-Thorp, 1994).

As hyrax middens are indicators of fossil diet (Scott and Vogel, 2000) the application of stable carbon isotope analysis to these samples can register palaeoenvironmental changes. It must be noted that the stable carbon isotope values are only indirect indicators of palaeoenvironmental changes as they record the variation in the amounts of C_3, C_4 and CAM plants in the hyraxes' diets. Therefore they primarily reflect the hyraxes' dietary selection (Scott and Vogel, 2000). However as hyraxes have wide dietary preferences (as many as 79 species of grass, shrubs and trees (Hoeck, 1975)) their diet is representative of the local vegetation. Therefore, changes in a hyrax population's diets would be a result of changes in the local vegetation and if a change is recorded over a larger area, stable carbon isotope signals can possibly reflect regional environmental change patterns (Scott and Vogel, 2000).

In summary, the $\delta^{13}C$ signal recorded in hyrax midden material can provide a spatially integrated indicator of the changing dominance of either C_3 or C_4 vegetation in the landscape over time. More specifically, $\delta^{13}C$ variations in hyrax midden material located within predominately C_3 vegetated areas (like the Cederberg (Vogel, 1978)) can signify changes in plant water-use efficiencies. Changes in water availability and associated broader environmental conditions for plant communities can then be inferred from this signal.

4.5.3 Stable nitrogen isotopes

Nitrogen (N) is present as N_2 gas in the atmosphere, is well mixed and essentially has a $\delta^{15}N$[3] value of 0‰. Large variation in $\delta^{15}N$ values is evident, within and between ecosystems and their components, relative to the nitrogen isotopic composition of the atmosphere (Ambrose, 1991). Estimation of nitrogen isotopic discrimination can be complex (Adams and Sterner, 2000; Robbins *et al.*, 2005).

Enrichment and depletion in $\delta^{15}N$ values can be attributed to a variety of biochemical and physical processes occurring firstly within the soil profile, then with the plants and

[3] $\delta\ ^{15}N$: the abundance of the heavier nitrogen isotope, ^{15}N, relative to the lighter one, ^{14}N

finally the animals that eat the plants [Processes reviewed in: Hoering, 1955; Shearer and Kohl, 1978; Letolle, 1980; Schoeninger and DeNiro, 1984; Heaton, 1986]

4.5.3.1 Stable nitrogen isotopic variations in vegetation

Plant nitrogen (N) isotopic discrimination is influenced by the net effect of a range of processes relating to the availability of water and nutrients (Tilman, 1988, Dawson *et al.*, 2002) and is indicative of N cycling on different spatial and temporal scales (Nadelhoffer and Fry, 1994). These processes predominately occur within the soil profile, $\delta^{15}N$ soil values therefore influence the $\delta^{15}N$ values of the vegetation.

Plant $\delta^{15}N$ values have a negative relationship with water availability; that is, $\delta^{15}N$ values for vegetation (and soils, Aranibar *et al.*, 2004) are more depleted with increasing precipitation (Heaton, 1987; Austin and Vitousek, 1998; 2004; Handley *et al.*, 1999). This phenomenon has been observed on both regional (Shearer *et al.*, 1978; Heaton *et al.*, 1986, Heaton, 1987; Vogel, 1990; Austin and Vitousek, 1998; Aranibar *et al.*, 2004; Swap *et al.*, 2004) and global (Schulze *et al.*, 1991; Handley *et al.*, 1999; Amundson *et al.*, 2003) scales.

The progressively depleted $\delta^{15}N$ signature in both soil and vegetation with increasing precipitation suggests that N cycling is more open in xeric areas (Cook, 2001; Austin and Vitousek, 1998). In spite of potentially more rapid turnover in these areas, accumulated losses of N relative to N pools are greater (Handley *et* al., 1999). These losses occur when N (enriched in ^{14}N relative to soil) is lost through leaching and N gaseous exchanges, which results in the N that is remaining in the system being ^{15}N-enriched. In mesic areas, most of the N is accumulated in both live and dead biomass. The remaining N pool is therefore small (there are fewer losses relative to turnover) and the system becomes less enriched in ^{15}N. Consequently, more closed N cycling occurs in these wetter environments (Austin and Vitousek, 1998; Handley *et al.*, 1999).

Aranibar *et al.* (2004) supports the above 'openness' theory that ^{15}N-enrichment occurs in plants and soils in arid areas. They also found that soil organic carbon and C:N ratios decrease with aridity. This is probably due to lower biomass (increase of grasses and a decrease of woody vegetation) supporting the idea of lower internal recycling. Therefore, as observed, ^{15}N enrichment occurs with decreasing precipitation. Low C:N ratios in arid areas would enhance processes that cause N losses enriching the soil in ^{15}N (Brady and Weil; 1999). These studies highlight that although N cycling at regional levels involves many complex processes, spatial and temporal variability of precipitation play a significant role on isotope signatures and N cycling in the soil-plant system.

4.5.3.2 Stable nitrogen isotope signals in animals

$\delta^{15}N$ values are most commonly used to record dietary behaviour and provide trophic level information in animals (Ambrose and DeNiro, 1986a, b; 1989). A 3 - 4 ‰ enrichment in ^{15}N along each level in the food chain has been observed, meaning that carnivores have higher $\delta^{15}N$ values than herbivores which have higher values than plants (Wada *et al.*, 1975; DeNiro and Epstein, 1981; Minagawa and Wada, 1984; Schoeninger and De Niro, 1984; Schoeninger, 1985; Sealy *et al.*, 1987; Sponheimer *et al.*, 2003b). This enrichment with increasing trophic level in an ecosystem can be used to determine trophic position. However the mechanism producing this trophic level enrichment is poorly understood.

Herbivore $\delta^{15}N$ values are strongly affected by environmental factors, particularly water availability (Heaton *et al.*, 1986). A negative relationship between $\delta^{15}N$ bone collagen and water availability has been demonstrated in African (Heaton *et al.*, 1986; Sealy *et al.*, 1987), Australian (Grocke *et al.*, 1997; Murphy and Bowman, 2006), European (Iacumin *et al.*, 1997; Iacumin *et al.*, 2000; Stevens *et al.*, 2008) and North American (Cormie and Schwarcz, 1996) herbivores. As the $\delta^{15}N$ signal is preserved in fossil animal material (such as herbivore bone collagen and for this project, hyraceum), these animal $\delta^{15}N$ signatures can be used to investigate past climate change and reconstruct palaeoenvironmental conditions (Ambrose and DeNiro, 1986a, b; 1989).

This relationship between $\delta^{15}N$ in animal material and water availability is thought to exist because of the negative relationship between plant $\delta^{15}N$ and water availability, or the direct effect of water stress on the nitrogen metabolism of animals or a combination of both these theories.

A number of authors have thought that the affect of an increase in $\delta^{15}N$ values in plants with decreasing water availability is insufficient to cause the increase in $\delta^{15}N$ in herbivores that eat these plants (Ambrose and DeNiro, 1986a, b; Sealy *et al.*, 1987;

Ambrose, 1991). Models have proposed that the animal's metabolism is directly responsible for strong isotopic discrimination in arid areas (Ambrose and DeNiro, 1986a, b; Sealy *et al.,* 1987; Ambrose, 1991). These hypotheses centre around the fact that herbivores from arid environments may have low drinking water requirements and conserve water by excreting urine with a high concentration of ^{15}N-depleted urea, leading to increased animal $\delta^{15}N$ (Ambrose and DeNiro, 1986a, b; Ambrose, 1991). Sealy *et al.* (1987) postulate that in addition, to urea recycling in animals in arid areas, another physiological process involving the production and digestion of symbiotic bacteria in the digestive tract, might lead to an increase in $\delta^{15}N$. Subsequent studies have recently contended the influence that animal metabolisms have on animal $\delta^{15}N$ values in favour of direct environmental controls (Sutoh *et* al., 1993; Ponsard and Averbuch, 1999; Schwartz *et al.*, 1999; Iacumin *et al.*, 2000; Stevens and Hedges, 2004; Murphy and Bowman, 2006; Mannel *et al.*, 2007).

Murphy and Bowman (2006) examined the variation in $\delta^{15}N$ of both grass and herbivore (kangaroo) bone collagen across Australia. They assessed whether the offset between grass and bone collagen $\delta^{15}N$ values was constant with respect to water availability. They found that both grass and bone collagen $\delta^{15}N$ showed a strong negative (non-linear) correlation with water availability (figure 4.7). The slopes of these correlations were similar and there was a near-constant offset between grass and collagen $\delta^{15}N$ (Murphy and Bowman, 2006). This result supports the idea that metabolic processes have little discernable effect on herbivore $\delta^{15}N$ and that dietary $\delta^{15}N$ is the primary cause of a negative relationship between $\delta^{15}N$ in animals and water availability.

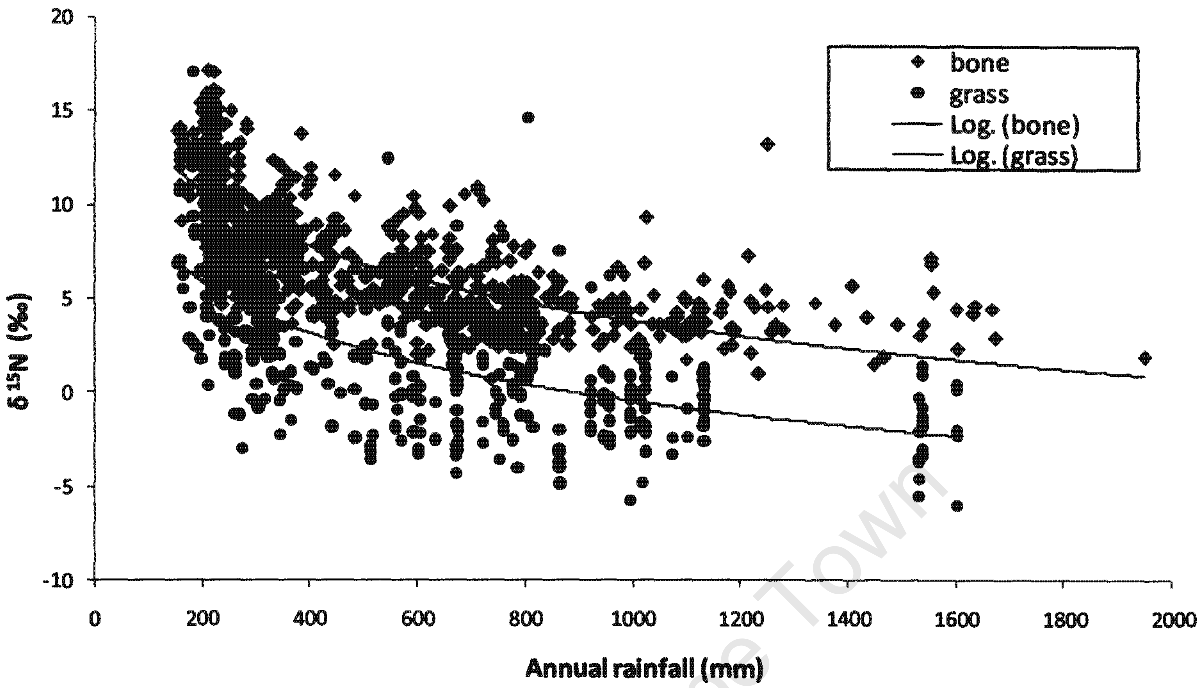


Figure 4.7: The relationship between animal tissue and vegetation $\delta^{15}N$ values and precipitation (Murphy and Bowman, 2006)

It can be concluded that animal metabolism does not seem to directly affect the relationship between $\delta^{15}N$ and rainfall, as strong correlations between enriched $\delta^{15}N$ and rainfall in C_3 (Swap *et al.*, 2004) and C4 vegetation (Murphy and Bowman, 2006) and soils (Aranibar *et al.*, 2004; Handley *et al.*, 1999) have been identified. The mechanisms for the observed link between $\delta^{15}N$ and rainfall have not been clearly established, but are thought to relate to the relative 'openness' of the N cycle (as outlined in section 4.5.3.1) which in turn is controlled by climate (Stevens *et al.*, 2008).

4.5.3.3. The application of stable nitrogen isotope analysis to hyrax middens

Urinary urea is the major form within which mammals excrete nitrogen (Ambrose, 1986). Researchers that subscribe to the theory that the metabolism of animals is directly responsible for the $\delta^{15}N$ enrichment in animal tissue with increasing aridity argue that, as the animals are $\delta^{15}N$-enriched their urine becomes depleted in $\delta^{15}N$ (Ambrose and DeNiro, 1986a, b, Ambrose, 1991).

hyraxes. The outcome of this experiment was that there was no significant fractionation between the isotopic values of the hyraxes feed and their urine. Despite the multitude of physiological, anatomical, and dietary factors that potentially govern herbivore $\delta^{15}N$ values, this supplementary study shows that it is possible to disregard the metabolism hypothesis when studying the isotopic variation found in hyrax middens. It therefore provides quantitative substantiation for the current interpretation of both carbon and nitrogen isotope signals of hyrax midden material.

In summary, N isotopic signatures reported for precipitation gradients in various locations around the world have shown an enrichment of ^{15}N in soil, plant and animal samples associated with arid regions (Shearer *et al.*, 1978; Heaton *et al.*, 1986, Heaton, 1987; Sealy, 1987; Vogel, 1990; Schulze *et al.*, 1991; Evans and Ehleringer, 1993, 1994; Handley *et al.*, 1999; Amundson *et al.*, 2003; Aranibar *et al.*, 2004; Swap *et al.*, 2004). Therefore $\delta^{15}N$ variations within hyrax midden material can be used to identify periods of aridity, as they reflect the $\delta^{15}N$ signatures of the plants consumed by the hyraxes.

Given the nature of hyraxes – specifically their wide dietary preferences and restricted range (they remain within a radius of 60 m from their shelters (Sale, 1965)) – and the large proportions of time incorporated in samples taken from midden deposits, the stable carbon and nitrogen content of hyrax middens represent an excellent integrated proxy for studying environmental variability.

4.5.4 Sub-sampling for isotope samples

As midden material is highly stratified, sequential isotope sampling with depth can take place at a potentially high temporal resolution. Sub-sampling for isotope analysis can be conducted at a much higher resolution than pollen sub-sampling as the amount of material needed for analysis is considerably smaller (~ 2 mg). Sampling of midden deposits for isotope analysis at can be taken every ~ 1 to 3 mm using a *Dremel MultiPro* drill with a diamond-tipped dental drill (Chase, unpublished) (figure 4.7). Samples (the dust that originates from the drill holes) are collected and placed in air-tight centrifuge tubes and labelled accordingly.

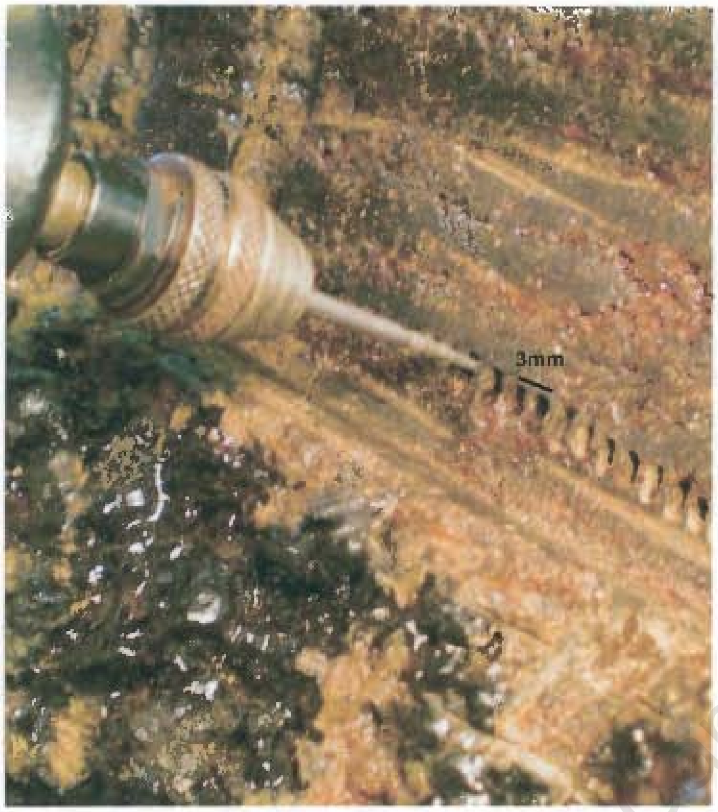


Figure 4.8: Isotope sub-sampling

4.5.5 Laboratory preparation and analysis

Stable isotope analyses are carried out in specialized laboratories using isotope ratio mass spectrometry. Conventional laboratory preparation for both the samples and the standards (chocolate and Valine) took place in the Department of Archaeology's Archaeometry Research Unit. Samples were then analysed with a Thermo Finningan Delta Plus XP mass spectrometer connected to a Thermo Flash EA 1112 by a Conflo III device.

4.6 RADIOCARBON ANALYSIS: ESTABLISHING CHRONOLOGIES

Radiocarbon (^{14}C) dating is the most appropriate dating technique to obtain absolute chronologies as hyrax middens are very rich in organic material. Samples from the selected middens were taken and sent to an appropriate laboratory for analysis. Samples of about 25 g were removed from the top and the bottom section of each midden sample respectively for conventional radiocarbon dating. In addition, approximately 1 g of material is taken from relevant depths (decided according to the isotope results) for AMS (Accelerated Mass Spectrometry) radiocarbon dating in order to construct a higher resolution age-depth model.

Holocene ages were calibrated by means of version 1.5 of the CALIB programme (Stuiver and Reimer, 1993) using the SHcal04 calibration curve (McCormac *et al.*, 2004). The SHcal04 calibration curve was selected as it was specifically formulated for age calibration in the Southern Hemisphere and is the most suitable curve for the Holocene *viz.* for ages between 0 – 11 000 cal yr BP (McCormac *et al.*, 2004). Late Pleistocene ages (beyond 11 000 cal yr BP) were calibrated by means of the programme CalPal using the CalPal-2007-Hulu curve (Weninger and Joris, 2004). The programmes used for calibration converts radiocarbon ages to calibrated calendar years by calculating the probability distribution of the sample's true age.

4.5 CONCLUSION

Middens are very useful archives of palaeoenvironmental information. Hyrax middens are particularly potent palaeoenvironmental tools due to the specific nature and formation of these middens and their location in arid and semi-arid areas where other palaeoenvironmental proxies are scarce. This chapter has illustrated how the application of both palynology and isotope geochemistry to hyrax middens provides detailed quantitative information on past vegetation communities and climate induced variability for a given location. The results of these well-defined analyses for De Rif are presented in the next chapter.

5 Results

5.1 INTRODUCTION

Having described the midden formation, the contemporary and palaeoenvironmental context of the Cederberg and the sampling, laboratory and analytical methods employed, results of the analyses are now presented for the De Rif middens. New late Quaternary palaeoenvironmental evidence for the Cederberg is the focus of this chapter.

5.2 RADIOCARBON AGES

Radiocarbon ages were calculated and calibrated following the methodologies outlined in the previous chapter (section 4.6) and is presented in Table 5.1 and Table 5.2.

While the possibility of discontinuous accumulation of material is a consideration in any stratified deposit, the fact that there are no obvious visible breaks in the deposition of DR-1 and DR-2, together with the ages obtained from these middens, indicate that there are no significant hiatuses. Therefore, because the overall trend is generally linear, it is possible to use linear interpolations between each calibrated radiocarbon age to estimate ages for undated isotope and pollen samples. This approach has been used in Gil-Romera *et al.* (2006; 2007) and Scott and Woodborne (2007a; b). Furthermore, of 69 ages obtained from 11 other middens there have been no age reversals and all the age-depth models for these middens have exhibited strong linear patterns (Chase *pers. comm.*)

The outcomes of the radiocarbon analyses therefore place the results of the palaeoenvironmental techniques employed in this study, and presented below, in the most plausible and parsimonious temporal setting.

5.3 POLLEN ANALYSIS

Pollen counts of 250 grains per sample were carried out for 9 samples taken from DR-1 and 26 samples from DR-2 (see Appendix C for absolute counts). The relative percentage pollen diagrams, presented below (figures 5.2 and 5.3), were constructed in the DOS spreadsheet programme Tilia version 2.0.b.4 and drawn in the vector graphics programme TGView version 2.0.2 (Grimm, 1991). These diagrams are divided into pollen assemblage zones visually based on changes in the pollen taxa changes (Moore *et al.*, 1991) and using the statistical output of CONISS (Constrained Incremental Sum of Squares) (Grimm 1987) (Appendix D). DR-1 and DR-2's pollen assemblage zones are described in sections 5.6.2 and 5.7.2 respectively.

The pollen data was also ordinated by principal component analysis (PCA) using the programme STATISTICA 8 (as outlined in chapter 4, section 4.3.5). The result of the statistical analysis is given in section 5.4.

In addition, modern pollen spectra were analysed to determine the nature of contemporary pollen distributions. Modern pollen spectra included fresh hyrax pellet samples (an amalgamation of three pellets per sample) and surface soil samples collected in the immediate vicinities of DR-1 and DR-2.

5.4 CHARCOAL ANALYSIS

Counts of charcoal fragments 75 μm^2 and greater were carried out simultaneously with the pollen counts. The summary of these counts are graphically displayed in the pollen diagrams for DR-1 and DR-2 (figures 5.2 and 5.3 respectively) and descriptions of the overall charcoal distributions are given in sections 5.6.3 and 5.7.3.

5.5 STABLE ISOTOPES

Samples from the De Rif middens were measured for their stable carbon and nitrogen contents as described in section 4.5.4 and the raw mass spectrometer outputs can be found in Appendix E. The results of these analyses are described in section 5.6.4 and 5.7.4.

5.6 DE RIF 1

5.6.1 Chronology and midden accumulation

The results of the radiocarbon analysis for DR-1 and the calibration of these results are presented in Table 5.1.

Table 5.1: Radiocarbon and calibrated Holocene ages (using curve SHcal04 (McCormac *et al.*, 2004)

Sample	Midden	Measurement method	^{14}C age yr BP	1 sigma error	calibration data	95.4 % (2σ) cal age ranges	relative area under distribution	median probability (cal yr BP)
A-14607.1	DR-1	GPC	830	85	SHCal04	cal BP 562 - 604	0.0723	719
						cal BP 627 - 848	0.851686	
						cal BP 860 - 907	0.076014	
A-14608	DR-1	GPC	3425	112	SHCal04	cal BP 3372 - 3892	1	3620
UBA-9244	DR-2	AMS	6467	73	SHCal04	cal BP 7170 - 7439	0.993946	7339
						cal BP 7451 - 7457	0.006054	
UBA-9245	DR-2	AMS	8804	35	SHCal04	cal BP 9561 - 9573	0.020627	9730
						cal BP 9582 - 9901	0.979373	
UBA-9246	DR-2	AMS	9819	37	SHCal04	cal BP 11109 - 11117	0.002246	11201
						cal BP 11122 - 11248	0.997754	
UBA-9247	DR-2	AMS	10057	31	SHCal04	cal BP 11273 - 11630	0.963303	11473
						cal BP 11633 - 11635	0.001534	
						cal BP 11670 - 11701	0.035163	

Table 5.2: AMS dates and calibrated ages for the late Pleistocene (using CalPal-2007-Hulu curve (Weninger and Joris, 2004))

Sample	Midden	Measurement method	^{14}C age yr BP	^{14}C Std Error	Calibration data	Age (cal yr BP)	Calibrated Std Error
UBA-9248	DR-2	AMS	10596	37	CalPal 2007 Hulu	12650	40
UBA-8797	DR-2	AMS	10576	36	CalPal 2007 Hulu	12640	40
UBA-9249	DR-2	AMS	13184	39	CalPal 2007 Hulu	16040	260
UBA-9793	DR-2	AMS	13755	45	CalPal 2007 Hulu	16970	40
UBA-9004	DR-2	AMS	14016	43	CalPal 2007 Hulu	17130	40
UBA-9791	DR-2	AMS	16193	82	CalPal 2007 Hulu	17130	150
UBA-9005	DR-2	AMS	21842	65	CalPal 2007 Hulu	25150	210
UBA-9792	DR-2	AMS	19955	69	CalPal 2007 Hulu	23790	100
UBA-9006	DR-2	AMS	19738	56	CalPal 2007 Hulu	23580	80
UBA-9790	DR-2	AMS	23393	84	CalPal 2007 Hulu	28150	80
UBA-8798	DR-2	AMS	20752	77	CalPal 2007 Hulu	24760	70

DR-1 formed within the late Holocene and represents just over 3600 years of accumulation. It is calculated that on average (based on the above two radiocarbon ages and assuming an approximately constant rate of accumulation) about 1 cm of material accumulated every 460 years. The termination of accumulation of midden material at approximately 719 cal yr BP was not caused by changes in environmental conditions but due to the limitations of space within the shelter (figure 2.8). This further supports the hypothesis that there was continuous, rather than episodic, accumulation within these middens.

5.6.2 Pollen analysis results

Pollen concentrations for DR-1's samples ranged between 5.8 $x10^4$ and 1.7 $x10^5$ grains per gram with an average of 9.3 $x10^4$, which is higher than averages found in Selaine *et al.* (in review) and similar to averages reported in Meadows and Sugden (1991), Scott and Woodborne (2007a, b) and Gil-Romera *et al.*, (2007).

The inherent limitations associated with pollen analysis in general (outlined in section 4.3.6) are reflected in DR-1's pollen results (figure 5.1); with low taxonomic diversity resulting from the difficulty of identifying pollen types to generic or species level, as well as possible selectiveness in the variety of pollen preserved in hyraceum. While the overall pollen assemblage for DR-1 shows very little variation, with the sequence being dominated by the presence of typical dry mountain fynbos taxa, subtle changes are evident and are described below.

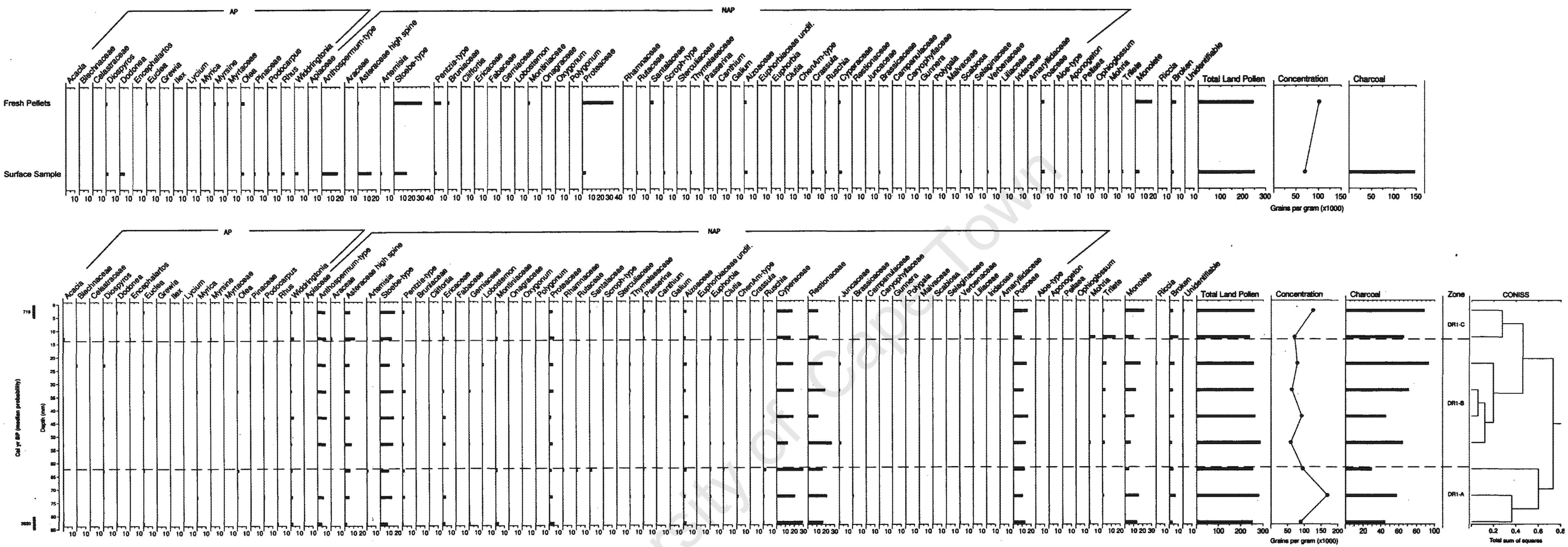


Figure 5.1: De Rif 1 relative percentages pollen diagram

5.6.2.1 Zone DR-1-A (83 – 63 mm, approximately 3 600 to 2 300 cal yr BP)

This zone is characterised by high proportions of Restionaceae, Cyperaceae, Asteraceae and Poaceae pollen. Asteraceae pollen is comprised predominantly of low-spine *Stoebe*-type pollen (which includes various *Stoebe* and *Elytropappus* spp.), as well as undifferentiated high-spine Asteraceae. DR-1-A has the highest percentages of Cyperaceae in the sequence, especially at the top of the zone with pollen from this taxon accounting for 33% of the total pollen found at that level. Percentages of Proteaceae and *Anthospermum*-type pollen are also relatively high. Ericaceae pollen is only found near the base of the zone but at low concentrations. Pollen of the following taxa are present at very low levels (0.5 – 4%) throughout the zone: *Pentzia*-type, Aizoaceae, *Euphorbia*, Montinaceae, *Passerina* and Ruschia. Brassicaceae and Bruniaceae pollen occurs only in this zone. Cheno/Am-type pollen peaks in the middle of this zone. Although there are only small proportions of arboreal pollen by comparison with shrub pollen in DR-1-A, the continued presence of *Widdringtonia* throughout the zone should be noted. Other woody elements present, but at very low concentrations include: *Dodonea*, *Diospyros*, *Euclea*, *Mysine, Olea* (highest at the top of the zone) and *Rhus*.

5.6.2.2 Zone DR-1-B (63 – 14 mm, approximately 2 300 to 1 000 cal yr BP)

As in the previous zone, DR-1-B is dominated by high concentrations of Asteraceae (*Stoebe*-type and high-spine Asteraceae), Restionaceae, Cyperaceae and Poaceae pollen. Proteaceae pollen is also consistently present throughout this zone as well as the other two zones (averaging at 5%). However the difference is that there is a substantial peak in Restionaceae at the bottom of the zone where this pollen type reaches its highest percentage (34%) for the sequence. Where Restionaceae pollen peaks, Cyperaceae pollen drops to its lowest percent (16%). (By referring to the absolute counts, Appendix C, it is clear that this relationship is not an artefact of the data representation as relative frequencies) Although Poaceae pollen is high in DR-1-B, it remains consistently high throughout the whole record and therefore does not vary substantially between zones. *Anthospermum*-type pollen displays moderately high percentages (between 10 -11%) in this zone. In general, there are lower frequencies of woody elements; the exception is an increase in *Diospyros* towards the top and a peak in *Widdringtonia* towards the base of DR-2-B. Although displaying low frequencies throughout the record, there is a peak in Ericaceae pollen towards the bottom of the zone.

5.6.2.3 Zone DR-1-C (14 – 0 mm, approximately 1 000 to 700 cal yr BP)

This zone showed the lowest concentrations of arboreal pollen, with only *Acacia, Euclea* and *Widdringtonia* reaching percentages between 1 - 3%. The proportions of Asteraceae (high-spine variety), Anthospermum and Proteaceae pollen are high at the base of the zone but decrease at the top. *Stoebe*-type pollen is at its highest frequency at the top of this zone (19%). Poaceae concentrations are also high throughout the zone. Cyperaceae and Restionaceae pollen frequencies are consistently high but are at lower proportions compared to the other two zones. Pollen taxa that are present throughout DR-1-C but at low percentages include: Montinaceae, Ericaceae, *Cliffortia Passerina*, Aizoceae, *Cheno/Am*-type and Verbenaceae.

5.6.2.4 Modern pollen spectra

In the surface sample, the most prominent pollen type is Asteraceae (25%) with the undifferentiated high-spine variety and *Stoebe*-type (*Stoebe* and *Elytropappus*) accounting for equal proportions of the total. The proportion of *Anthospermum*-type pollen is high in both the fossil record and surface soil sample, conversely, Pinaceae pollen was found in the surface sample while not in the fossil record. The surface sample collection includes slightly elevated concentrations of *Olea*, *Crassula*, *Rhus* and *Widdringtonia* pollen. There are substantially lower percentages of Cyperaceae, Restionaceae and Poaceae in the surface and modern pellets than in the midden sequence. Proteaceae and *Stoebe*-type pollen dominates the fresh hyrax pellets pollen, comprising a total of 65%.

These findings highlight the fact that fresh hyrax pellets, as a representation of the modern pollen spectra, should be used with caution as they may correspond to no more than a single meal. Whereas a high degree of dietary bias may be evident in fresh pellets, surface soil samples form over several years and therefore are better indicators of the modern pollen assemblage found at the site.

5.6.3 Charcoal Analysis

The frequency of charcoal fragments fluctuates somewhat across all three zones. However there is an overall increase towards the top on the sequence, with the largest proportion of charcoal found from the top of zone DR-1-B and throughout DR-1-C.

5.6.4 Stable isotope analysis

The average value of -27.18‰ found at DR-1 is very close to the mean value for C_3 vegetation (Pate, 2001), as would be expected considering the fynbos vegetation at the site. Established in the previous chapter, $\delta^{13}C$ isotopic values within a C_3 ecosystem, like that of De Rif, can indicate changes in the hydrological balance within the system (Pate, 2001; Schnyder, 2006). The low amplitude fluctuations in $\delta^{13}C$ (from -26.79 to -27.68‰) that are evident at DR-1 are likely to indicate changes in the water-use efficiencies of the system over time, with less depleted $\delta^{13}C$ reflecting drier conditions (figure 5.2). Despite the small changes in the $\delta^{13}C$ values, these changes can indicate large variations in WUE.

The $\delta^{13}C$ variations may be effected by the amount of succulents (CAM) in the hyraxes' diet. An increase in CAM plants could possibly lead to an enrichment in the $\delta^{13}C$ record as CAM $\delta^{13}C$ values range between the $\delta^{13}C$ value of C_3 and C_4 plants. However, there are no clear correlations between the percentages of succulent pollen and the $\delta^{13}C$ signals in both the De Rif middens.

In comparison to the value of 2.2‰ which is the average of the modern isotope results (see Appendix E) and the range of $\delta^{15}N$ values for DR-2 (figure 5.5), DR-1's range of -1.6 – 0‰ indicates relatively wet conditions at the site over the period of accumulation (figure 5.2).

The $\delta^{13}C$ and $\delta^{15}N$ signals for DR-1 (figure 5.2) exhibit a coeval relationship which is consistent with the argument presented in Chapter 4. In general, $\delta^{13}C$ and $\delta^{15}N$ values become gradually more enriched towards the top of the sequence indicating slightly less moisture availability from about 2 500 cal yr BP to 950 cal yr BP. However, overall the small variation in both the $\delta^{13}C$ and $\delta^{15}N$ contents of DR-1 signifies that very little environmental change occurred at DR-1 during the late Holocene.

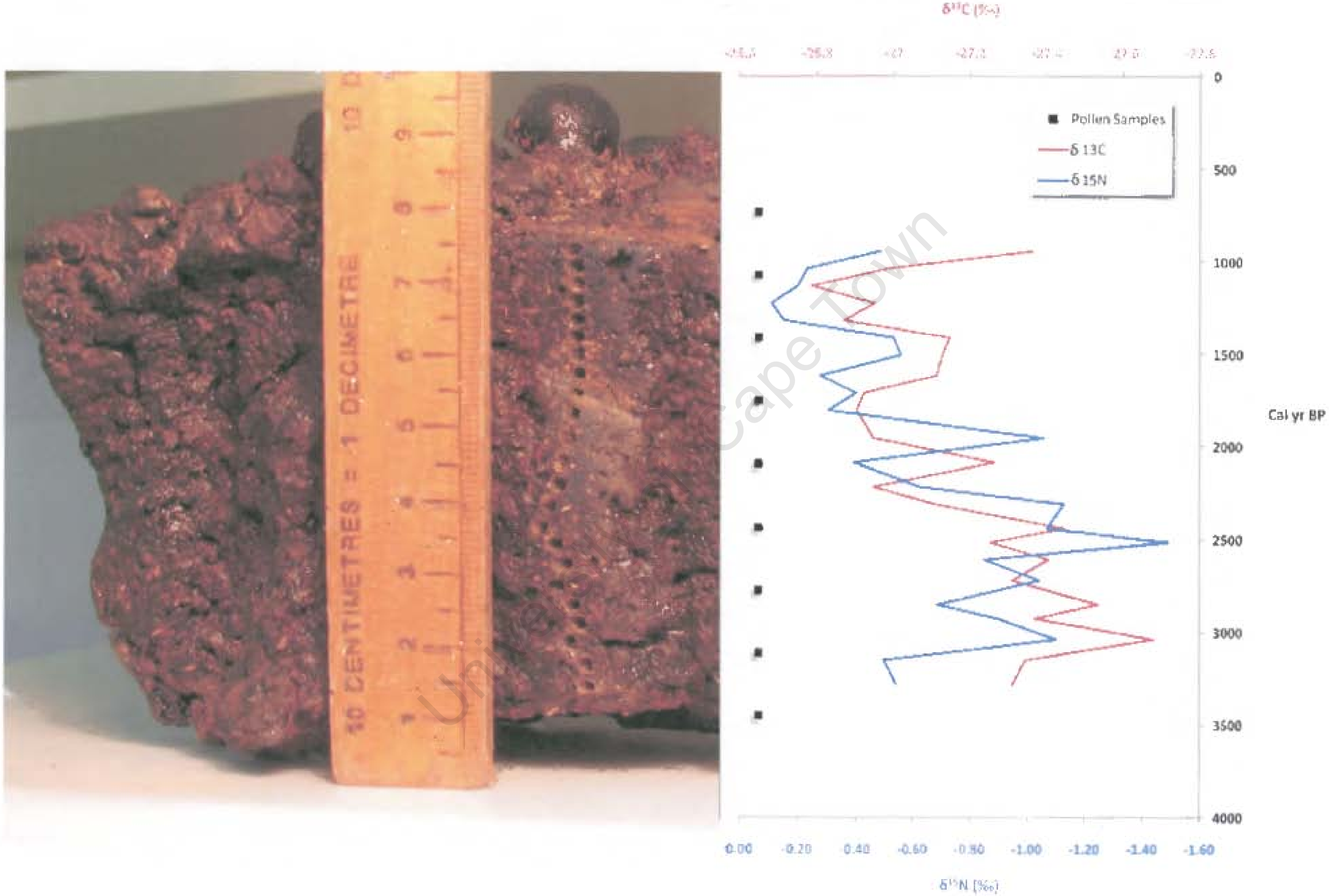


Figure 5.2: De Rif 1 stable carbon and nitrogen isotopes and pollen sample locations

5.7 DE RIF 2

5.7.1 Radiocarbon analysis: calibration and age model

Sub-samples from DR-2 were taken from two distinct, but overlapping sections (the top section labelled DR-2-3 and the bottom labelled DR-2-2 (refer to figure 5.3 for images)). This was necessary as a portion of the midden appears to be burned (figure 5.3 C). In addition, some of the midden layers appear to have been deposited at differing angles, which is in contrast to DR-1's almost perfect horizontal stratigraphy. In light of this complexity, as well as the overall size of DR-2 (~ 70cm), greater chronological control was needed and therefore many more samples for AMS dating were taken in comparison to DR-1 (AMS samples taken according to significant excursions in the isotopic record). The results of the radiocarbon analyses and calibrations are presented in Tables 5.2 and 5.3.

As the results presented in tables 5.2 and 5.3 indicate, the chronology for DR-2 is more complex than that of DR-1. The AMS sample DR-2-3 was taken from a region of the midden consisting predominantly of faecal pellets (figure 5.3 D), as opposed to hyraceum. It seems probable that the pellet-rich layer found around DR-2-3 would have accumulated at a faster rate than the hyraceum at DR-2-3-80. This has resulted in DR-2-3 having a younger age estimate than the preceding age DR-2-3-80.

The fact that the age-depth curve for the top section exhibits a broadly linear trend and that the bottom section of the midden appears homogeneous (unlike the obvious change in deposition rate at the pellet layers in DR-2-3, figure 5.3 D), a linear age calculation was created (from an average of the slope coefficients of the linear trend lines) and extrapolated for the bottom half of DR-2-2 (refer to the age-depth curve displayed in figure 5.5). The use of a linear model for the lower half of DR-2-2 is supported by the findings of Scott and Woodborne (2007a;b) and the data from two other middens, namely Spitzkoppe and Zizou (Chase *et al.* in prep, data found in Appendix F) which all show linear midden accumulation. Greater resolution regarding the chronology of the lower portion of DR-2 can be attained with the extraction and analysis of further radiocarbon samples. This will be achieved in subsequent studies which lie beyond the scope of this project.

From this age-depth model it is clear that DR-2 formed over a substantial period encompassing the Holocene and part of the last glacial.

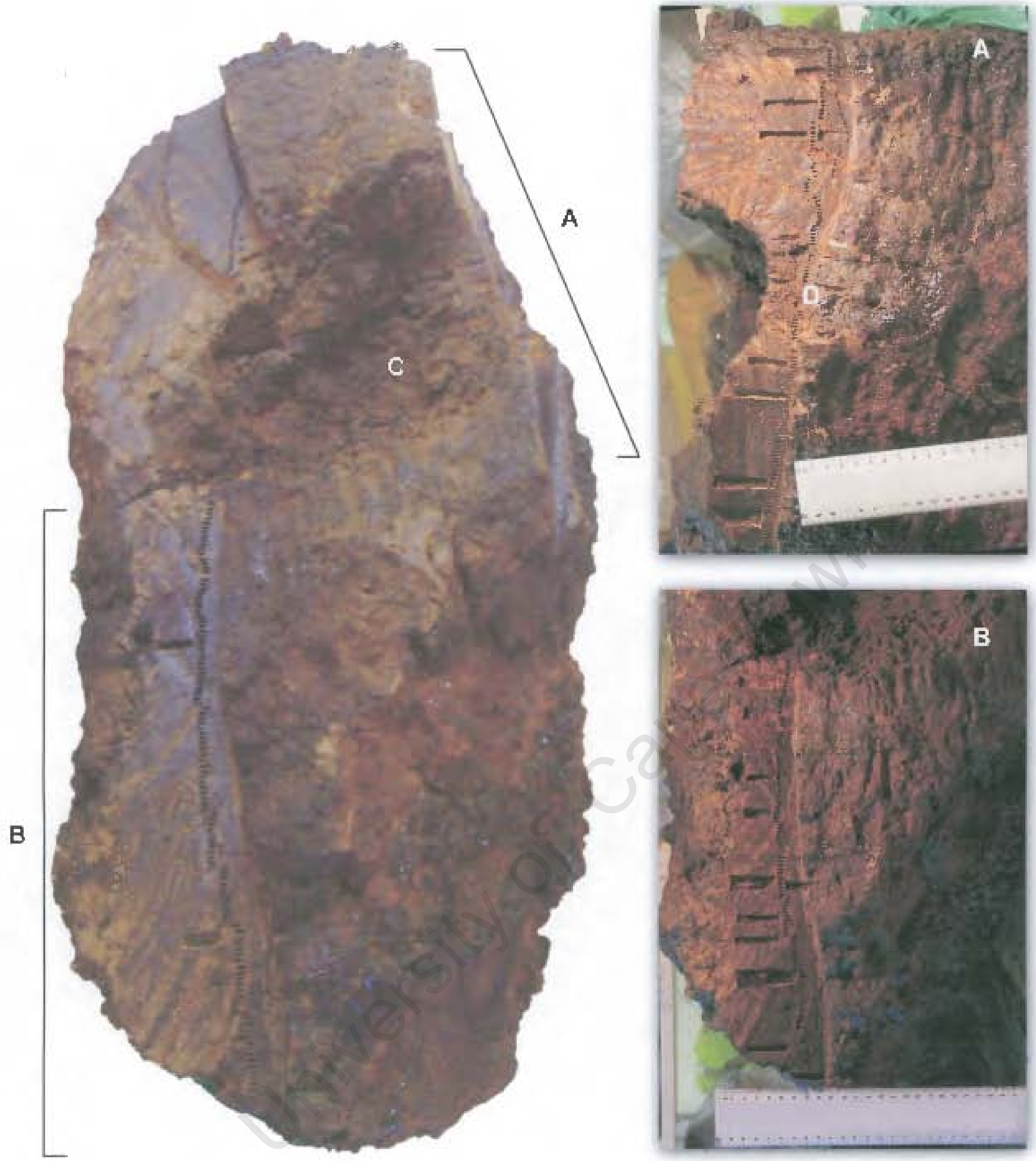


Figure 5.3: Images of De Rif 2 showing pollen and AMS sampling locations. A - Section DR-2-3; B - Section DR-2-2; C – Burnt area; D – pellet layer (total length of DR-2 is ~70 cm)

5.7.2 Pollen Analysis

Presented below (figure 5.4) is the relative pollen diagram for De Rif 2. Pollen concentrations for DR-2 were relatively high; ranging between 4 $x10^4$ and 2.2 $x10^5$ grains per gram with the average, 1.3 $x10^5$ grains per gram, being higher than the average for DR-1. The subsequent sections describe DR-2's pollen assemblage zones:

5.7.2.1 Zone DR-2-A (621 – 560 mm, approximately 29 000 – 26 000 cal yr BP)

Restionaceae, Cyperaceae and Poaceae pollen collectively constitute over 60% of the total proportion of land pollen for zone DR-2-A. Cyperaceae and Restionaceae have the highest concentrations at the base of the zone and then both taper off towards the top of the zone while Poaceae pollen concentrations do not vary significantly within the zone. Asteraceae pollen is represented in this zone by small proportions (1 – 5%) of *Stoebe*-type, *Pentzia*-type, *Artemisia* and the undifferentiated high spine grains. *Stoebe*-type is at its lowest concentration for the whole sequence in this zone. Typical fynbos elements, Proteaceae and Ericaceae pollen, are at low concentrations and do not vary much within the zone. *Dodonaea* and *Anthospermum*-type pollen are at their lowest concentration for the sequence. Pollen of woody elements, including *Acacia*, *Euclea*, *Myrsine*, *Podocarpus* and *Widdringtonia* are all present within DR-2-A, with *Widdringtonia* contributing the largest proportion of these taxa. Many taxa associated with aquatic environments are present within this zone, including Araceae (which reaches its maximum concentration in the sequence), Juncaceae, *Gunnera* and fern spores. Succulent taxa – Aizoaceae, *Euphorbia*, *Crassula* and *Ruschia* are present at this level but at very low percentages.

5.7.2.2 Zone DR-2-B (560 – 390 mm, approximately 26 000 – 19 000 cal yr BP)

The pollen taxon with the highest percentages within DR-2-B is Restionaceae, varying between 30 – 40% throughout the zone, with a maximum of 41% at ~20 700 cal yr BP. Cyperaceae pollen frequencies are also high and increase from the top (7%) to their maximum (18%) at about 24 500 cal yr BP then drop off at the very bottom to 12%. A prominent feature of this zone is the high proportions of Asteraceae pollen with coinciding peaks in Asteraceae high spine variety, *Stoebe*-type and *Pentzia*-type at approximately 21 200 cal yr BP. Proteaceae, Ericaceae and *Ruschia* are all present throughout DR-2-B but at low frequencies. Relatively high concentrations of Poaceae pollen is a further prominent feature throughout this zone. Campanulaceae and *Canthium* are at their maximum for the sequence, with peaks in their concentrations at the top of the zone.

Widdringtonia pollen reaches its highest frequencies, peaking at 5.6% around ~20 700 cal yr BP. There are small peaks in the concentrations of Blechnaceae (at its highest frequency for the sequence) and *Euclea* pollen (which is present throughout the zone) towards the top and middle of the zone respectively. *Myrica*, *Myrsine*, *Diospyros* and *Dodonaea* pollen are all present throughout the zone but at very low proportions.

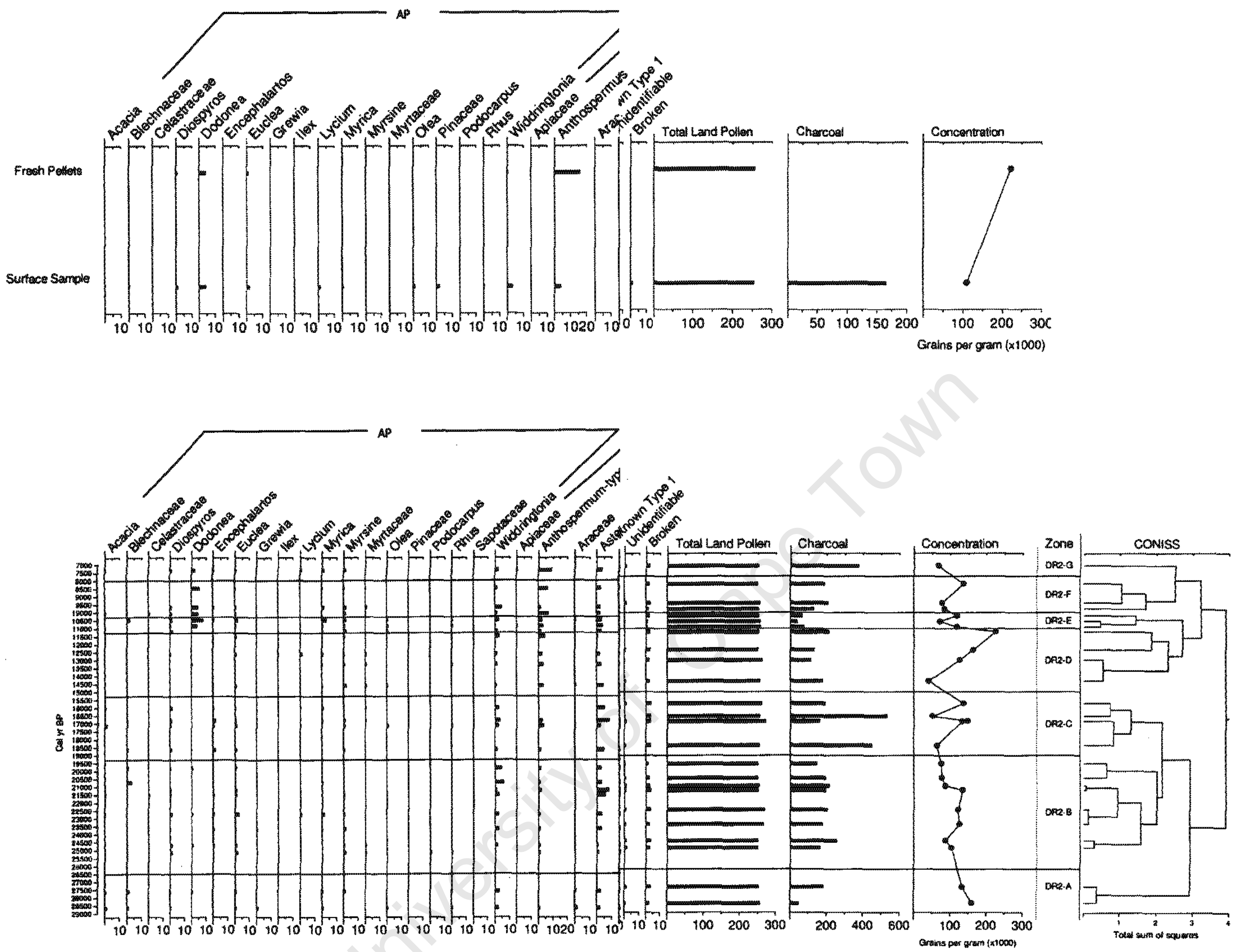


Figure 5.4: De Rif 2 relative percentages pollen diagram

5.7.2.3 Zone DR-2-C (390 – 310 mm, approximately 19 000 – 15 000 cal yr BP)

Restionaceae pollen concentrations, as in previous zones, are high with the maximum percentage for this taxon in the sequence being achieved at the base of this zone. From this maximum (45%), Restionaceae pollen concentrations decline consistently to 25% at the top of DR-2-C. Cyperaceae pollen peaks in the middle of the zone (17 000 cal yr BP) and tapers towards the bottom. There are large proportions of Asteraceae pollen throughout the zone, especially *Stoebe*-type which varies between 11 – 23%. *Stoebe*-type and *Pentzia*-type reach their maximum concentrations for the zone at about ~17 000 cal yr BP. *Anthospermum*-type pollen concentrations are low, with a small peak in the middle of the zone. Ericaceae pollen is absent from the bottom of the zone and peaks towards the top of the zone. Proteaceae pollen is absent towards the top of DR-2-C and at its lowest concentration for the sequence at the bottom of this zone. Most of the other shrubs and succulents that can be found in this zone are at very low frequencies (0.5 – 2%). Similarly, all the arboreal elements are either absent or at very low concentrations, except *Widdringtonia* pollen which is at a relatively high percentage in the middle of the zone and decreases both towards the top and the bottom of the zone.

5.7.2.4 Zone DR-2-D (310 – 235 mm, approximately 15 000 – 11 500 cal yr BP)

This zone is characterised by a lower proportion of Restionaceae pollen (in comparison with the previous zones) with the exception of a rise in this taxon at the top of the zone where it reaches 43%. Cyperaceae pollen also increases towards the top of this zone but peaks at 12 600 cal yr BP then decreases to 13% at 11 500 cal yr BP, the top of the zone. Poaceae and *Anthospermum*-type pollen are consistently present in DR-2-D, at about 6% and 3% respectively. Ericaceae pollen in this zone is relatively high in comparison to other the zones. *Ruschia* and Juncaceae pollen are also present throughout the zone but at low percentages (~0.5 – 2%). Thymelaeaceae, *Scrophulariaceae*-type and Bruniaceae pollen exhibit small peaks in the middle of the zone, at about 13 000 cal yr BP, and are absent for the rest of the zone. Proteaceae pollen concentrations are relatively high throughout the zone and reach a maximum at about the same time as the previous shrub taxa. *Stoebe*-type also peaks at about 13 000 cal yr BP and decreases either side of this central point. *Pentzia*-type pollen is highest for the sequence at the base of DR-2-D and substantially decreases towards the top of the zone. The same pattern is evident for high spine Asteraceae pollen, reaching its lowest concentration for the sequence at the top of the zone. Woody elements for this zone are at very low percentages with *Widdringtonia* pollen lower than in previous zones.

However there are small peaks in *Lycium,* near the top of the zone, and *Myrsine* at the base of the zone.

5.7.2.5 Zone DR-2-E (235 – 100 mm, approximately 11 500 – 10 300 cal yr BP)

Cyperaceae and Restionaceae are the dominant taxa in DR-2-E and are generally highest at the base of the zone and decrease unevenly towards the top of the zone. *Stoebe*-type concentrations are lowest in comparison to all other zones. *Artemisia* and *Pentzia*-type pollen are also low, while Ericaceae concentrations remain constant at about 3%.

There are greater percentages of woody elements in this zone compared to previous ones with a peak in Blechnaceae at the top of DR-2-E and the first appearance of a prominent amount of *Dodonaea* pollen. *Dodonaea* reaches its highest concentration near the top of the zone with corresponding peaks in *Myrica* and *Euclea* pollen. Proteaceae pollen is at its highest proportion for the sequence (12%) with a peak coinciding with the arboreal taxa. Montiniaceae, *Scrophulariaceae*-type and *Canthium* are all present but at very low pollen concentrations.

5.7.2.6 Zone DR-2-F (100 – 40 mm, approximately 10 300 – 8 000 cal yr BP)

Cyperaceae and Restionaceae pollen concentrations are greatest at the base of DR-2-F and encompass 44% of the total land pollen for that level. Proportions of these pollen types substantially drop at ~9 700 cal yr BP then rise again to about ~15% at the top of the zone. Poaceae pollen proportions in this zone are relatively high in comparison to other zones, especially towards the top of the zone where the frequencies reach up to 10%.

Anthospermum-type pollen percentages are consistently elevated at about 6-7% except for a drop to 1% at ~9 700 cal yr BP. *Stoebe*-type pollen increase to 25% in the middle of the zone, while other Asteraceae types are fairly low. Proteaceae percentages are very consistent at 3-4% for the whole of DR-2-F. Ericaceae pollen increases towards the top but concentrations remain low (1-3%) throughout the zone. The following taxa have very low pollen concentrations, exhibiting small peaks towards the bottom of the zone: Thymelaeaceae, *Passerina*, *Euphorbia*, *Crassula* and *Aloe*-type.

Arboreal pollen levels are generally lower than in DR-2-E. However, *Dodonaea* has relatively high concentrations throughout the zone and *Widdringtonia* pollen percentages reach 4% in the middle of the zone.

5.7.2.7 Zone DR-2-G (40 – 10 mm, approximately 8 000 – 7 300 cal yr BP)

Although this zone is only represented by one pollen sample, it remains distinct from the previous zone (as indicated by the CONSISS results, figure 5.3). Cyperaceae, Restionaceae and Poaceae pollen represent the largest proportion of DR-2-G. However, the percentages of Cyperaceae and Poaceae are both lower than that found in DR-2-F. The percentage of *Anthospermum*-type is high (9.2%), which is the maximum percentage for the sequence. *Stoebe*-type pollen is relatively low in comparison with the top of DR-2-F. Other Asteraceae pollen types display low concentrations. Ericaceae pollen is absent from the top of the zone, whereas Montiniaceae, Rutaceae, *Passerina* and *Galium* pollen are present. Proteaceae pollen percentage is 5%, higher than in zone DR-2-F. Woody elements have low proportions; with a decrease in percentage of Dodonaea and a slight increase in *Myrica, Mysine* and *Widdringtonia* pollen in comparison to DR-2-F.

5.7.2.9 Modern Pollen Spectra

Diospyros and *Dodonaea* pollen percentages in the surface sample and fresh pellets are similar and are also comparable to the amounts present in the topmost pollen assemblage zone - DR-2-G. The same pattern is evident for *Euclea*, Montiniaceae and Asteraceae high-spine variety. The surface sample has a percentage of *Stoebe*-type pollen that is very similar to that of the percentage in DR-2-G whereas the pellets record a much lower proportion. In the fresh pellet sample, *Pentzia*-type pollen is relatively high. In comparison, *Widdringtonia* pollen was absent from the fresh pellet sample and contributes only about 3% of the total land pollen found in the surface sample. Ericaceae pollen is relatively higher in both the pellet and surface soil samples in comparison to DR-2-G. *Anthospermum*-type pollen concentrations are relatively high in the fresh pellet sample, which concurs with results found at DR-2-G, although in the surface sample there is a much lower proportion of this taxon. Cyperaceae pollen achieves high percentages in the fresh pellet sample, contributing to 40% of the total land pollen, whereas in the surface sample by comparison, this taxon reaches only 17% and is more similar to DR-2-G. Restionaceae pollen is absent in the pellet sample and present in the surface sample although only at a very low percentage (2.4%). Poaceae pollen is also absent in the pellet sample, while in the fresh pellet sample it comprises 5%.

From the description of the modern pollen spectra from both DR-1 and DR-2, it is evident that greater taxonomic diversity can be found in the surface samples and that, generally, the surface samples are more similar to fossil pollen assemblages than are fresh pellets.

Therefore it can be concluded that pollen spectra in surface soil samples are a more reliable indicator of vegetation found at the sites at present.

5.7.3 Charcoal Analysis

Charcoal amounts for the pollen assemblage zone DR-2-A are low in comparison to other zones, especially at the base of this zone. For DR-2-B charcoal amounts are similar to the adjoining zones but decrease slightly towards the top of the zone. Charcoal amounts for DR-2-C are similar to the previous zones' counts however there are two significant deviations: peaks at the base (~19 000 cal yr BP) and in the middle (~17 000 cal yr BP) of the zone. For DR-2-D, charcoal amounts are relatively consistent throughout the zone and are at similar levels to the adjoining zones; however there is a slight decrease in the middle of the zone at ~12 500 cal yr BP. Charcoal counts for DR-2-E are markedly low, reaching the lowest amount for the sequence at 10 850 cal yr BP. DR-2-F's charcoal counts are similar to the counts for DR-2-B and DR-2-C. Overall charcoal amounts are highest in the topmost zone, DR-2-G (except for the peaks found in DR-2-C).

5.7.4 Stable isotope analysis

The stable carbon and nitrogen isotope curves are presented in figure 5.4 together with the locations of the pollen samples in relation to the isotopic records and the age-depth model applied to both the pollen and isotope samples.

In contrast to the relatively small fluctuations in the $\delta^{15}N$ values for DR-1 (with a range of less than 2 ‰), there is significant variation in $\delta^{14}N$ values for DR-2 (range of 13 ‰). Significant excursions in the $\delta^{13}C$ record are evident (absolute range being -28.34 to -25.99 ‰, with an average of 27.45 ‰). These variations of greater enrichment and depletion mirror similar deviations in the $\delta^{15}N$ record, highlighting the strong coeval relationship between these two variables.

Regions of significant enrichment in $\delta^{15}N$ and $\delta^{13}C$ can be identified as periods within which more arid conditions may have prevailed at the site. The two most significant excursions, where both $\delta^{13}C$ and $\delta^{15}N$ values deviate, occur between ~22 000 – 21 000 cal yr BP and ~12 700 – 11 500 cal yr BP. Accordingly, the following are periods that have more negative $\delta^{14}N$ and $\delta^{13}C$ values and thereby indicate times of greater moisture availability when wetter climatic conditions may have prevailed: ~25 000 - 24 300 cal yr BP, ~17 000 – 15 000 cal yr BP and 11 500 – 10 500 cal yr BP.

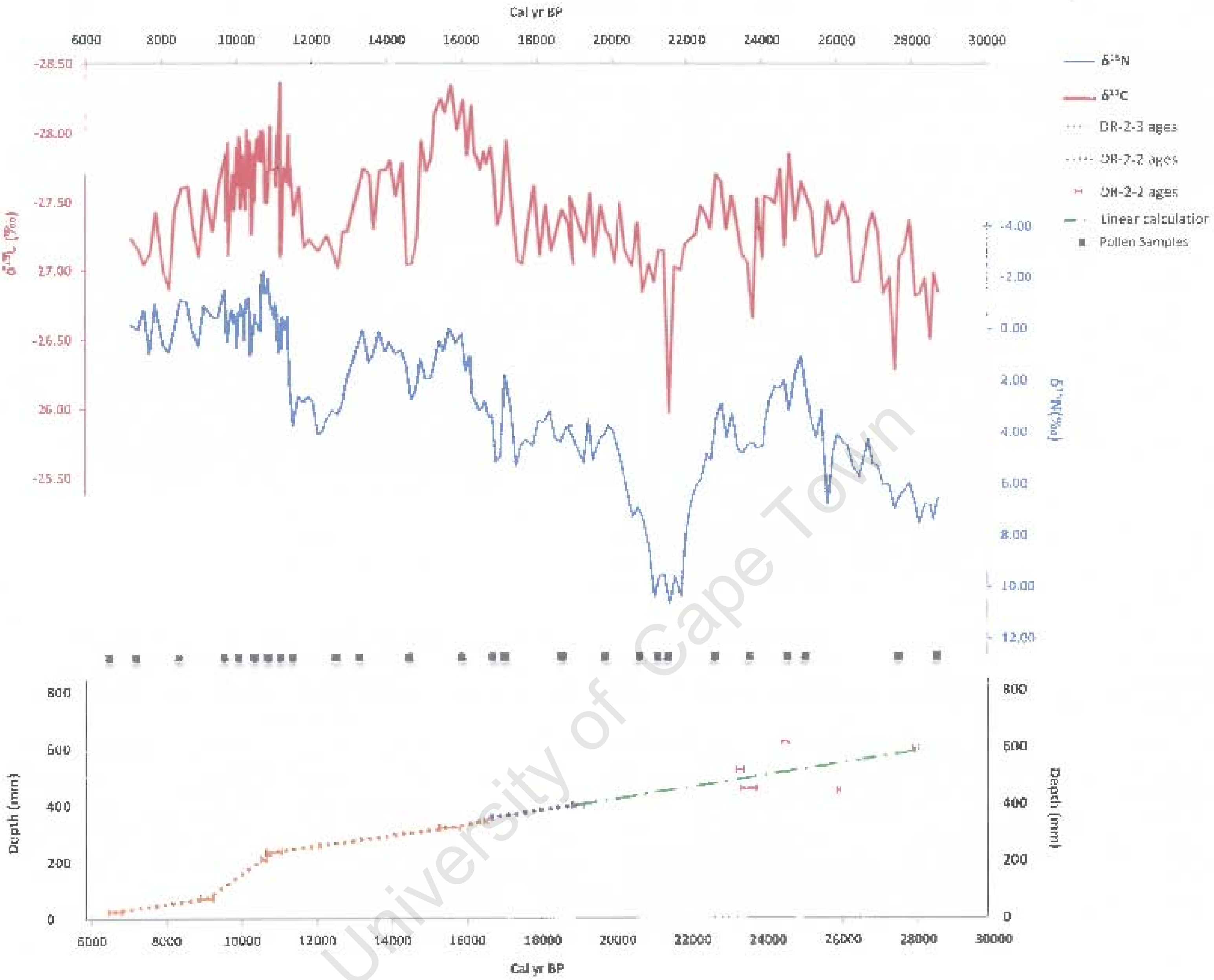


Figure 5.5: De Rif 2 stable carbon and nitrogen isotopes, location of pollen samples. DR-2-2 and DR-2-3 ages (with error bars) directly used for the age-depth model (orange and purple points connected by dotted lines) and DR-2-2 ages not directly used (pink points with error bars) used to create the linear calculation (green dot and dashed line)

5.4 STATISTICAL ANALYSIS OF POLLEN DATA

The PCA was run on pollen percentages of 25 environmentally sensitive indicator taxa selected from a combined DR-1 and DR-2 pollen dataset. Interpretation of the principal components derived from this data set was attempted in order to identify major environmental parameters influencing the selected taxa.

The analysis created a correlation matrix which determined the principal components/eigenvectors. The variables – the selected pollen taxa – were expressed in relation to these components. The first three principal components (PC1, 2 and 3) account for ~40 % of the total variance and may be considered significant (refer to figure 5.6). Due to the orthogonal nature of eigenvectors, to maximise the factor loadings the eigenvectors were rotated using STATISTICA's *Varimax* rotation method. The factor loadings for the three components (table 5.5) probably represent climatic gradients that have a dominant influence on the selected taxa. The loading value of ±0.15 was determined as significant, as below this value a rapid decrease, where values approached 0, was observed.

Table 5.4: PC1, 2 and 3 values and their explained variance

Principal component	Eigenvalue	% of the total variance
1	3.614816	14.45926
2	3.117874	12.47150
3	2.873191	11.49276

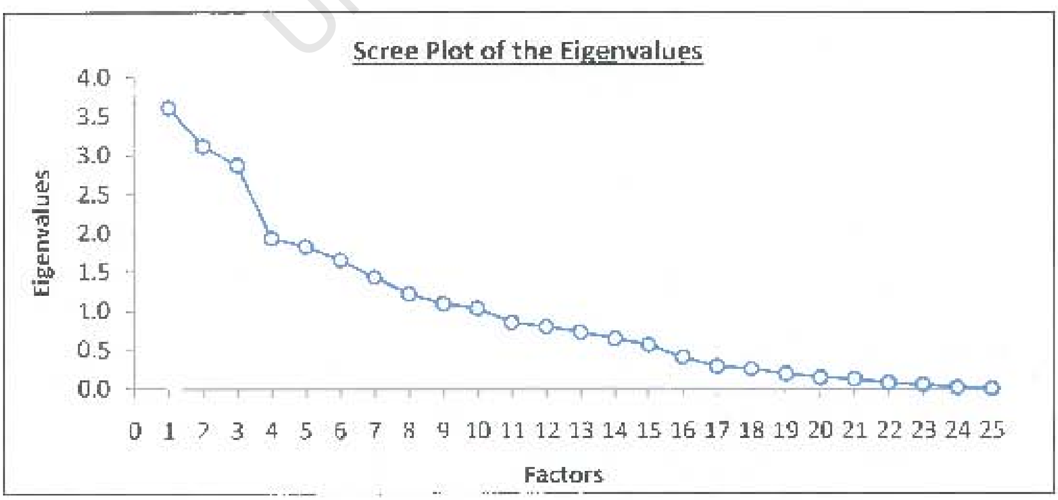


Figure 5.6: Line plot of eigenvalues showing major break after factor 3

Table 5.5: Factor loadings:
Significant positive values are highlighted in red and significant negative values are highlighted in blue.

Selected Taxa	PC1	PC2	PC3
Aizoaceae	0.81	0.09	0.10
Aloe-type	-0.08	-0.94	-0.02
Anthospermum-type	0.20	-0.21	0.01
Artemisia	-0.08	0.00	-0.03
Asteraceae high spine	0.22	0.06	-0.03
Campanulaceae	-0.05	0.00	-0.05
ChenAm-type	0.01	0.06	0.00
Cliffortia	-0.12	0.24	0.01
Cyperaceae	0.08	0.15	0.60
Dodonea	-0.12	-0.22	-0.06
Ericaceae	-0.16	0.25	-0.07
Euclea	0.02	-0.02	-0.05
Euphorbia	-0.08	0.02	-0.03
Lobostemon	0.13	-0.01	0.00
Olea	0.12	0.05	0.08
Passerina	0.02	-0.11	0.06
Pentzia-type	-0.07	0.06	0.00
Poaceae	0.93	0.03	-0.02
Podocarpus	0.07	0.04	-0.01
Proteaceae	-0.17	0.07	0.15
Restionaceae	-0.37	0.30	-0.42
Rhus	0.13	0.02	0.07
Ruschia	0.04	0.01	0.09
Scroph-type	-0.07	-0.14	-0.01
Stoebe-type	0.11	-0.13	0.04

The three taxa with significant negative loadings for PC1 are Restionaceae, Proteaceae and Ericaceae. All three are typical fynbos families and ecologically are associated with cooler and/or wetter conditions. In contrast, most of the taxa with significant positive loadings (e.g. Aizoceae and *Anthospermum*-type) are non-fynbos taxa and are in general associated with warmer and/or drier environments. The loading for Poaceae is also a high positive value which could indicate that fynbos and Poaceae have contrasting environmental tolerances; with increases in fynbos taxa associated with reductions in Poaceae cover. PC2 has high negative loadings for dry karroid taxa such as *Aloe-type*, *Dodonaea* and *Anthospermum*-type. High positive values were observed for Ericaceae, *Cliffortia* and Restionaceae, all of which can favour cooler/wetter conditions. Restionaceae and Cyperaceae load at opposite ends of PC3 which is consistent with the observation from the pollen diagram for DR-2 (figure 5.3) that these two taxa co-vary to some degree throughout the sequence.

Proteaceae and Cyperaceae load on the same side of PC3 indicating that there is a possibility that PC3 is also related to some factor relating to moisture availability; with Cyperaceae and Proteaceae associated with cool, moist environments and Restionaceae often inhabiting more open, dry areas and often favouring nutrient-poor sandy substrates. However, due to the fact that the taxon Restionaceae is at the family level, it incorporates a number of different genera and therefore is associated with a wide range of environmental conditions. Without identifying pollen to the genus and/or species level the significance of PC3 as an environmental indicator remains uncertain.

The first two PCs, therefore, seem to reflect either moisture and/or temperature gradients with possible influencing factors being evaporation, rainfall seasonality and overall moisture availability. The factor scores for PC1 and PC2 are presented in figure 5.6.

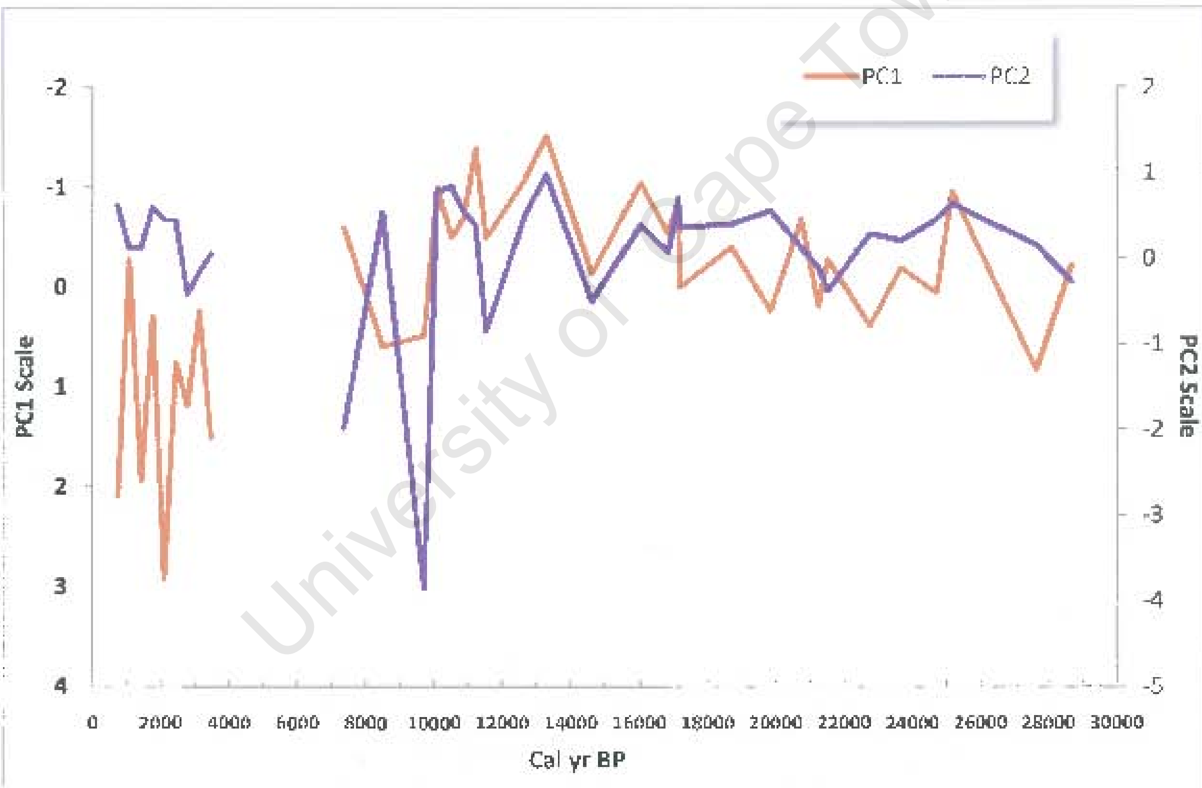


Figure 5.6: Component scores for the combined DR-1 and DR-2 pollen data set (PC1 scale inverted for convenience of interpretation)

5.5 CONCLUSION

This chapter has presented the pollen and isotopic data derived from the De Rif middens. The pollen record from DR-1 indicates that dry mountain fynbos taxa were present at the site for the period of accumulation ~700 – 3 600 cal yr BP and that very few changes in vegetation communities were evident for this period. The stable carbon and nitrogen curves exhibit small variations and support the conclusion drawn from the pollen record that no significant environmental change occurred at the site during this period.

Analysis of the modern pollen spectra from both DR-1 and DR-2 illustrate that; in general, surface soil samples should be used instead of fresh hyrax pellets as they seem to display greater taxonomic diversity and are therefore a better indicator of modern pollen assemblages.

Midden accumulation at DR-2 encompasses a substantial period from ~7000 – 28 000 cal yr BP and covers the last glacial-interglacial transition. One would therefore expect the pollen record for DR-2 to reflect great changes in vegetation community structures in response to different glacial and interglacial climates. However, the majority of the taxa within the DR-2 pollen assemblage exhibited only relatively subtle changes in frequencies. Noteworthy exceptions include the rapid increase in two dry Karoo indicator taxa: *Dodonaea* and *Anthospermum*-type, at ~11 500 cal yr BP.

The variations in $\delta^{15}N$ and $\delta^{13}C$ values within the isotopic record for DR-2 highlight the coeval relationship between these two variables and reflect changes in water availability at the site. In contrast to the pollen sequence, great variation can be found within the isotopic record; with the most significant deviations, reflecting periods of less water availability, occurring at ~22 000 – 21 000 cal yr BP and ~12 700 – 11 500 cal yr BP. The significance of these periods in relation to regional and hemispheric climate change is discussed in the following chapter.

The statistical analysis on the pollen data elucidated underlying climatic factors that influenced the selected indicator taxa. greater detail on the implications of the statistical analysis is provided in the next chapter.

6 Discussion and Environmental Reconstruction

6.1 INTRODUCTION

As the radiocarbon analyses have indicated, the hyrax middens extracted from the De Rif area have formed over long periods of time; therefore allowing the establishment of an extensive multi-proxy record of environmental change for the Cederberg Mountains. Chapter 6 initially presents an assessment of the overall palaeoenvironmental record. This is followed by more detailed discussions of specific sections of the record that are significant in terms of regional and hemispheric climate change.

6.2 LATE QUATERNARY ENVIRONMENTAL RECONSTRUCTION

6.2.1 Discussion of the overall De Rif record

The analysis of the stable carbon and nitrogen contents of the De Rif middens presents the opportunity to investigate the value of isotope geochemistry in midden studies. Since fynbos vegetation is dominated by plants that utilise the C_3 photosynthetic pathway, the $\delta^{13}C$ signature of organic sediments is primarily determined by leaf-level changes in plant water-use efficiency and, thereby, the effective precipitation around the midden sites (Pate, 2001; Schnyder *et al.*, 2006). Variations in $\delta^{15}N$ in the De Rif isotope records exhibit strong positive correlations with the $\delta^{13}C$ values, supporting inferences that $\delta^{15}N$ in plants is determined to a large extent by variations in precipitation and the 'openness' of the nitrogen cycle (Handley *et al.*, 1999; Swap *et al.*, 2004; Aranibar *et al.*, 2004; Murphy and Bowman, 2006). Significant excursions in the DR-2 $\delta^{13}C$ record are evident with these variations of enrichment and depletion mirroring similar deviations in the $\delta^{15}N$ record, highlighting the strong coeval relationship between these two variables, and the reliability of each as proxy for water availability. The two most significant periods of enrichment in the $\delta^{13}C$ and $\delta^{15}N$ records are from ~ 22 000 cal yr BP to 21 000 cal yr BP falling around the time of the LGM and the period ~ 12 700 – 11 500 cal yr BP coinciding with the Younger Dryas. These two events are discussed in sub-sections 6.2.2 and 6.2.3 respectively. The strong correlation between $\delta^{13}C$ and $\delta^{15}N$ in both the DR-1 and DR-2 records, the high temporal resolution of these records as well as the presence of distinctive events in the DR-2 record that may be interpreted as corresponding to significant climate changes emphasizes the enormous potential for the use of the isotopic content of hyrax middens as palaeoenvironmental indicators.

An assessment of the overall pollen assemblages indicates that typical mountain fynbos taxa were present at De Rif throughout the last 28 ka. Generally, there were no major changes in pollen taxa assemblages throughout the period in question, supporting findings of Meadows and Sugden (1991) of relatively stable environmental conditions in the Cederberg during the late Pleistocene and Holocene. This is a conclusion that stands in sharp contrast to the distinct excursions in the stable isotope records, as well as the greater variability found in the pollen sequence from Pakhuis Pass to the northeast (Scott and Woodborne, 2007a, b). Reasons invoked to explain the absence of marked vegetation changes in the central Cederberg include the dominating influence of the geology, elevation and the resilience of fynbos (Meadows and Sugden, 1991). The diversity in the relief as well as edaphic factors in combination with winter rainfall are thought to be the reason for the existence of upland centres of species richness and this combination of factors seems to be responsible for fynbos persisting in the Cape Fold mountains (Deacon *et al.*, 1992). In addition, fynbos growth forms can remain essentially unchanged over a great range of rainfall regimes – from less than 300 mm per annum to exceeding 3 000 mm per annum (Cowling and Holmes, 1992; Linder *et al.*, 1992). Therefore if no critical climate threshold is reached, it may be that mountain fynbos can persist despite climate change. Furthermore, climate change is only one mechanism driving fynbos ecosystem dynamics. Fire intensity and frequency play an important role in fynbos ecological functioning (Richardson and van Wilgen, 1992). However, mountain fynbos has specifically adapted to fire and exhibits a wide range of fire-survival mechanisms and is resilient under many different fire regimes (Richardson and van Wilgen, 1992). Therefore due to high levels of resilience, mountain fynbos at a community level is able to persist despite climate change and changes in the fire regime. There is a strong probability that changes to both fire regimes and climate change are more evident at the genus or species level. The presence of definable climate change events within the higher resolution isotope records therefore suggests that there is the possibility that the pollen records, limited by low taxonomic resolution, may mask or seemingly subdue changes in the vegetation communities at the sub-genus level.

Despite the relatively minor changes in the characteristics of various Cederberg pollen assemblages (e.g. Meadows and Sugden, 1991; Scott and Woodborne, 2007a, b), it remains possible to infer past climate conditions from a number of ecologically sensitive pollen taxa (Meadows and Sugden, 1991; Scott and Cooremans, 1992). To explore these variations, the ecological affinities of the taxa found in the pollen records were identified using previous palynological studies in the Cederberg including Meadows and Sugden (1991) and Scott and Woodborne (2007, a, b) in conjunction with fynbos ecological guides (e.g. van Rooyen and Steyn, 1999).

Table 6.1: **Ecologically sensitive pollen taxa found in the De Rif pollen assemblages**

INDICATOR TAXA	
Wetter and/ or cooler	**Drier and/ or warmer**
Stoebe-type	Asteraceae high spine
Podocarpus	Aizoceae
Widdringtonia	*Crassula*
Ericaceae	*Dodonaea*
Proteaceae	*Anthospermum*-type
Passerina	*Pentzia*-type
Aquatics	*Euphorbia*
(including: *Aponogeton*, Blechnaceae, Araceae,	*Ruschia*
Juncaceae and fern spores)	*Aloe*-type

Taxa presented in table 6.1 were particularly useful as indicators of changes in moisture and or temperature conditions and the changing frequencies of these taxa are discussed in the following subsections.

6.2.2 De Rif: The last glacial period

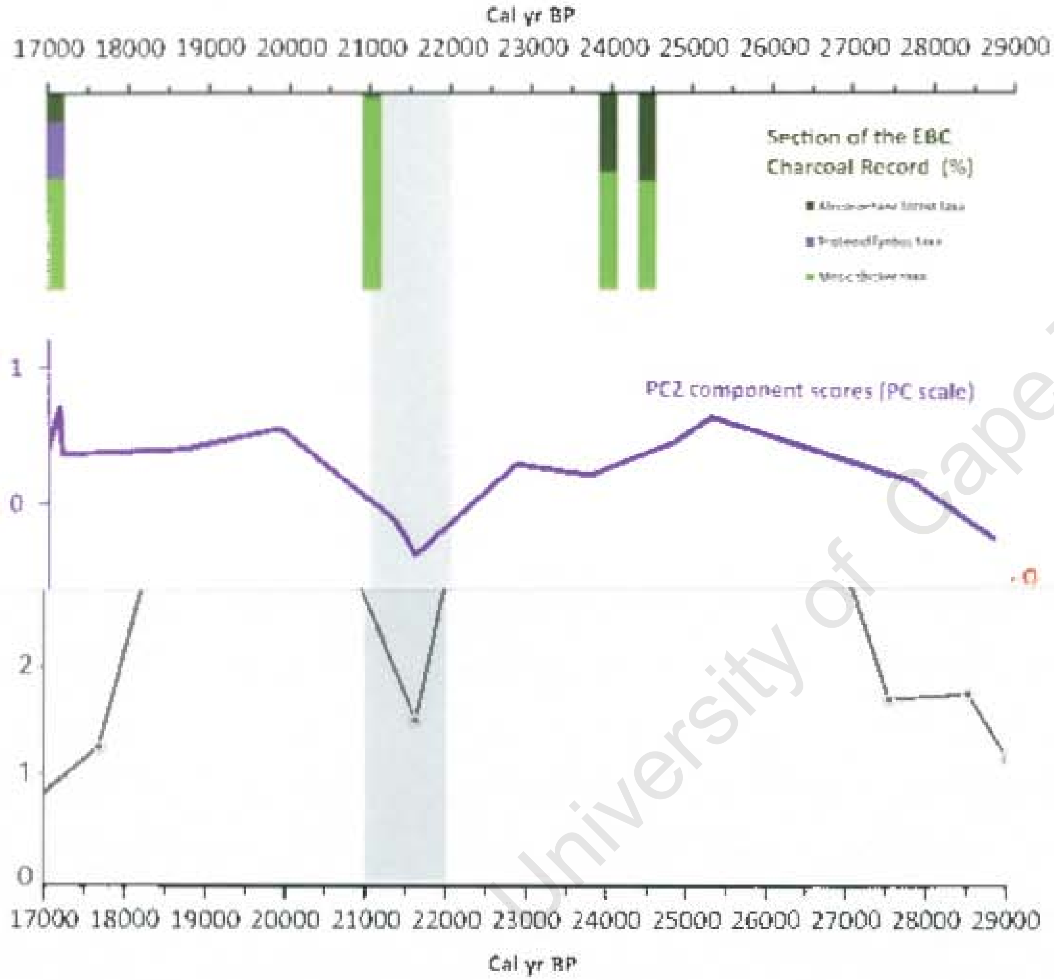
The isotope and pollen records indicate that greater moisture was available during the period between ~ 26 000 cal yr BP and ~ 24 000 cal yr BP in comparison to the LGM. The distinct excursion enrichments in the isotopic records from ~ 22 000 – 21 000 cal yr BP indicate a prominent shift to drier conditions during this time. The inferences made from changes in indicator taxa for this period correlates to some degree with the isotopic records, with a slight drop in the overall proportion of wet indicator taxa at 21 500 cal yr BP and a distinct peak in the combined percentages of dry indicator taxa (figure 6.1).

Analysing the PCA results (refer to chapter 5) and comparing PC2 to the stable isotope curves for DR-2 points to the possibility that PC2 represents a moisture gradient; with negative scores representing periods within which there are greater percentages of dry Karoo elements. One of these periods, dated to around 21 500 cal yr BP, correlates with the significantly enriched region of the isotope curves, confirming the possibility that water availability was reduced at this time (figure 6.1).

Recent interpretations of previously established palaeoenvironmental records for the region have generally pointed towards a LGM that was homogeneously and consistently cooler and rather wetter than present day (refer to chapter 3); a conclusion that stands in contrast to the inferences made from the De Rif records. All of the previous records, however, are both of significantly lower resolution and temporally discontinuous. None represent the LGM in its entirety (e.g. Elands Bay: Parkington *et al.*, 2000), and in some instances, inferences have been made about the LGM period from records that do not actually cover this episode at all (e.g. Driehoek: Meadows and Sugden, 1991).

Examining the Elands Bay Cave charcoal record in more detail (figures 3.2 and 6.1) indeed confirms that the LGM *per* se is represented by samples at 20 767 and 23 708 cal yr BP. Furthermore, the sample at 20 767 cal yr BP consists entirely of 'mesic thicket' as defined by Parkington *et al.* (2000), indicating conditions drier than those either before or immediately after the LGM (figure 6.1). Further, the mesic thicket group consists of *Diospyros glabra*, *Dodonaea angustifolia*, *Olea europaea ssp. africana*, *Colpoon compressum* and *Ficus cf. cordata* - most of which are found today in a variety of habitats and are capable of withstanding dry conditions. Therefore, despite previously published interpretations and, taken together with the discontinuous nature of the record, the charcoal record from Elands Bay Cave is not inconsistent with the conclusion that a more tightly defined LGM at De Rif was characterised by significantly drier conditions.

The isotope records, and to a lesser degree the pollen data, indicate that from just after 21 000 cal yr BP to 18 000 cal yr BP moisture availability seems to increase with slightly more depleted $\delta^{15}N$ and $\delta^{13}C$ values accompanied by decreases in the percentages of dry indicator taxa (with especially low values for *Dodonaea* and *Anthospermum*-type) and increases in some of the wet indicator taxa (e.g. *Widdringtonia* and Ericaceae).



2000)

- DR-2 PC2 component scores curve (negative values = less moisture availability)
- DR-2 warm and/or dry indicator pollen taxa percentages
- DR-2 stable carbon and nitrogen isotope values
- Antarctic sea ice presence values for the Atlantic sector (Stuut *et al.*, 2004)

Scott and Woodborne (2007b) conclude from the pollen record together with the principal components from the Pakhuis Pass hyrax midden site (which is in close proximity to De Rif (figure 3.1)) that cold, relatively dry conditions prevailed at the site during the period 22 000 – 21 000 cal yr BP. This is inferred from the presence of asteraceous pollen, mainly *Stoebe*-type (including *Elytropappus*) and fynbos elements (Ericaceae, *Passerina* and *Cliffortia*).

The Pakhuis Pass record also indicates that temperature and moisture generally increased from 21 000 – 19 000 cal yr BP while from 16 000 cal yr BP warm, dry conditions prevailed as suggested by the substantial increase in *Dodonaea* (Scott and Woodborne, 2007b). However, the sharp variations in the assemblage (as well as the PCA component score curves) suggest that the predominant environmental signal is characterised by a high degree of variability, especially during the LGM. In addition, the higher proportion of *Stoebe*-type pollen in the sequence during the LGM does not allow for detailed insight into the moisture conditions at the site as it was not possible to identify the contributing species (Scott and Woodborne, 2007a,b). Moreover, *Stoebe*-type pollen occurred throughout most of southern Africa at this time and the associated taxa can clearly adapt to a range of habitats and environmental conditions (Scott *et al.*, 1997; Scott *et al.*, 2004). A further consideration is the nature of the sampling done on the Pakhuis midden – 24 separate hyraceum slabs were sampled and a composite record was pieced together from these blocks. Therefore it does not represent one continuous midden sample like that of DR-2, presenting the possibility of greater contamination and weaker chronological control.

Analysing key indicator taxa extracted from the overall Pakhuis pollen assemblage emphasises the broad trends, highlights the high degree of variability within the record and indicates that in general, the site received greater moisture during the last glacial period in comparison to the Holocene. This appears again to be in contrast with the overall impression gained from the De Rif records that there was a discrete episode of greatly decreased moisture availability within the LGM. This may perhaps be explained by geographical position of the two sites, which are in different parts of the Cederberg (refer to figure 3.1) and could be expected, therefore, have responded uniquely to changes in different climatic drivers. Pakhuis Pass, on the north-easterly, Karoo side of the range, may well have experienced greater proportions of summer rainfall during the LGM as a response to increased easterly flow over the continent during this time (Scott and Woodborne, 2007b; Tyson, 1989; 1999). De Rif, on the other hand, lies on the western side, and consequently may have been influenced to a greater degree than Pakhuis by westerly wave dynamics – discussed in the subsequent paragraphs.

It is proposed here that the key driver underlying climate variability captured in the De Rif records during this period is variation in both the latitudinal position and intensity of the westerly wave belt. As has often been suggested (e.g. van Zinderen Bakker, 1976; Stuut *et al.*, 2004; Chase and Meadows, 2007), this is likely to be related to Antarctic sea ice extent via its influence on thermal gradients in the Southern Ocean and its control on the latitudinal movement of oceanic and atmospheric fronts in this region. As figure 6.1 illustrates, there is a strong correlation between De Rif's isotopic records and sea ice presence in the Atlantic sector of the Southern Ocean. Therefore, during periods within which Antarctic sea ice was extended, the polar vortex expanded and there was a resultant northward shift of the westerly wave belt (Stuut *et al.*, 2004). This would have lead to intensification and/or increase in frequency in the moisture-bearing frontal systems which are responsible for precipitation in the WRZ (Tyson, 1986; Stuut *et al.*, 2004; Chase and Meadows, 2007). A retreat in sea ice would result in a poleward shift in the fronts and therefore, barring the attenuating influence of other moisture-bearing systems, a reduction in rainfall for this area.

An important control on climate dynamics over large temporal and spatial scales is orbital forcing mechanisms. The combination of reduced eccentricity, a reduction in southern hemisphere summer insolation and an obliquity minimum, together with cooler glacial temperatures, would most probably have resulted in general to the development of more extensive Antarctic sea ice during and before the LGM period (Chase and Meadows, 2007). However the precise impact and extent to which these large-scale forcings influence southern African climates and more specifically SWC climate dynamics remains unresolved. In addition, as the reduction in sea ice presence and the resultant arid episode in the De Rif records indicate, regional variations did occur within the LGM period in response to dynamics on a smaller scale than orbitally-forced changes.

Returning to the record, it is notable that, during the period ~26 500 – 22 500 cal yr BP, when there was increased sea ice, the isotope records record greater moisture availability at De Rif. The lower sea ice presence recorded around 21 000 cal yr BP are then associated with a marked decrease in De Rif moisture availability inferred from the marked enrichments in $\delta^{15}N$ and $\delta^{13}C$ values and corresponding increase in dry indicator pollen taxa in the DR-2 record (figure 6.1). From 20 500 to 18 500 cal yr BP, sea ice extent increases again, resulting in enhanced winter rainfall which in turn corresponds to enrichments in the isotopic records. From 18 500 cal yr BP, as climates exhibit a warming trend, sea ice diminishes significantly and has less influence on the climate dynamics of the De Rif area. The isotope records from this point onwards are generally more depleted and therefore indicate broadly increasing moisture availability towards the last glacial – interglacial transition period. With the loss of significant changes in sea ice extent and therefore the correspondingly decreased influence of the westerlies, there seems to be a shift to the dominance of other climatic drivers.

The high resolution inherent in the isotope records provides the opportunity points to the possibility that, despite conclusions drawn from previously established records, this period was in fact not characterised by consistently wet conditions but rather that within a generally mesic phase there was a discrete and dramatic arid episode from 22 000 to 21 000 cal yr BP in response to fluctuations in sea ice presence in the Southern Ocean.

6.2.3 The Last Glacial-Interglacial Transition (LGIT, 18 000 – 11 500 cal yr BP)

The second most significant period of enrichment in the $\delta^{15}N$ and $\delta^{13}C$ records occurred between 12 700 – 11 500 cal yr BP, which corresponds to the YD (12 900 – 11 500 cal yr BP (Alley, 2000)) climatic event recorded widely in northern hemisphere terrestrial and marine records. The pollen assemblage for this transition period does not provide definitive evidence in support of the isotope record which signifies markedly decreased moisture availability. Pollen representation provides rather mixed signals. For example, relatively low proportions of moisture indicators such as Proteaceae and *Stoebe*-type at 11 508 cal yr BP may provide some indication of drier conditions then, as indeed does the peak in *Anthospermum*-type, while Restionaceae peaks at 11 508 cal yr BP and may suggest greater moisture availability (Meadows and Sugden, 1990). However, restios are widely distributed and pollen frequencies reflect a conflation of the changing distributions of many genera within this family - some of which are adapted to high-lying mesic environments and others to more xeric conditions.

The results from the PCA and the pollen indicator curves also do not show an unequivocal YD event. Analysing the entire record, it appears that greater deviations between the isotope records and PC2 seem to occur both during and after the LGIT; with the isotopes and scores mirroring each other during the last glacial period and deviating from each other during the Holocene. This may indicate that vegetation and climatic variations were very different during the Holocene and the late Pleistocene and that the overall indications of stability within the pollen assemblage may be masking changes at levels beyond the scope of the resolution of the pollen data as discussed in section 6.2.1. These deviations also emphasize the likelihood that pollen/vegetation (as well as statistical analysis results on pollen) and isotopic records reflect different responses and timing to climate changes and cannot always be directly compared.

This could be the result of the resilience of fynbos taxa to climate change especially if the change was short-lived.

On a global scale, the transition from glacial to interglacial conditions was indeed dynamic with episodes of renewed glacial conditions punctuating the general warming trend. Notable among these episodes is the YD. The most generally accepted cause of the YD event is a large discharge of melt water into the North Atlantic basin, ultimately resulting in the weakening of the Thermohaline Circulation (Broecker, 1998, 2006). Considering its likely origin, the YD is predictably most pronounced in the northern hemisphere (Peteet, 1995), more particularly in the North Atlantic Basin, whereas in the southern hemisphere evidence of its impact and extent has proved more cryptic.

Identifying manifestations of the YD in the southern hemisphere is complicated not only by a relative dearth of reliable records compared to the northern hemisphere, but also due to the existence of the Antarctic Cold Reversal (ACR) (14 500 -12 500 cal yr BP (EPICA community members, 2006)). Speculation exists over the differing influence of the YD and ACR in the records from the southernmost regions (Fitzsimons, 1997; Vandergoes and Fitzsimons, 2003; Hajdas *et al.*, 2006; Turney *et al.*, 2007). In southern Australasia, a strong ACR signal dominates the records (Turney *et al.*, 2003; Vandergoes *et al.*, 2008). In South America there seems to be a transition zone between ~43° and 38°S (Abarzua *et al.*, 2004) with high latitudes being influenced by the ACR (Sugden *et al.*, 2005) and the sub-tropical areas exhibiting a YD signal (Baker *et al.*, 2001; Moreno *et al.*, 2001). Therefore, generally it seems that the influence of the ACR only extended to the higher latitudes of the southern hemisphere (poleward of ~ 41°S) while at mid-latitudes, climate changes were synchronous with the northern hemisphere (figure 6.2).

In southern Africa, evidence for the YD event has not been unequivocally demonstrated in existing terrestrial records (cf. Scott, 1995; Chase and Meadows, 2007). An oxygen isotope record from terrestrial snail shells at Bushman Rock Shelter in the Transvaal (Abell and Plug, 2000) and the sea-surface temperature record from marine molluscs record at Elands Bay (Cohen *et al.*, 1992) (outlined in chapter 3) shows a cooling between ~12 000 – 11 000 cal yr BP (figure 6.2). From the marine records, a distinct period of lowered sea-surface temperatures (SSTs) corresponding to the YD period is noticeable in the core GeoB1023-5 and from a record of upwelling intensity from the Benguela system (Farmer *et al.*, 2005) (figure 6.2). The absence of an unequivocal YD event in the majority of the terrestrial records found in southern African emphasises the significance of the definite YD event apparent in the De Rif isotopic records.

Based on strong correlations with the Benguela system upwelling intensity record (Farmer *et al.*, 2005) (figure 6.2), it appears that, during the YD, there was a southward shift in the South Atlantic High Pressure (SAHP) system resulting in the intensification of atmospheric and oceanic circulation systems in the region (Dupont *et al.*, 2004). Increased coastal upwelling and associated reductions in SSTs would have resulted in decreased evaporative potential and cooler and drier conditions, and it is likely that the reduced moisture availability indicated in the stable isotope record from De Rif during the YD is a response to this SAHP intensification.

While there remains some uncertainty regarding the exact spatial and temporal character of the YD manifestation in the southern hemisphere as a whole, the correlations presented in figure 6.2 clearly suggest interhemispheric climatic response during the LGIT, with the northern hemisphere strongly influencing all but the high latitudes of the southern hemisphere.

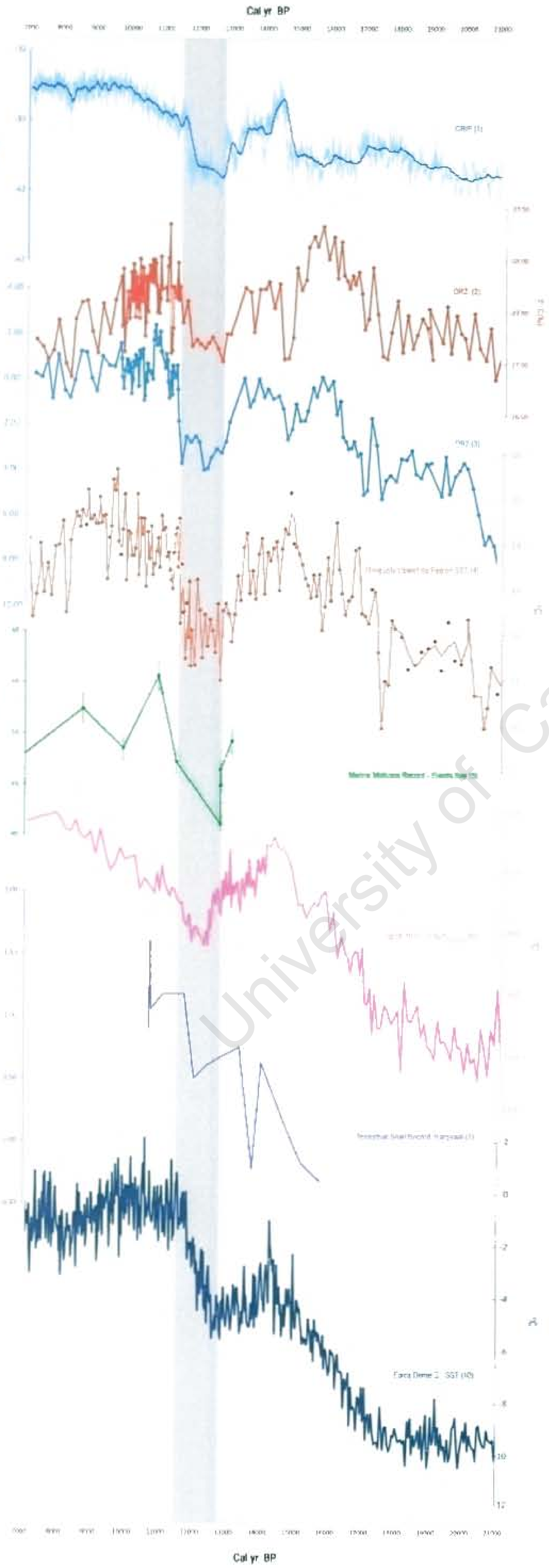


Figure 6.2: Composite graph of the last glacial-interglacial period:

1. Greenland Ice Core $\delta^{18}O$ record (Dansgaard, *et al.*, 1993; GRIP Project Members, 1993; Grootes *et al.*, 1993)
2. De Rif 2 $\delta^{13}C$
3. De Rif 2 $\delta^{15}N$
4. Benguela Upwelling Region sea surface temperatures derived from *N.pachyderma* (left coiling) (Farmer *et al.*, 2005)
5. Marine mollusc record from Elands Bay (% Aragonite in *Patella granularis* shells) (Cohen *et al.*, 1992)
6. Marine core GeoB 1023 – 5 alkenone-derived SST record (Kim *et al.*, 2002)
7. Terrestrial snail (*Achatina* sp.) record from Bushman's Shelter in the Transvaal region, South Africa (Abell and Plug, 2000)
8. Antarctic ice core SST record (Bintanja *et al.*, 2005 Jouzel *et al.*, 2007; Parrenin *et al.*, 2007)

6.2.4 The Holocene

As the DR-2 sequence only extends to ~7 000 cal yr BP and DR-1 encompasses the last ~3 500 years, the De Rif record only covers the early and late Holocene periods.

6.2.4.1 The early Holocene section: ~ 11 500 – 7 000 cal yr BP

Both the stable carbon and nitrogen values are comparatively less enriched compared to the LGM and YD periods (figure 5.5) as well as the modern averages (Appendix E), therefore this period of the Holocene is generally characterised by greater moisture availability. The isotope values are relatively constant throughout this section, especially the $\delta^{15}N$ values which average 0‰. The $\delta^{13}C$ record is more variable with less enriched values from ~11 000 – 10 000 cal yr BP, signifying greater moisture availability during this period. This is followed by progressively more enrichment towards the younger part of the sequence, possibly indicating a decrease in moisture towards the mid-Holocene (figure 6.2).

Corresponding to lower levels of isotopic enrichment from ~11 000 cal yr BP to 10 000 cal yr BP are peaks in arboreal taxa such as *Myrica* and *Euclea*, and Proteaceae at 10 500 cal yr BP (found within pollen assemblage zone DR-2-E). However, there is also an increase in two dry indicator taxa at this time. *Anthospermum*-type increases through this section culminating in the greatest concentration of this taxon at the top of the sequence at 7 300 cal yr BP. There is also the appearance of and sharp increase in *Dodonaea* from 10 850 cal yr BP.

The pollen evidence from Pakhuis Pass (Scott and Woodborne, 2007 a,b), Driehoek and Sneeuberg vleis (Meadows and Sugden, 1991, 1990) support inferences made from the De Rif records of more humid conditions prevailing during the early Holocene. Whereas, the Elands Bay Cave charcoal assemblage exhibits a peak in xeric thicket taxa between 11 000 – 9 000 cal yr BP (Parkington *et al.*, 2000) highlighting the possibility that lowland coastal regions and montane areas could have responded differently to climate change during some periods (refer to chapter 3).

The drying trend evident in $\delta^{13}C$ record and characterised by the significant increase in *Anthospermum*-type and *Dodonaea* pollen provides some indication of the possibility of a warm dry HA, which is consistent with inferences made from various other palaeoenvironmental proxies from both lowland and montane sites in the region (Baxter, 1989, Scott, 1994, Parkington *et al.*, 2000; Meadows and Baxter, 2001; Meadows *et al.*, 1996; Meadows and Baxter, 1999; Selaine *et al.*, in review).

During the Holocene interglacial, climate variability at De Rif seems to have responded to the same oceanic and atmospheric drivers that were responsible for changes in the previous sections. In contrast to the YD, upwelling intensity within the Benguela system during the early Holocene was reduced as indicated by increased SSTs for the period ~ 11 000 – 8 000 cal yr BP (Farmer *et al.*, 2005) (figure 6.2). This would have resulted in increased evaporative potential and therefore potentially wetter conditions, which correlates to the observed increased moisture availability.

Enhanced upwelling once gain resulted in decreased SSTs from ~ 8 000 – 6 000 cal yr BP (Farmer *et al.*, 2005) and subsequently drier conditions. In addition, a decrease in moisture availability during the mid-Holocene is thought to be related to a decrease in the amount and/ or intensity of the frontal systems associated with a contraction or southward displacement of the westerly wave belt (Tyson and Preston-Whyte, 2000; Chase and Meadows, 2007). A southward shift in the westerlies would have also affected easterly wave dynamics with a strengthening Walker Circulation resulting in an increased dominance of tropical easterly flow over the continent (Tyson, 1999). The increase in the dry indicator taxa during this period possibly corresponds to pollen transport regimes associated with an increase in easterly flow off the Karoo. This would have resulted in an increase in xeric Karoo taxa such as *Anthospermum*-type and *Dodonaea*.

6.2.4.2 The late Holocene section: ~ 3 500 – 950 cal yr BP

This section is represented in the DR-1 records. The isotope results indicate that, in comparison to the modern isotope averages and the DR-2 range, relatively moist conditions prevailed at the site, especially within the earlier portion of the record from ~3 500 – 2 300 cal yr BP. A slight enrichment in both the $\delta^{13}C$ and $\delta^{15}N$ values from ~2 300 cal yr BP to 950 cal yr BP suggests that there was less available moisture at the top of the sequence. The increased proportion of charcoal fragments from ~1 500 cal yr BP falls within this slightly drier period. Despite this, the overall $\delta^{13}C$ and $\delta^{15}N$ ranges only exhibit very small variations signifying that minimal environmental change occurred at DR-1 during the late Holocene. Consistent with the inferences made from the overall isotope records, the pollen assemblage for DR-1 reveals very little variability, with the sequence being dominated by the presence of typical mountain fynbos taxa (refer to figure 5.1).

The pollen evidence from Driehoek and Sneeuberg vleis for the Holocene period also indicates that very modulated environmental changes took place (Sugden, 1989; Meadows and Sugden, 1990, 1991). A similar conclusion can be drawn from nearby Truitjes Kraal 4 (TK-4) with both the isotope and pollen data suggesting that there have been no major variation in precipitation during the Holocene (Selaine *et al.*, in review). In addition, figures 6.3a and b illustrate that, despite being from different locations and therefore having different absolute ranges as well as being sampled slightly differently, the isotope records from DR-1 and TK-4 exhibit similar trends. [The reason for the less depleted nitrogen signal at TK-4 in comparison to the $\delta^{15}N$ records from De Rif is due to the differences in their microclimates – De Rif is a high altitude mountain catchment whereas Truijes Kraal is situated in a more open environment at a lower altitude and the difference in precipitation between these two sites is presently about 120 mm].

In contrast to the minimum variation in the isotope and pollen data from the above records, evidence from Pakhuis Pass indicates greater variability from ~2 500 to the present (Scott and Woodborne, 2007a,b). This could, however, simply be a result of greater local climate variability due to Pakhuis Pass' sensitive position in the rain shadow of the Cederberg. Also it is possible that Pakhuis Pass was again influenced by greater amounts of summer rainfall.

Inferences from Cecilia Cave, Grootdrift and Klaarfontein of increased humidity relative to the HA during the period 4 000 – 2 000 cal yr BP (Baxter, 1989; Meadows and Baxter, 1999; Meadows and Baxter, 2001) support the depleted DR-1 isotope values which is especially evident between ~3 500 – 2 300 cal yr BP. Wetter conditions during this time may have been the result of a relative increase in the influence of the westerlies after the HA (Chase and Meadows, 2007).

As the De Rif record for the Holocene period is discontinuous and represented by data from two separate middens, it is not possible to resolve this period as tightly as the other sections. However, it does seem that the overall conclusion that can be drawn from the available information is that, in comparison to the major climate changes discussed in sections 6.2.2 and 6.2.3, relatively stable conditions prevailed in the Cederberg during the Holocene.

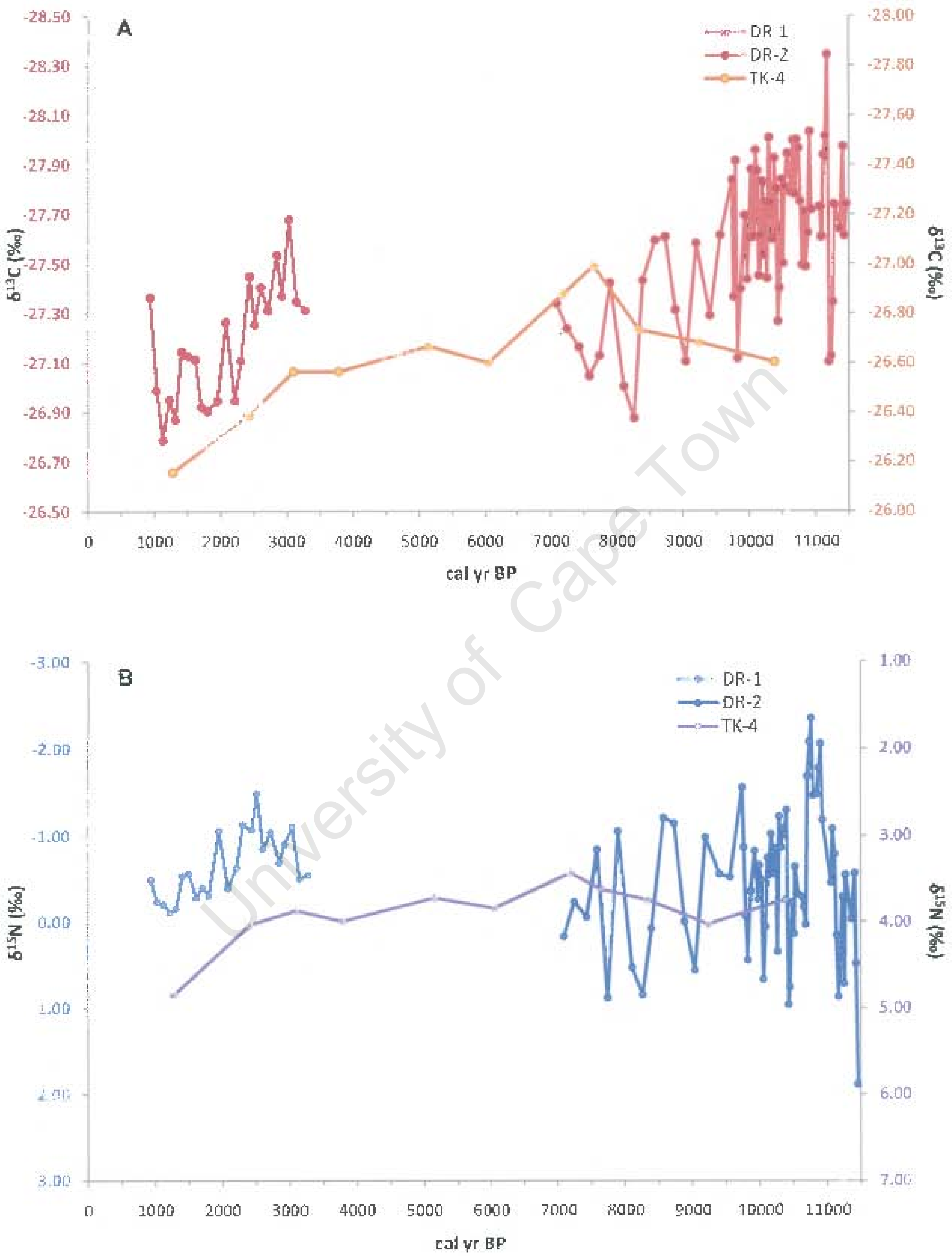


Figure 6.3: De Rif 1 & 2 (DR-1 & DR-2) and Truitjes Kraal (TK-4) δ13C (A) and δ15N (B) isotopes

6.3 CONCLUSION

The major findings that have been presented and discussed within this chapter are the following:

- The De Rif isotope and pollen records indicate that the last glacial period was generally characterised by mesic conditions, a conclusion which is supported by various other records from the SWC. However, the high resolution DR-2 isotope record shows that this period was punctuated by a discrete arid episode from 22 000 – 21 000 cal yr BP. Correlations to changes in Antarctic sea ice presence and its influence on the latitudinal position and/or intensity of the westerly wave belt provides the mechanism for the observed environmental changes during this period.
- A significant period of isotopic enrichment, indicating a decrease in moisture availability, is evident during the period 12 700 – 11 500 cal yr BP correlating to the YD climatic event. The pollen record as well as the PCA results does not fully support the isotope records. This suggests that the pollen records may be limited by low taxonomic resolution and may mask or subdue climate dynamics and/or that fynbos taxa are particularly resilient to climate change especially if the change is over relatively short periods.
- The YD signal in the De Rif isotope records is strongly linked to variations in SSTs and upwelling intensity within the Benguela system and provides key evidence for interhemispheric climate change during the LGIT.
- The early Holocene, especially the period from ~11 000 to 10 000 cal yr BP, seemed to have been wetter, followed by a decrease in moisture towards the mid-Holocene.
- The DR-1 isotope and pollen records signify that minimal environmental change occurred during the late Holocene, which is an outcome that is supported by the findings of other studies in the Cederberg area.

7 Synthesis and Conclusions

7.1 INTRODUCTION

By analysing the pollen and isotope data derived from the De Rif middens; this study has produced a multi-proxy record that represents a significant contribution to the palaeoenvironmental history of the Cederberg and the southwestern Cape. This chapter begins with a synthesis of the key outcomes of the study detailing the major palaeoenvironmental changes that have been inferred from the De Rif records. This is followed by a review of the original aims and objectives and concludes with a brief outline of future research directions.

7.2 PALAEOENVIRONMENTAL SYNTHESIS

Previous palaeoenvironmental records and reviews have indicated that conditions were generally cooler and wetter than present day along the western margin of southern Africa during the last glacial period (Schalke, 1973; Klein *et al.*, 1999; Meadows and Baxter, 1999; Klein and Cruz-Uribe, 2000; Parkington *et al.*, 2000; Stuut *et al.*, 2002; Lancaster, 2002; Chase and Meadows, 2007). The isotope and pollen records from De Rif generally support this inference as they show that greater moisture was available during this time. However, the distinct excursion in the DR-2 isotope records from ~ 22 000 – 21 000 cal yr BP indicate that this period was punctuated by a discrete arid episode.

The driving mechanism behind the observed climate variability at De Rif is tied to strong correlations between the isotope records and Antarctic sea ice presence and the influence of changing sea ice extent on the latitudinal position and/or intensity of the westerly wave belt. With an extension of sea ice, the polar vortex would have expanded leading to an intensification and/or increase in frequency in the moisture-bearing frontal systems which are responsible for precipitation in the WRZ (van Zinderen Bakker, 1976; Tyson, 1986; Stuut *et al.*, 2004; Chase and Meadows, 2007). In contrast, a retreat in sea ice, such as the one at ~ 21 000 cal yr BP, would have resulted in a poleward shift in the frontal systems and therefore a reduction in rainfall.

The De Rif records suggest that the last glacial period was not homogeneously and consistently wetter than present day, pointing to the possibility that the LGM period was more of a transitional phase that therefore should not be considered as the best representation of southern African glacial conditions.

Moving out of the last glacial period, when climates begin to exhibit a warming trend, the influence of sea ice dynamics is considerably reduced. The De Rif records are generally more depleted and therefore indicate broadly increasing moisture availability towards the LGIT. With the loss of significant changes in sea ice extent and the corresponding decreased influence of the westerlies, different mechanisms start to drive climate change in the SWC including regional intensifications of oceanic and atmospheric systems.

Within the LGIT, there is an abrupt return to near-glacial environments as a result of the presence of the YD episode (12 900 – 11 500 cal yr BP (Alley, 2000)). The De Rif isotope records indicate that the period 12 700 – 11 500 cal yr BP was characterised by significantly decreased moisture availability and provide the first clear manifestation of the YD in southern Africa. The LGIT period seems to have responded to climate dynamics associated with west coast SSTs and shifts in the SAHP cell with the De Rif isotope records strongly correlating to the Benguela system upwelling intensity record (Farmer *et al.*, 2005). Increased coastal upwelling and associated reductions in SSTs would have resulted in decreased evaporative potential and cooler and drier conditions; and it is likely that the reduced moisture availability, indicated in the stable isotope record from De Rif during the YD, is a response to this SAHP intensification.

The De Rif records help to differentiate between the relative influence of the YD and ACR and supports the hypothesis that the influence of the ACR only extended to the higher latitudes of the southern hemisphere (poleward of ~ 41°S) while at mid-latitudes, climate changes were synchronous with the northern hemisphere.

Despite the fact that the De Rif records do not cover the Holocene in its entirety, when viewed in conjunction with other palaeoenvironmental records in the Cederberg, it can be inferred that relatively stable conditions prevailed in this region during this period (Meadows and Sugden, 1990, 1991; Selaine *et al.*, in review).

7.3 REVIEW OF AIM AND OBJECTIVES

The primary aim of this research was to use hyrax middens to investigate the vegetation dynamics and associated environmental conditions in the Cederberg over the last 28 ka, through the application of pollen analysis and stable isotope geochemistry.

To address this aim a thorough examination of the contemporary environment of the De Rif site took place (chapter 2) and a review of the existing palaeoenvironmental records for the Cederberg and the southwestern Cape was undertaken (chapter 3). The review highlighted the discontinuous nature of the available records and emphasised the lack of an overall cohesive palaeoenvironmental history for the southwestern Cape.

The potential for the use of hyrax middens in palaeoenvironmental studies was firmly established in chapter 4. The identification, sampling and analysis of material from the hyrax middens DR-1 and DR-2 made it possible to meet the specific objectives outlined in chapter 1 and generate the results presented in chapter 5. Through the use of radiocarbon analysis a high resolution chronology of accumulation was established. Pollen was extracted from the midden material and two pollen records illustrating the vegetation community structures over the periods: ~700 – 3 500 cal yr BP and ~7 000 – 28 000 cal yr BP were constructed. The stable carbon and nitrogen isotope results that were produced were particularly successful in revealing significant changes in moisture availability at the study area during the accumulation periods. Chapter 6 discussed the results of the study against the backdrop of previous palaeoenvironmental records for the region (as reviewed in chapter 3) and presented correlations between the De Rif records and other southern African climate proxies highlighting possible mechanisms for the observed climate change events.

7.4 FUTURE RESEARCH DIRECTIONS

Given the limited number of published records for the SWC and the discontinuous temporal and spatial nature of these records, further work in support of the findings from this project needs to be undertaken to fully resolve the palaeoenvironmental history of this region. Furthermore, previous interpretations of many of these records for the region have been formulated using information that is potentially ambiguous, with many inferences being made about the environment during key climate change periods such as the LGM despite the fact that this period has been poorly represented and inaccurately dated. Therefore, a thorough re-assessment of many of these existing records will be undertaken.

Another aspect that will be explored in a future research project will be the extent and nature of past changes in the seasonality of rainfall. This will be achieved by the expansion of the work done at De Rif, the re-examination of other sites in the region such as Pakhuis Pass and Driehoek vlei and the exploration of new sites.

In addition, more detailed analysis will be done on the De Rif pollen data in order to fully understand and quantify the principle mechanisms underlying past vegetation responses to the climates changes observed in the isotope record. As pollen data reflects the integrated effects of both climatic and biotic processes the analysis of this type of data can be complex. To identify the ecological controls and main climate dependencies of specific indicator taxa bioclimatic modelling will be used. Predictive modelling of species environmental requirements and their geographic distributions using maximum entropy techniques within the programme *Maxent* (Phillips *et al.*, 2006) will be used to determine the specific ecological constraints of important pollen taxa. To enable quantitative reconstructions of palaeoclimates, the *pdf* (probability density function) method will be investigated. This method focuses on probability density functions as botanical-climatological transfer functions that statistically describe climate (temperature or moisture) - species relationships (Kühl *et al.* 2002). This method determines the climate dependencies of individual taxa and enables the use of both modern climate data and fossil pollen data to reconstruct past climates.

Further, new sites within the Western Cape will be examined and pollen analysis will be carried out in order to expand the spatial extent of the research. In summary, four factors exemplify the significance of the findings that will emanate from these future research directions, namely:

- Greater understanding of Western Cape contemporary environments and palaeoenvironments.
- Improved understanding of regional and hemispheric circulation dynamics.
- Climatic context for understanding the region's biodiversity.

7.5 CONCLUSION

Southern African palaeoenvironments have responded to a complex range of climate controls, located in the heart of the SWC; the Cederberg has been no exception. Despite the examination of existing palaeoenvironmental records in the Cederberg, the exact nature of past environmental conditions in this area as well as the overall SWC region remains to be fully resolved.

In order to elucidate environmental conditions in the Cederberg and the SWC during the late Quaternary and synthesise the existing palaeoenvironmental records, new evidence in the form of two hyrax midden deposits from De Rif were examined. Through the application of pollen analysis to the hyrax midden material, local plant communities were inferred and, through this, a palaeoenvironmental reconstruction of prevailing conditions over the period of midden accumulation was produced. Stable carbon and nitrogen isotope analysis applied to the midden material registered palaeoenvironmental changes by identifying variations in water-use efficiencies and therefore provided significant information on changing water availabilities over the last 28 ka. The pollen and stable isotope results cast new light on two key climate change periods, namely the LGM and the YD and provided links to how changes in SSTs, expansions of the circumpolar vortex and shifts of the westerlies have modified regional climates.

Therefore, the establishment of the De Rif record not only provides greater insight into the environmental history of the SWC during the last 28 ka but also places southern African palaeoenvironments within the broader hemispheric climate dynamics of the late Quaternary.

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APPENDIX A: GIS SHAPEFILES

1. Geology of South Africa shapefile: Council of Geosciences, obtained from African Earth Observatory Network (AEON)
2. Vegetation types, biome types, national and provincial boundaries, towns and cities and national park boundaries shapefiles: Vegmap 1996 and 2006:

   A. B. Low and A. G. Rebelo (eds)., 1996. Fynbos Biome. Vegetation of South Africa, Lesotho and Swasiland. Pretoria, Department of Environmental Affairs and Tourism.

   Mucina, L., and Rutherford, M. C. 2006. The Vegetation of South Africa, Lesotho and Swaziland. South African National Biodiversity Institute, Pretoria.

APPENDIX B:

HYRAX MIDDEN POLLEN SAMPLE PREPARATION USING ZINC CHLORIDE HEAVY LIQUID SEPARATION

- Determine the type and amount of spike to be added (used lycopodium 1 tablet per sample).
- Set up a test tube rack with 2 sets of 50 ml centrifuge tubes (one will hold sample; the other the stir stick for the sample).
- Weigh samples (generally need at least 1g of material is required to assure sufficient pollen concentrations.
- In clean 50 ml centrifuge tubes, add ~25 ml of distilled water (DW) to sample. Allow to sit for several minutes in warmed water bath and then with a stirring rod/Vortex mixer gently break up sample (or leave in DW and 10% HCl overnight).
- Add 2-3 drops of tertiary butyl alcohol (TBA) to wet down any floating particles; centrifuge for 5 minutes at 3000 rpm and decant.

<u>Section A: Material preparation</u>

1. Sieve the sample using ~160 µm sieve, washing through sieve using DW.
2. Pour into 50 ml centrifuge tubes, balance with DW, centrifuge for 5 minutes at 3000 rpm, and decant.
3. Repeat until all sieved liquid has been centrifuged.
4. Add about 1 ml of 10% HCl to each sample initially and stir in very gently. Control foaming by adding 1-2 drops TBA.
5. Add another ~5 ml of 10% HCl, do not let the reaction overflow the test tube.
6. Add a lycopodium tablet
7. Heat samples for about 10 minutes in gently boiling water bath. When the reaction is complete, centrifuge and decant.

8. Add about 6 ml of 10% KOH to each sample and stir gently.
9. Heat with occasional stirring in actively boiling water bath for 10 to 20 minutes.

10. Remove from heat: fill with DW, stir, add TBA, centrifuge and decant.
11. Rinse with DW again and check for obvious clumping.
12. Repeat this KOH step again.
13. Repeat rinsing 3 to 5 times, adding TBA when necessary. Stop when clear or almost clear. This removes many < 3 μ particles that interfere with pollen counting.

<u>Section B: Heavy liquid separation</u>

1. Dissolve zinc chloride in 10% HCl to achieve a specific gravity (SG) of 2.0. The formula for the heavy liquid SG 2.0 = 225g of zinc chloride per 100 ml 10% HCl.
2. After decanting rinse at the end of Section A., pour in ~ 20 ml of heavy liquid, cap and mix.
3. Bend and double rubber tubing, and insert into separate 50 ml centrifuge tube.
4. Pour sample into rubber tubing, making an effort to fill each side to the same level.
5. Balance the tubes by weighing and putting water into the centrifuge tubes (not the rubber tubing) until all tubes are the same weight.
6. Centrifuge for 5 minutes at 3000 rpm.
7. For each sample, wash a 50 ml glass beaker with DW.
8. When centrifuge cycle is finished, remove from centrifuging and gently pull rubber tube out of the centrifuge tube until the suspended material is about 1 cm above lip of centrifuge tube. If the liquid is not clear below the suspended material, return tubes t the centrifuge and run another cycle. If the liquid is still not clear, the SG of the heavy liquid may be incorrect.
9. If a distinct skim of suspended material is evident, holding the tube upright, pinch off one end of the rubber tube with a pair of needle-nosed pliers just below the material.
10. Making sure to keep the tube upright, tip the pinched off end of the tube into the prepared glass beaker, and rinse several times with DW. Be sure you maintain a firm grip on the pliers.
11. Repeat with other end of the tube, using the same beaker.
12. The remainder of the heavy liquid can be discarded.

13. Put contents of the beakers into centrifuge tubes, balance with DW ensuring that enough is added to reduce the SG of the liquid (~30 ml including sample and residual heavy liquid) and centrifuge.
14. Decant, refill with DW, and centrifuge again, repeating 2-3 times.
15. Transfer to properly labelled, dry ½ dram shell vials.

Section C: Microscope slide mounting

1. Place glass slides and beaker of glycerol jelly on hot plate
2. Add 2 drops of liquid glycerol to each slide
3. Using a pipette extract some of the pollen preparation from the dram shell vials and place 1-2 drops of the pollen sample on each slide
4. Gently mix the two substances and evenly spread the resultant mixture across the surface of the slides
5. Allow for the evaporation of the remaining water by leaving the slides on the hot plate for approximately a minute
6. Take slides off the heat and seal with coverslips

[Method adapted from the Limnological Research Centre, University of Minnesota]

APPENDIX C: ABSOLUTE POLLEN COUNTS

Sample Name	Average Depth (mm)	Age (cal yr BP)	Acacia	Blechnaceae	Celastraceae	Diospyros	Dodonea	[illegible]	Euclea	Grewia	Ilex	Lycium	Myrica	Myrsine	Myrtaceae	Olea	Pinaceae	Podocarpus	Rhus	Widdringtonia
DR1 COUNTS																				
Modern pellets			0	0	0	2	0	0	2	0	0	0	1	4	2	3	0	0	0	0
Surface sample			0	0	1	5	14	0	0	0	0	0	1	1	0	7	2	3	8	9
DR1-1	3	732	0	0	0	0	2	0	2	0	0	0	0	0	1	1	0	0	0	4
DR1-3	13	1072	3	0	0	1	0	1	0	0	0	0	1	2	0	0	0	0	1	8
DR1-5	23	1412	0	2	0	5	0	0	1	0	0	0	0	2	0	0	0	0	0	2
DR1-7	33	1752	0	0	0	1	0	0	2	0	0	0	1	0	0	2	0	0	0	3
DR1-9	43	2052	0	0	0	3	0	0	2	0	0	0	0	0	0	0	0	1	1	6
DR1-11	53	2432	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	3
DR1-13	63	2772	0	0	0	2	0	0	2	0	0	0	0	1	0	4	0	0	0	3
DR1-15	73	3112	0	0	0	1	0	0	0	0	0	0	1	1	0	1	0	1	2	4
DR1-17	83	3452	1	1	0	0	2	0	2	0	0	0	0	1	0	0	0	0	3	6
DR2 COUNTS																				
Modern pellets			0	0	0	2	11	0	3	0	0	0	1	1	0	0	0	0	0	1
Surface sample			0	1	0	5	10	0	4	0	0	3	2	0	0	3	4	0	1	8
DR2-3rd-24	25.25	7339	1	0	0	2	6	1	2	0	0	2	3	3	0	0	0	0	0	5
DR2-3rd-41	47.25	8482	0	0	0	0	15	0	1	0	0	0	1	1	1	0	0	0	0	4
DR2-3rd-58	71.25	9696	0	0	0	2	12	2	2	0	0	0	3	4	2	0	0	0	0	14
DR2-3rd-104	103.5	10074	1	1	2	2	12	0	2	0	0	0	0	3	1	0	0	0	0	2
DR2-3rd-141	143.25	10497	0	5	0	3	21	2	5	0	0	0	8	2	0	1	0	0	1	6
DR2-3rd-173	176.5	10850	0	0	0	1	10	0	2	0	0	0	1	2	0	1	0	0	1	1
DR2-3rd-204	209.25	11230	0	0	0	4	1	0	0	0	0	0	1	4	0	1	0	0	0	4
DR2-3rd-222	234.5	11563	0	0	0	0	0	0	2	0	0	0	0	1	0	0	0	0	0	7
DR2-3rd-245	254.75	12649	0	0	0	1	0	0	3	0	1	4	2	7	2	0	0	0	0	4
DR2-2nd-266	276	13276	0	0	0	0	2	0	1	0	0	0	1	2	2	0	0	0	1	1
DR2-2nd-353	303.25	14614	0	0	0	0	1	0	3	0	0	0	1	5	2	1	0	0	0	2
DR2-3rd-303	319	16024	1	0	0	3	0	1	1	0	0	1	2	0	1	0	0	0	0	8
DR2-2nd-411	340.25	16831	0	1	0	2	0	4	2	0	0	0	1	2	1	0	0	0	0	8
DR2-3rd-325	354.5	17151	2	1	0	1	0	1	3	0	0	1	0	0	0	2	0	0	1	7
Dr2-3rd-340	364.5	17182	2	0	0	1	1	1	0	0	0	0	0	2	0	1	0	0	0	5
DR2-2nd-392	385	18679	0	7	0	2	1	4	3	0	0	0	0	2	0	0	0	0	0	4
DR2-2nd-50	408.75	19835	0	3	0	1	2	0	2	0	0	0	0	0	0	0	0	0	0	11
DR2-2nd-56	425	20731	0	7	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	14
DR2-2nd-455	438.75	21254	0	0	0	1	0	0	2	0	0	0	0	0	0	0	0	0	0	7
DR2-2nd-500	447.5	21503	1	0	1	1	0	1	2	0	0	0	0	1	0	0	0	0	0	8
DR2-2nd-483	471	22742	1	0	0	4	2	2	7	0	0	2	4	2	0	0	0	0	0	6
DR2-2nd-502	490.5	23654	0	0	0	0	1	1	1	1	0	0	1	2	0	0	0	0	0	7
DR2-2nd-530	512.75	24894	0	0	0	3	2	1	3	0	0	0	0	1	1	0	0	1	0	4
DR2-2nd-561	522.5	25190	0	0	0	3	0	0	4	1	0	0	0	3	1	0	0	2	1	1
DR2-2nd-588	575.25	27617	2	4	0	1	2	0	3	0	0	0	2	3	0	0	0	1	1	7
DR2-2nd-590	597.25	28946	3	3	0	1	0	0	7	3	0	0	2	0	0	1	0	0	1	8

Sample Name	Apiaceae	Anthospermum-type	Araceae	Asteraceae high spine	Artemisia	Stoebe-type	Pentzia-type	Bromaceae	Cliffortia	Ericaceae	Fabaceae	Lamiaceae	Lobostemon	Molluginaceae	Onagraceae	Oxygonum	Polygonum	Proteaceae	Rhamnaceae	Rutaceae	Santalaceae	Scroph type	Sterculiaceae	Thymelaeaceae	Passerina
DR1 COUNTS																									
Modern pellets	0	0	0	2	0	76	18	3	0	0	0	0	0	4	0	0	0	63	0	0	8	1	0	0	0
Surface sample	0	43	0	28	3	35	5	0	0	1	0	0	0	0	0	0	0	8	0	3	1	3	1	4	1
DR1-1	0	22	0	16	1	42	4	0	1	4	0	1	0	3	0	0	0	8	0	0	1	1	0	0	4
DR1-3	0	22	3	27	1	20	0	0	1	4	0	0	0	4	0	0	0	12	0	0	0	0	0	0	2
DR1-5	0	23	0	14	1	27	4	0	0	0	0	0	4	0	0	0	0	11	0	0	0	2	2	1	1
DR1-7	0	24	0	14	1	37	8	0	0	4	0	3	1	0	0	0	0	11	0	0	0	0	0	1	0
DR1-9	0	26	0	14	1	39	3	0	0	8	0	0	0	3	0	0	0	5	1	0	0	0	0	0	2
DR1-11	0	25	0	22	0	40	3	0	0	8	0	1	1	0	0	0	0	10	0	0	0	1	0	0	0
DR1-13	0	0	0	15	3	23	4	0	0	0	0	0	0	4	0	0	0	6	2	3	5	0	0	0	1
DR1-15	0	15	0	13	0	35	5	1	1	8	0	0	0	0	0	0	0	8	0	0	0	0	0	1	2
DR1-17	0	12	0	5	1	23	1	0	0	6	0	2	0	8	0	0	0	13	0	0	0	1	0	0	1
DR2 COUNTS																									
Modern pellets	0	40	0	10	4	18	12	0	1	4	1	0	0	6	0	0	0	0	0	1	2	0	4	0	0
Surface sample	0	9	0	15	1	54	2	2	1	2	0	1	3	5	0	0	0	1	2	2	0	7	1	0	0
DR2-3rd-24	1	23	0	9	4	21	4	0	0	0	0	0	2	2	0	0	0	13	0	3	1	1	4	0	1
DR2-3rd-41	0	16	0	7	4	32	3	0	3	8	0	2	0	2	0	0	0	9	2	0	0	0	0	1	0
DR2-3rd-58	0	4	0	8	0	64	1	0	0	3	0	2	0	4	0	0	0	9	0	1	0	4	3	3	1
DR2-3rd-104	0	13	0	3	1	20	1	1	0	2	0	2	0	1	0	0	1	8	0	0	1	3	1	5	7
DR2-3rd-141	0	6	2	8	0	15	5	0	0	8	0	1	0	3	0	1	0	31	1	1	0	2	0	0	0
DR2-3rd-173	1	8	0	10	2	10	3	0	0	8	0	0	0	4	0	1	0	28	0	1	1	2	2	1	0
DR2-3rd-204	0	4	0	7	1	22	2	0	0	5	2	0	1	4	0	0	0	16	0	0	0	1	2	0	1
DR2-3rd-222	0	11	0	1	1	19	3	0	0	8	0	4	0	0	0	0	0	7	0	0	2	0	0	6	2
DR2-3rd-245	0	7	0	5	2	12	0	1	0	2	0	0	0	2	0	0	0	17	2	0	0	0	0	0	1
DR2-2nd-266	0	9	0	7	1	38	11	3	0	10	0	2	0	0	0	0	0	22	1	0	1	2	0	4	1
DR2-2nd-353	0	9	2	14	0	23	27	0	0	16	0	0	0	0	0	1	0	11	[illegible]	0	1	0	0	0	0
DR2-3rd-303	0	1	0	13	3	32	15	1	0	15	0	2	1	0	0	0	0	0	0	0	0	0	2	0	1
DR2-2nd-411	0	6	0	21	2	40	0	1	0	6	0	2	0	0	1	0	0	0	0	0	4	2	1	1	2
DR2-3rd-325	0	8	0	5	2	32	11	2	0	13	0	0	0	0	0	0	0	2	0	0	7	0	0	0	0
Dr2-3rd-340	0	4	0	6	1	60	18	0	3	12	0	0	0	0	0	0	0	1	0	0	2	1	0	0	0
DR2-2nd-392	0	4	0	12	2	28	5	0	0	0	0	0	2	0	0	0	0	0	0	0	1	1	0	0	0
DR2-2nd-50	0	4	0	7	3	34	4	3	0	7	0	0	0	0	0	0	0	6	1	1	0	1	0	1	1
DR2-2nd-56	0	2	0	7	5	16	2	1	0	5	2	1	0	0	0	0	0	5	0	0	0	0	0	1	0
DR2-2nd-455	1	4	0	20	2	38	13	0	0	8	0	0	0	0	0	0	0	2	0	0	2	2	0	1	0
DR2-2nd-500	0	0	0	14	1	78	10	1	0	13	0	0	0	0	0	0	0	5	0	0	1	0	0	0	0
DR2-2nd-483	0	2	0	8	0	42	0	0	0	7	1	0	0	1	3	0	0	3	0	1	1	1	0	0	0
DR2-2nd-502	0	3	0	8	0	42	4	1	2	10	0	0	0	1	1	0	0	9	0	0	1	2	0	0	1
DR2-2nd-530	0	2	0	2	2	32	2	4	1	5	0	0	0	0	0	1	0	1	2	1	0	1	0	[illegible]	[illegible]
DR2-2nd-561	0	2	0	2	1	43	2	0	3	7	0	0	2	0	2	0	0	4	0	2	0	0	1	0	0
DR2-2nd-588	0	1	2	6	5	11	3	0	0	2	0	0	1	0	2	0	0	5	0	1	3	3	0	2	1
DR2-2nd-590	0	2	5	5	1	15	4	0	0	6	0	0	0	0	0	1	0	5	0	0	1	0	0	0	0

APPENDIX C: ABSOLUTE POLLEN COUNTS continued

Cambium	Galium	Aizoaceae	Euphorbiaceae undif	Euphorbia	Clutia	ChenAm-type	Crassula	Ruschia	Cyperaceae	Restionaceae	Juncaceae	Brassicaceae	Campanulaceae	Caryophyllaceae	Gunnera	Polygala	Malvaceae	Scabiosa	Selaginaceae	Verbenaceae	Liliaceae	Iridaceae	Amaryllidaceae	Poaceae	Aloe-type	Aponogeton	Pellaea	Celluloseum	Mohria	Trilete	Monolete	Riccia	Algae cells	Unknown Type 1	Unidentifiable	Charcoal	Broken	Exotics	Total Land Pollen	Weight (g)	Concentration (grains per gram)
0	0	6	0	0	0	0	1	1	4	1	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	18	0	5	0	3	0	3	22	245	2.04	101444.6301
0	1	8	1	1	1	0	5	3	8	1	0	3	0	0	0	0	0	2	0	3	0	0	0	8	2	0	1	0	1	1	4	0	2	0	2	146	5	27	250	2.46	86845.04067
0	0	7	0	1	0	1	1	2	45	29	1	0	0	0	0	0	0	0	0	1	0	0	0	40	0	0	0	0	0	1	21	0	12	0	2	86	9	9	258	4.25	125344.1569
0	0	5	0	2	0	1	0	0	36	27	0	0	0	0	0	0	0	0	0	1	0	0	0	21	0	0	0	0	6	14	9	0	0	0	0	65	22	39	238	1.83	85572.87467
0	0	8	1	1	0	2	0	0	47	41	4	0	0	0	0	0	0	0	0	0	0	0	0	37	0	0	0	0	0	4	17	1	7	0	0	53	13	31	257	1.06	76004.64847
0	0	5	0	0	0	0	2	0	48	48	1	0	0	0	0	0	0	0	0	0	0	0	0	26	0	0	0	0	0	2	12	0	0	0	0	71	6	33	255	2.29	62706.6310
0	0	13	0	0	0	1	0	1	48	30	0	0	0	0	0	0	0	1	0	0	0	0	0	42	0	0	0	0	0	3	10	0	0	0	0	46	12	22	263	2.42	91798.06536
0	0	3	0	7	1	1	1	1	35	75	5	0	0	0	0	0	0	0	0	0	1	0	0	26	0	0	0	0	1	2	6	0	0	0	0	64	7	42	266	2.15	56863.45526
0	0	7	0	2	1	1	0	7	74	40	1	0	0	0	0	0	0	0	0	0	0	0	0	31	0	0	0	0	0	0	4	0	0	0	0	29	10	29	252	1.76	55026.73465
0	0	4	0	2	0	4	0	2	56	56	0	2	0	0	0	0	0	0	0	1	0	0	0	26	0	0	0	0	0	1	15	0	0	0	0	57	18	16	279	1.93	187886.9756
0	0	7	0	1	0	0	1	1	72	41	1	0	0	0	0	0	0	0	0	1	0	0	0	22	0	0	0	0	1	0	13	0	0	0	0	44	7	13	250	4.03	86879.2741
12	5	5	1	0	0	0	1	4	62	0	4	0	0	0	0	0	0	0	0	1	1	3	0	0	4	0	0	0	1	4	5	0	13	0	0	0	9	13	256	2.14	222301.3064
0	3	2	7	3	2	1	10	1	43	6	10	3	0	0	0	0	0	1	0	4	0	1	0	12	0	0	0	1	0	3	10	1	5	0	2	164	3	20	263	2.14	109846.1075
4	3	1	0	2	0	0	2	2	24	48	6	1	0	0	1	1	0	1	1	5	2	2	1	16	2	0	2	0	0	8	23	3	3	7	2	373	5	103	250	0.56	38328.95431
1	0	0	0	2	0	0	1	3	34	50	4	0	0	0	0	2	1	0	0	3	1	0	0	26	0	0	0	0	0	7	15	1	4	2	0	199	5	39	251	0.88	137916.4104
2	0	2	0	1	0	0	0	0	27	32	8	0	0	0	0	0	0	0	0	3	1	1	0	23	4	0	0	0	0	4	19	1	5	1	3	205	7	62	236	0.98	76265.72067
0	0	0	1	7	0	0	5	0	52	58	2	0	0	0	0	1	0	0	0	0	0	0	0	10	0	0	0	0	0	2	10	2	2	0	1	129	4	56	262	1.01	84300.81809
4	0	0	1	2	0	0	0	3	27	51	1	0	0	0	0	1	0	0	0	5	1	0	0	17	0	0	0	0	0	6	8	1	8	0	0	67	5	47	262	0.84	118814.8536
1	0	0	0	0	0	0	0	0	65	71	0	0	0	0	0	1	0	0	0	0	0	0	0	18	0	0	0	0	0	4	3	0	0	0	1	36	2	61	258	0.62	71623.72779
3	0	0	1	0	0	2	0	7	60	57	4	0	0	1	0	0	1	0	2	0	0	0	0	13	0	0	3	0	0	0	4	1	0	1	0	75	2	41	256	0.58	116838.4077
2	0	0	0	0	0	0	0	1	34	109	2	0	0	0	0	1	0	0	0	0	1	4	2	16	1	0	1	0	0	2	24	0		0	1	212	8	23	252	0.9	226227.8281
1	0	2	0	0	0	0	7	4	75	62	5	0	0	0	0	0	0	0	1	2	2	1	0	13	0	0	0	0	0	2	10	4	1	0	2	131	7	27	250	1.05	163971.2522
0	0	1	0	0	1	2	1	2	50	61	2	0	0	0	0	1	0	0	1	1	1	0	1	10	0	0	0	0	0	2	25	2	1	3	1	113	5	42	250	0.97	127141.4968
2	0	2	1	1	0	0	0	3	53	44	1	0	0	0	0	0	1	0	0	1	0	0	0	16	0	0	0	0	0	3	3	4	7	3	2	177	5	108	256	1.08	40785.73989
0	0	1	0	1	0	1	1	0	73	67	10	0	1	0	0	0	1	0	0	2	2	2	2	14	0	0	1	1	0	4	11	4		0	3	182	3	48	260	0.77	198408.7433
0	1	1	1	2	1	3	3	2	17	70	5	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	3	23	4		0	1	530	3	93	254	0.99	51266.23221
0	0	4	0	1	0	0	0	0	44	66	5	0	0	0	0	0	0	0	0	0	1	0	0	17	0	0	0	1	0	5	7	1		6	2	161	8	39	251	0.61	147652.2001
0	3	2	0	2	0	0	3	0	25	60	4	0	0	0	0	0	0	0	0	1	0	0	0	21	0	0	0	0	0	0	9	1		0	5	153	6	39	239	0.93	132890.1177
0	1	2	1	3	0	0	3	0	20	116	2	0	0	2	0	0	0	0	0	2	0	0	0	19	0	0	0	0	0	1	21	3		1	2	416	8	65	264	1.13	64262.51872
4	0	0	0	0	0	1	1	0	18	94	3	0	5	0	0	0	0	1	1	0	0	1	0	25	0	0	0	0	0	3	12	0		0	1	147	3	70	250	0.88	75418.01948
0	1	1	0	0	0	1	2	0	41	102	7	1	0	0	0	0	0	0	0	0	1	3	1	13	0	0	2	0	0	6	7	0		0	2	193	5	55	250	1.1	76799.7562
0	0	1	1	1	1	2	1	0	23	84	0	0	0	2	0	0	0	0	0	1	1	0	0	25	0	0	0	0	2	8	13	4		0	2	214	6	50	253	1.09	86268.0367
0	2	2	0	0	1	1	5	0	36	78	4	0	0	2	0	0	0	0	0	0	2	0	2	17	0	0	2	0	0	1	33	5		1	2	193	5	36	250	0.96	134425.6368
2	0	3	0	0	0	1	0	0	25	78	3	0	0	3	1	0	0	0	0	0	3	2	0	28	0	0	0	4	5	3	13	6		0	3	205	8	46	261	0.67	121180.4783
1	1	4	0	0	0	2	4	0	34	83	6	0	2	2	0	0	0	0	0	0	0	1	0	17	0	0	0	0	0	0	19	5		1	2	177	6	40	266	0.98	128086.9266
2	0	0	0	1	0	2	2	0	44	78	5	0	0	5	0	0	0	0	1	3	0	0	0	23	0	0	0	0	0	0	8	3		0	3	256	8	30	250	1.78	86998.06967
1	0	0	1	0	2	0	1	0	30	85	1	0	0	0	0	0	0	0	1	3	0	0	0	23	0	1	0	0	0	0	7	1		0	4	163	6	34	250	1.32	103514.5287
0	0	4	1	1	0	1	7	1	40	64	6	0	0	0	1	0	0	0	0	0	1	0	0	25	0	1	1	0	0	0	12	2		0	3	102	9	41	251	0.86	132285.9762
0	0	0	1	4	1	0	3	3	61	78	2	0	2	0	0	0	1	0	0	0	1	0	0	23	0	0	1	1	0	1	12	6		0	2	47	9	33	256	0.9	160176.7003

APPENDIX D: CONISS RESULTS

DR1:

Tilia Program CONISS   3 Aug 2008   09:51:27 AM
Number of samples = 9
Number of variables = 72
Data converted to proportions
Square root transformation
Dissimilarity coefficient is Edwards and Cavalli-Sforza's chord distance

Constrained Incremental Sum of Squares Cluster Analysis

Stage	Clusters merged		Increase in dispersion	Total dispersion	Within-cluster dispersion	Mean within-cluster dispersion
1	4	5	0.05575004	0.05575004	0.05575004	0.02787502
2	4	6	0.06242782	0.1181779	0.1181779	0.03939262
3	3	4	0.07394216	0.19212	0.19212	0.04803
4	1	2	0.08493422	0.2770542	0.08493422	0.04246711
5	8	9	0.08557671	0.362631	0.08557671	0.04278836
6	1	3	0.1003041	0.4629351	0.3773584	0.06289306
7	7	8	0.1321488	0.5950839	0.2177255	0.07257518
8	1	7	0.1259089	0.7209928	0.7209928	0.08011031

Sample	numbers
1	3
2	13
3	23
4	33
5	43
6	53
7	63
8	73
9	83

DR2:

Tilia Program CONISS 3 Aug 2008 11:43:27 AM
Number of samples = 27
Number of variables = 75
Data converted to proportions
Square root transformation
Dissimilarity coefficient is Edwards and Cavalli-Sforza's chord distance

Constrained Incremental Sum of Squares Cluster Analysis

Stage	Clusters merged		Increase in dispersion	Total dispersion	Within-cluster dispersion	Mean within-cluster dispersion
1	20	21	0.1644742	0.1644742	0.1644742	0.08223709
2	22	23	0.1842264	0.3487006	0.1842264	0.09211319
3	24	25	0.1884158	0.5371163	0.1884158	0.09420789
4	15	16	0.1923283	0.7294446	0.1923283	0.09616416
5	26	27	0.2075527	0.9369974	0.2075527	0.1037764
6	18	19	0.2190047	1.156002	0.2190047	0.1095023
7	7	8	0.2190641	1.375066	0.2190641	0.1095321
8	11	12	0.2245883	1.599655	0.2245883	0.1122942
9	13	14	0.2693973	1.869052	0.2693973	0.1346987
10	15	17	0.2725469	2.141599	0.4648752	0.1549584
11	3	4	0.2921968	2.433796	0.2921968	0.1460984
12	1	2	0.2943111	2.728107	0.2943111	0.1471556
13	20	22	0.2943616	3.022468	0.6430622	0.1607655
14	13	15	0.3219969	3.344465	1.056269	0.2112539
15	6	7	0.345436	3.689901	0.5645002	0.1881667
16	20	24	0.3480989	4.038	1.179577	0.1965961
17	3	5	0.3559967	4.393997	0.6481935	0.2160645
18	9	10	0.3662694	4.760266	0.3662694	0.1831347
19	18	20	0.3887607	5.149027	1.787342	0.2234178
20	13	18	0.3754738	5.524501	3.219086	0.247622
21	9	11	0.4179691	5.94247	1.008827	0.2522067
22	1	3	0.4899967	6.432467	1.432501	0.2865003
23	6	9	0.4999321	6.932399	2.073259	0.2961799
24	13	26	0.5331123	7.465511	3.959751	0.2639834
25	1	6	0.787309	8.25282	4.293069	0.3577558
26	1	13	1.734041	9.98686	9.98686	0.3698837

Sample numbers

1	6624.252
2	7351.944
3	8495.461
4	9691.941
5	10070.25
6	10486.43
7	10832.81

8	11176.58
9	11486.97
10	12487.97
11	13316.98
12	15109.24
13	16040.11
14	16974.35
15	17041.09
16	17511.87
17	18256.86
18	19250.18
19	20001.7
20	20531.04
21	20766.29
22	21687.73
23	22452.32
24	23324.75
25	23617.41
26	24229.15
27	24484.28

APPENDIX E: MASS SPECTROMETER OUTPUTS

DE RIF 1 ISOTOPE RESULTS:

Sample Name	Analysis Number	Weight (mg)	%N	d15N/14N	Standard Corrected d15N/14N	%C	d13C/12C	Standard Corrected d13C/12C	C:N ratio
DR1-1	14578	2.05	7.330248	-0.052	-0.48513	123.3901	-21.408	27.364	16.833
DR1-2	14561	1.98	7.407699	0.143	-0.23322	125.1217	-21.029	-26.9875	16.89077
DR1-3	14573	1.88	7.286419	0.269	-0.20194	119.1037	-20.827	-26.7869	16.34599
DR1-4	14581	2.01	6.64358	0.301	-0.11049	123.5871	-20.991	-26.9498	18.60249
DR1-5	14580	2.04	6.446369	0.261	-0.15295	122.1162	-20.911	-26.8703	18.94341
DR1-6	14576	2.09	6.224832	-0.097	-0.53289	125.8949	-21.188	-27.1455	20.22462
DR1-7	14585	1.99	6.135104	-0.121	-0.55836	128.4283	-21.17	-27.1276	20.93336
DR1-8	14583	2.13	6.102966	0.143	-0.27818	117.5909	21.155	-27.1127	19.26783
DR1-9	14560	1.99	6.355474	-0.018	-0.40242	121.9553	-20.963	-26.922	19.18902
DR1-10	14565	2.07	5.913712	0.172	-0.30621	112.5109	-20.945	-26.9041	19.02544
DR1-11	14572	2.08	7.209639	-0.525	-1.05548	138.1176	-20.988	-26.9468	19.15735
DR1-12	14579	1.99	6.714682	0.033	-0.39492	128.5774	-21.308	-27.2647	19.14869
DR1-13	14567	1.93	6.747988	-0.126	-0.62656	137.0327	-20.988	-26.9468	20.3072
DR1-14	14570	2.08	7.14652	-0.592	-1.12751	131.8043	-21.151	-27.1087	18.44315
DR1-15	14584	2.05	6.825366	-0.602	-1.06884	139.112	-21.493	-27.4465	20.38162
DR1-16	14566	1.94	7.142072	-0.929	-1.48978	138.7324	-21.297	-27.2538	19.42468
DR1-17	14582	2.07	6.87169	-0.397	-0.85126	143.7648	-21.449	-27.4048	20.92132
DR1-18	14568	1.95	7.093187	-0.511	-1.04043	139.3954	-21.355	-27.3114	19.65201
DR1-19	14588	1.97	7.546957	-0.244	-0.6889	141.7478	-21.58	-27.5349	18.78212
DR1-20	14569	1.96	7.039601	-0.379	-0.89853	131.7433	-21.414	-27.37	18.7146
DR1-21	14577	1.97	7.651596	-0.633	-1.10174	147.6122	21.725	-27.6789	19.29169
DR1-22	14564	2.08	7.084199	-0.009	-0.50079	139.4301	-21.39	-27.3462	19.68185
DR1-23	14571	2.06	7.91067	-0.048	-0.54271	151.1229	-21.355	-27.3114	19.10368

DE RIF 2 ISOTOPE RESULTS:

Sample Name	Analysis Number	Weight (mg)	%N	d15N/14N	Standard Corrected d15N/14N	%C	d13C/12C	Standard Corrected D13C/12C	C:N ratio
DR-2-3-6	24190	1.591	1.97	0.26	-0.23	41.97	-23.47	27.24	21.26
DR-2-3-7	24168	1.554	2.09	0.42	-0.05	41.94	-23.40	27.16	20.08
DR-2-3-8	24191	1.522	1.86	-0.31	0.84	41.55	-23.29	-27.05	22.30
DR-2-3-10	24187	1.530	1.81	-0.51	-1.05	45.93	-23.65	-27.42	25.36
DR-2-3-11	24173	1.590	2.13	0.97	0.53	40.35	-23.25	27.00	18.95
DR-2-3-12	24170	1.530	2.19	1.26	0.85	43.66	-23.12	-26.88	19.94

DR-2-3-16	24202	1.550	1.96	0.47	0.00	39.22	-23.54	-27.31	19.97
DR-2-3-17	24167	1.531	2.13	1.00	0.56	41.34	-23.35	-27.11	19.37
DR-2-3-19	24203	1.552	1.95	-0.05	-0.56	46.75	-23.52	-27.29	23.99
DR-2-3-21	24219	1.497	2.26	-0.97	-1.55	43.81	-24.05	-27.84	19.42
DR-2-3-22	24185	1.557	1.89	-0.33	-0.87	44.07	-23.59	-27.37	23.33
DR-2-3-23	24223	1.600	2.05	0.41	-0.06	45.49	-24.12	-27.92	22.19
DR-2-3-25	24188	1.526	1.83	0.14	-0.36	42.99	-23.63	-27.40	23.49
DR-2-3-30	24182	1.520	1.92	1.10	0.67	42.30	-23.83	-27.61	21.98
DR-2-3-31	24232	1.502	1.97	0.53	0.06	44.81	-24.16	-27.96	22.77
DR-2-3-34	24199	1.536	1.90	-0.48	-1.02	45.22	-23.83	-27.61	23.76
DR-2-3-37	24206	1.553	1.83	-0.32	-0.85	44.31	-23.96	-27.75	24.26
DR-2-3-38	24189	1.536	1.92	0.80	0.35	46.03	-23.67	-27.44	23.95
DR-2-3-39	24218	1.560	2.20	-0.66	-1.22	45.28	-24.21	-28.01	20.62
DR-2-3-40	24181	1.570	2.07	-0.33	-0.86	46.08	-23.96	-27.75	22.22
DR-2-3-41	24178	1.596	2.09	-0.53	-1.08	45.42	-23.82	-27.60	21.73
DR-2-3-42	24224	1.547	2.33	-0.47	-1.01	46.31	-24.13	-27.93	19.85
DR-2-3-44	24166	1.525	2.09	1.37	0.96	45.56	-23.50	-27.27	21.77
DR-2-3-48	24214	1.547	2.15	-0.12	-0.64	44.84	-24.02	-27.81	20.85
DR-2-3-49	24213	1.533	2.19	0.17	-0.32	45.28	-24.15	-27.95	20.67
DR-2-3-52	24163	1.545	1.94	0.50	0.03	45.35	-23.99	-27.78	23.43
DR-2-3-53	24234	1.549	1.83	-1.10	-1.68	45.26	-24.20	-28.00	24.74
DR-2-3-54	24204	1.527	1.86	-1.46	-2.08	46.97	-24.17	-27.97	25.23
DR-2-3-57	24208	1.588	1.88	-0.91	-1.48	46.41	-23.93	-27.71	24.72
DR-2-3-58	24197	1.505	1.94	-0.90	-1.47	48.07	-23.71	-27.49	24.82
DR-2-3-59	24192	1.580	1.89	-1.18	-1.78	46.52	-23.84	-27.63	24.65
DR-2-3-60	24227	1.564	1.82	-1.45	-2.06	46.74	-24.23	-28.03	25.73
DR-2-3-64	24221	1.539	2.28	-0.26	-0.79	47.07	-24.14	-27.94	20.61
DR-2-3-65	24236	1.556	2.17	0.62	0.16	46.64	-24.22	-28.02	21.52
DR-2-3-66	24231	1.547	2.11	1.28	0.87	47.49	-24.53	-28.34	22.50
DR-2-3-67	24200	1.594	1.90	0.80	0.35	45.24	-23.34	-27.10	23.86
DR-2-3-68	24196	1.575	2.02	0.20	-0.29	46.16	-23.37	-27.13	22.81
DR-2-3-69	24195	1.538	1.91	1.14	0.72	45.31	-23.58	-27.35	23.71
DR-2-3-70	24205	1.553	1.92	-0.04	-0.55	46.43	-23.95	-27.74	24.21
DR-2-3-72	24217	1.505	2.30	-0.06	-0.57	45.35	-24.18	-27.97	19.75
DR-2-3-74	24226	1.594	2.29	2.23	1.88	38.89	-23.96	-27.74	16.95
DR-2-3-76	24222	1.601	2.70	2.86	2.56	40.19	-23.82	-27.60	14.89
DR-2-3-79	24179	1.536	2.54	3.08	2.80	39.69	-23.43	-27.19	15.60
DR-2-3-80	24171	1.589	2.77	4.23	4.03	38.80	-23.39	-27.15	14.01
DR-2-3-81	24172	1.569	2.75	4.17	3.97	39.90	-23.44	-27.20	14.49
DR-2-3-83	24165	1.580	2.38	3.37	3.11	42.70	-23.38	-27.15	17.94
DR-2-3-84	24177	1.573	2.30	3.52	3.27	39.10	-23.27	-27.03	17.03

DR-2-3-90	24235	1.518	2.29	1.63	1.24	39.74	-23.91	-27.69	17.32
DR-2-3-95	24174	1.607	2.15	1.31	0.89	42.77	-23.76	-27.54	19.92
DR-2-3-96	24233	1.575	2.21	1.19	0.77	40.26	-23.98	-27.77	18.23
DR-2-3-100	24228	1.543	2.10	1.51	1.12	38.01	-24.13	-27.93	18.13
DR-2-3-104	24210	1.542	2.08	0.84	0.40	40.14	-24.42	-28.23	19.25
DR-2-3-106	24184	1.575	2.06	0.41	-0.07	43.26	-24.51	-28.32	20.99
DR-2-3-107	24186	1.577	2.08	0.94	0.50	40.89	-24.21	-28.01	19.63
DR-2-3-109	24183	1.523	2.14	1.93	1.57	39.72	-24.04	-27.83	18.55
DR-2-3-110	24225	1.588	2.21	1.40	0.99	38.75	-24.37	-28.18	17.55
DR-2-3-111	24220	1.543	2.68	2.87	2.57	37.30	-24.06	-27.86	13.92
DR-2-3-112	24216	1.528	2.71	3.06	2.78	36.68	-24.01	-27.80	13.54
DR-2-3-113	24169	1.529	2.17	3.36	3.10	35.09	-23.94	-27.73	16.14
DR-2-3-115	24180	1.572	2.39	3.05	2.76	38.32	-23.98	-27.77	16.02
DR-2-3-117	24198	1.559	2.44	3.54	3.29	38.11	-23.90	-27.68	15.63
DR-2-3-119	24207	1.523	2.66	5.07	4.93	37.56	-23.66	-27.44	14.11
DR-2-3-120	24215	1.551	2.74	4.23	4.03	36.20	-23.59	-27.36	13.23
DR-2-3-121	24237	1.568	2.35	3.61	3.37	36.06	-24.14	-27.93	15.33
DR-2-3-122	24209	1.606	2.23	2.99	2.70	37.46	-24.12	-27.91	16.83
DR-2-3-123	24164	1.548	2.28	2.01	1.65	38.66	-24.32	-28.13	16.93
DR-2-3-124	24201	1.589	2.24	1.95	1.59	40.88	-24.33	-28.13	18.28
DR-2-3-1	24297	1.505	2.59	4.06	3.91	31.71	-22.41	-26.25	12.26
DR-2-3-2	24357	1.536	2.28	2.87	2.64	32.54	-22.72	-26.58	14.30
DR-2-3-3	24318	1.573	2.22	2.51	2.27	35.42	-23.05	-26.93	15.99
DR-2-3-4	24342	1.583	2.36	1.22	0.90	38.46	-23.27	-27.16	16.30
DR-2-3-5	24344	1.591	2.16	0.54	0.17	39.61	-23.44	-27.34	18.33
DR-2-3-9	24338	1.593	2.25	1.21	0.88	44.29	-23.24	-27.13	19.69
DR-2-3-13	24320	1.506	1.85	0.45	0.08	41.45	-23.53	-27.43	22.34
DR-2-3-14	24316	1.522	1.88	-0.76	-1.20	43.17	-23.68	-27.59	22.94
DR-2-3-15	24328	1.582	1.94	-0.70	-1.14	42.56	-23.69	-27.61	21.88
DR-2-3-18	24335	1.546	2.00	-0.55	-0.98	41.27	-23.67	-27.58	20.62
DR-2-3-20	24346	1.555	2.09	-0.11	-0.52	42.07	-23.70	-27.62	20.14
DR-2-3-24	24304	1.576	1.80	0.80	0.45	45.47	-23.23	-27.12	25.21
DR-2-3-26	24347	1.598	1.92	-0.40	-0.82	42.40	-23.78	-27.70	22.09
DR-2-3-27	24325	1.607	1.94	0.13	-0.26	42.14	-23.53	-27.44	21.72
DR-2-3-28	24321	1.603	1.88	-0.25	-0.66	45.35	-23.69	-27.60	24.07
DR-2-3-29	24348	1.541	2.02	-0.08	-0.49	45.31	-23.95	-27.88	22.46
DR-2-3-32	24343	1.553	2.21	-0.32	-0.74	44.58	-23.95	-27.88	20.21
DR-2-3-33	24308	1.567	1.85	-0.14	-0.54	45.42	-23.55	-27.45	24.49
DR-2-3-35	24352	1.548	1.95	-0.39	-0.81	45.57	-23.91	-27.83	23.39
DR-2-3-36	24322	1.504	1.88	-0.15	-0.56	45.06	-23.63	-27.54	24.03
DR-2-3-43	24310	1.547	1.96	-0.84	-1.29	45.31	-23.88	-27.80	23.12

DR-2-3-45	24307	1.538	2.06	1.09	0.76	46.04	-23.50	-27.40	22.36
DR-2-3-46	24329	1.555	2.04	0.16	-0.23	45.56	-23.91	-27.84	22.29
DR-2-3-47	24306	1.595	1.92	0.51	0.14	45.88	-23.59	-27.50	23.88
DR-2-3-50	24319	1.604	1.90	0.10	-0.30	45.53	-23.86	-27.79	23.97
DR-2-3-51	24345	1.601	2.04	0.21	-0.17	47.32	-24.06	-28.00	23.16
DR-2-3-55	24311	1.566	1.76	-1.84	-2.35	46.46	-23.83	-27.75	26.37
DR-2-3-56	24309	1.528	1.76	-1.00	-1.46	47.66	-23.59	-27.50	27.13
DR-2-3-61	24337	1.595	2.05	-0.74	-1.18	46.66	-23.80	-27.72	22.75
DR-2-3-62	24354	1.552	1.94	-0.06	-0.46	45.35	-23.81	-27.73	23.33
DR-2-3-63	24339	1.579	2.13	-0.64	-1.08	46.44	-23.69	-27.61	21.78
DR-2-3-71	24326	1.528	1.90	0.35	-0.03	45.99	-23.73	-27.64	24.15
DR-2-3-73	24315	1.566	2.05	0.83	0.48	44.56	-23.70	-27.61	21.73
DR-2-3-75	24355	1.525	2.41	3.91	3.75	37.59	-23.50	-27.40	15.57
DR-2-3-77	24302	1.566	2.15	3.01	2.80	37.89	-23.28	-27.17	17.60
DR-2-3-78	24312	1.572	2.21	2.78	2.55	38.78	-23.34	-27.23	17.57
DR-2-3-82	24299	1.559	2.50	3.66	3.49	38.33	-23.36	-27.26	15.30
DR-2-3-85	24317	1.568	2.44	3.01	2.79	39.70	-23.39	-27.29	16.24
DR-2-3-86	24303	1.576	2.21	2.18	1.92	39.88	-23.39	-27.29	18.00
DR-2-3-89	24341	1.524	2.51	0.36	-0.01	42.65	-23.81	-27.73	16.99
DR-2-3-91	24336	1.585	2.17	1.28	0.96	38.85	-23.41	-27.31	17.93
DR-2-3-92	24333	1.502	2.27	0.41	0.03	42.68	-23.80	-27.72	18.79
DR-2-3-93	24353	1.554	2.15	1.15	0.82	41.90	-23.80	-27.72	19.47
DR-2-3-94	24330	1.603	2.11	0.81	0.46	40.60	-23.87	-27.79	19.23
DR-2-3-97	24340	1.583	2.32	1.63	1.33	35.25	-23.16	-27.05	15.17
DR-2-3-98	24300	1.537	2.20	2.90	2.68	33.20	-23.17	-27.06	15.08
DR-2-3-99	24351	1.605	2.21	2.49	2.24	33.25	-23.36	-27.25	15.05
DR-2-3-101	24324	1.539	2.14	2.13	1.86	36.34	-23.79	-27.71	16.98
DR-2-3-102	24301	1.575	2.23	2.12	1.85	38.07	-23.88	-27.81	17.08
DR-2-3-103	24298	1.567	2.12	1.72	1.43	40.27	-24.18	-28.12	18.99
DR-2-3-105	24305	1.584	1.80	1.13	0.80	37.61	-24.19	-28.13	20.93
DR-2-3-108	24334	1.507	2.28	0.48	0.11	40.98	-24.28	-28.22	18.00
DR-2-3-114	24323	1.565	2.33	3.25	3.05	37.49	-23.93	-27.85	16.06
DR-2-3-116	24356	1.534	2.54	3.59	3.41	38.46	-23.96	-27.89	15.12
DR-2-3-118	24327	1.520	2.67	5.19	5.11	37.20	-23.44	-27.34	13.95

Sample Name	Analysis Number	Weight (mg)	%N	d15N/14N	Standard Corrected d15N/14N	%C	d13C/12C	Standard Corrected D13C/12C	C:N ratio
DR 2-2 132	22637	1.562	2.712882	5.128	4.818581	40.24379	-23.821	-27.1159	14.83433
DR-2-2-3	22638	1.587	2.589227	3.659	3.349347	30.38379	-22.744	-26.0669	11.7347
DR-2-2-73	22639	1.594	2.756693	9.773	9.464323	30.40353	-23.595	-26.8958	11.02899
DR-2-2-149	22640	1.532	3.048698	7.158	6.848905	37.63475	-24.216	-27.5007	12.34453
DR-2-2-122	22641	1.575	3.043842	7.243	6.933919	37.22069	-23.935	-27.227	12.22819
DR-2-2-4	22642	1.569	2.63049	3.053	2.74325	35.15519	-23.117	-26.4302	13.3645
DR-2-2-16	22643	1.57	1.971192	0.582	0.271855	40.62908	-23.564	-26.8656	20.61143
DR-2-2-47	22644	1.576	2.110228	0.58	0.269855	44.60616	-24.22	-27.5046	21.13807
DR-2-2-146	22647	1.59	2.622057	3.89	3.580384	39.3649	-24.14	-27.4266	15.01299
DR-2-2-34	22648	1.59	2.152085	1.001	0.690922	38.25174	-24.047	-27.3361	17.77427
DR-2-2-66	22649	1.526	2.38688	1.971	1.661077	41.2825	-24.616	-27.8903	17.29559
DR-2-2-157	22650	1.567	2.51092	5.511	5.201642	33.99202	-24.131	-27.4179	13.53767
DR-2-2-116	22651	1.594	2.908094	9.935	9.626349	31.9759	-23.859	-27.1529	10.99548
DR-2-2-31	22652	1.53	1.936212	0.536	0.225848	39.19711	-24.057	-27.3458	20.24423
DR-2-2-98	22653	1.53	2.83826	4.68	4.37051	38.86539	-24.152	-27.4383	13.69339
DR-2-2-50	22654	1.509	2.146155	0.94	0.629913	43.84076	-24.191	-27.4763	20.42759
DR-2-2-77	22655	1.565	2.396558	2.029	1.719086	41.14005	24.707	-27.9789	17.16631
DR-2-2-25	22656	1.549	1.883002	-0.592	-0.90233	42.8435	-24.195	-27.4802	22.75277
DR-2-2-144	22657	1.527	2.644797	1.335	1.024976	40.87821	24.357	27.638	15.45609
DR-2-2-83	22658	1.53	2.621447	2.37	2.060141	40.65525	24.711	27.9828	15.5087
DR-2-2-26	22659	1.564	1.940973	-0.593	-0.90333	42.59792	24.158	-27.4442	21.94689
DR-2-2-32	22660	1.549	2.150788	-0.003	-0.31324	42.24022	24.037	-27.3263	19.63942
DR-2-2-103	22661	1.565	2.573101	3.745	3.43536	38.32127	-24.273	-27.5562	14.89303
DR-2-2-2	22662	1.539	2.648599	2.841	2.531216	31.18035	-22.85	-26.1701	11.7724
DR-2-2-92	22665	1.589	2.749443	4.572	4.262492	37.15009	-24.015	-27.3049	13.51186
DR-2-2-84	22666	1.534	2.801397	2.865	2.55522	41.58858	-24.433	-27.712	14.84566
DR-2-2-138	22667	1.494	2.63077	2.972	2.662237	40.42337	-24.239	-27.5231	15.36561
DR-2-2-58	22668	1.528	2.284324	2.303	1.99313	45.05628	-24.394	-27.6741	19.72413
DR-2-2-141	22669	1.527	2.759738	2.253	1.943122	39.0444	-23.887	-27.1802	14.14787
DR-2-2-81	22670	1.546	2.820617	3.008	2.698243	41.36353	-24.325	-27.6068	14.66471
DR-2-2-113	22671	1.581	3.285868	7.66	7.350985	36.59411	-23.548	-26.85	11.13682
DR 2-2-91	22672	1.583	2.948906	4.782	4.472526	37.93187	-23.753	-27.0497	12.86303
DR-2-2-39	22673	1.593	2.518417	0.007	-0.30324	41.17292	-23.796	-27.0916	16.34873
DR-2-2-133	22674	1.528	2.695617	4.768	4.458524	39.32949	-23.767	-27.0633	14.59016
DR-2-2-123	22675	1.56	2.892531	6.4	6.090784	35.69697	-23.97	-27.2611	12.34108
DR-2-2-30	22676	1.568	2.628903	2.944	2.634232	38.29576	-24.165	-27.451	14.5672

DR-2-2-89	22677	1.573	2.488325	3.238	2.928279	36.95632	-24.196	-27.4812	14.85189
DR-2-2-60	22678	1.512	2.095754	1.982	1.672079	38.97809	-23.595	-26.8958	18.5986
DR-2-2-107	22679	1.557	2.592522	4.273	3.963445	40.61685	-23.762	-27.0585	15.66693
DR-2-2-111	22680	1.561	2.74882	7.609	7.299977	33.96165	-23.739	-27.036	12.35499
DR-2-2-136	22683	1.506	2.553381	4.819	4.509532	38.94785	-23.796	-27.0916	15.25344
DR-2-2-155	22684	1.551	2.313232	6.047	5.737728	32.59204	-23.623	-26.9231	14.0894
DR-2-2-57	22685	1.529	2.238134	1.434	1.123991	40.24005	-23.907	-27.1997	17.97928
DR-2-2-126	22686	1.6	2.741876	5.373	5.06362	38.34791	-24.017	-27.3068	13.98601
DR-2-2-29	22687	1.557	1.924993	-0.037	-0.34724	40.14516	-23.848	-27.1422	20.8547
DR-2-2-145	22688	1.523	2.455541	2.783	2.473207	37.3028	-24.247	-27.5309	15.19127
DR-2-2-90	22689	1.558	2.725386	5.611	5.301658	35.33058	-23.78	-27.076	12.96351
DR-2-2-105	22694	1.51	2.645258	4.414	4.039695	38.13118	-23.822	-27.2934	14.41492
DR-2-2-97	22695	1.58	2.818922	4.578	4.205415	37.91343	-23.809	-27.2807	13.44962
DR-2-2-142	22696	1.545	2.248029	3.534	3.150468	35.18882	-24.381	-27.8396	15.65319
DR-2-2-37	22697	1.561	2.18488	0.346	-0.07096	40.09466	-23.832	-27.3032	18.35097
DR-2-2-82	22698	1.583	2.731232	2.277	1.880287	43.88803	-24.587	-28.0409	16.06895
DR-2-2-115	22699	1.555	3.233118	10.756	10.44819	32.13253	-23.444	-26.9241	9.93856
DR-2-2-42	22700	1.554	2.106108	2.105	1.706484	36.98802	-23.721	-27.1947	17.56226
DR-2-2-121	22701	1.57	3.154207	8.392	8.059407	36.84184	-23.72	-27.1938	11.68022
DR-2-2-65	22702	1.587	2.27651	1.779	1.377066	42.4473	-24.242	-27.7038	18.64578
DR-2-2-71	22703	1.566	2.380989	2.493	2.098552	42.89835	-24.272	-27.7331	18.01703
DR-2-2-112	22704	1.571	2.990361	7.273	6.928673	38.20471	-23.878	-27.3481	12.77595
DR-2-2-1	22705	1.556	2.575935	3.265	2.878647	31.89622	-22.664	-26.162	12.38239
DR-2-2-62	22706	1.565	2.107081	0.858	0.446408	43.5932	-23.936	-27.4048	20.6889
DR-2-2-152	22707	1.593	2.412685	4.737	4.366082	36.00374	-24.024	-27.4908	14.92268
DR-2-2-150	22708	1.572	2.318426	5.192	4.825853	35.21176	-23.867	-27.3374	15.18779
DR-2-2-117	22709	1.585	3.348929	9.86	9.542799	34.74497	-23.675	-27.1498	10.37495
DR-2-2-63	22712	1.556	2.19124	1.432	1.026427	40.14342	-24.163	-27.6266	18.31996
DR-2-2-20	22713	1.523	1.830249	0.006	-0.41453	42.35901	-23.631	-27.1068	23.14384
DR-2-2-106	22714	1.504	2.596107	4.093	3.715329	39.85087	-23.775	-27.2475	15.35024
DR-2-2-169	22715	1.545	2.403364	7.723	7.383392	29.54809	-23.507	-26.9856	12.29447
DR-2-2-55	22716	1.527	2.192432	1.45	1.044616	42.36008	-23.814	-27.2856	19.32104
DR-2-2-54	22717	1.553	2.146926	1.558	1.153748	41.64931	-23.58	-27.057	19.3995
DR-2-2-53	22718	1.564	2.048102	1.318	0.911232	42.46493	-23.93	-27.399	20.7338
DR-2-2-124	22719	1.516	2.492284	6.158	5.801982	34.88785	-24.002	-27.4693	13.99835
DR-2-2-80	22720	1.546	2.680053	3.843	3.462708	40.25412	-24.255	-27.7165	15.0199
DR-2-2-78	22721	1.592	2.493129	2.972	2.582575	41.82268	-24.57	-28.0243	16.77517
DR-2-2-69	22722	1.521	2.301376	1.3	0.893043	43.73358	-24.494	-27.95	19.00323
DR-2-2-79	22723	1.526	2.301059	3.043	2.654319	38.62661	-24.176	-27.6393	16.78645
DR-2-2-127	22724	1.542	2.703874	3.768	3.386921	40.26387	-24.232	-27.694	14.89118
DR-2-2-165	22725	1.57	3.148965	7.119	6.773059	34.55882	-23.337	-26.8195	10.97466

DR-2-2-129	22726	1.563	2.529608	4.594	4.221583	37.51647	-23.83	-27.3012	14.83094
DR-2-2-162	22727	1.568	2.259668	6.898	6.549741	27.91978	-23.617	-27.0931	12.3557
DR-2-2-101	22730	1.532	2.573984	4.181	3.804252	37.91995	-24.067	-27.5328	14.73201
DR-2-2-24	22731	1.582	1.963486	-0.616	-1.04305	42.58484	-23.969	-27.4371	21.68838
DR-2-2-158	22732	1.56	2.163671	5.698	5.337159	27.41552	-23.793	-27.2651	12.67084
DR-2-2-128	22733	1.501	2.782431	3.255	2.868542	40.3697	-24.175	-27.6383	14.50879
DR-2-2-6	22734	1.585	2.892737	1.841	1.439716	36.96772	-23.308	-26.7912	12.77949
DR-2-2-5	22735	1.549	2.639378	2.05	1.650907	34.33389	-23.115	-26.6026	13.00832
DR-2-2-156	22736	1.57	2.790916	4.602	4.229666	37.26015	-23.842	-27.313	13.35051
DR-2-2-46	22737	1.59	2.200581	-0.002	-0.42261	42.51179	-23.972	-27.44	19.31844
DR-2-2-119	22738	1.583	3.23479	9.935	9.618586	30.39307	-23.555	-27.0325	9.395685
DR-2-2-10	22739	1.593	2.132411	0.746	0.333234	35.2489	-23.448	-26.928	16.53007
DR-2-2-114	22740	1.562	2.830801	8.942	8.615174	30.14271	-23.574	-27.0511	10.64812
DR-2-2-28	22741	1.584	2.047386	-0.279	-0.70251	41.20675	-23.96	-27.4283	20.12652
DR-2-2-167	22742	1.527	2.277319	7.154	6.808426	27.1462	-23.466	-26.9456	11.92024
DR-2-2-35	22743	1.57	2.147549	-0.146	-0.56812	40.28182	-23.808	-27.2797	18.75711
DR-2-2-153	22744	1.592	2.461558	4.907	4.537864	35.26924	-23.904	-27.3735	14.32801
DR-2-2-148	22745	1.573	2.238097	3.521	3.137332	36.70282	-23.653	-27.1283	16.39911
DR-2-2-110	22748	1.556	3.026745	6.324	5.969723	38.24238	-23.678	-27.1527	12.63482
DR-2-2-168	22749	1.593	2.349305	7.213	6.868044	28.52765	-23.029	-26.5186	12.14301
DR-2-2-41	22750	1.585	2.100151	1.187	0.778858	36.42364	-23.332	-26.8147	17.34335
DR-2-2-100	22751	1.589	2.46676	4.093	3.715329	36.37828	-23.569	-27.0462	14.74739
DR-2-2-8	22752	1.55	2.147479	0.925	0.514111	34.36798	-23.115	-26.6026	16.00388
DR-2-2-44	22756	1.581	2.132828	1.345	1.131281	41.61651	-23.395	-26.586	19.51236
DR-2-2-76	22757	1.561	2.423147	1.296	1.082104	42.53832	-24.313	-27.4899	17.55499
DR-2-2-7	22758	1.519	2.26669	1.437	1.223615	38.856	-22.586	-25.7894	17.14217
DR-2-2-19	22759	1.557	2.319374	1.459	1.245694	44.38633	-23.422	-26.6126	19.1372
DR-2-2-21	22760	1.595	1.823021	-1.022	-1.24429	43.83746	-23.302	-26.4944	24.0466
DR-2-2-40	22761	1.557	2.053803	0.062	-0.15636	38.92127	-23.4	-26.5909	18.95083
DR-2-2-134	22762	1.561	2.417995	4.625	4.423158	38.92605	-23.477	-26.6667	16.09848
DR-2-2-9	22763	1.535	2.036918	1.336	1.122249	34.37814	-22.949	-26.1468	16.87753
DR-2-2-118	22764	1.555	3.495783	10.897	10.71787	31.62799	-22.794	-25.9942	9.047469
DR-2-2-68	22765	1.588	2.288133	1.813	1.600976	39.72878	-24.233	-27.4111	17.36297
DR-2-2-161	22766	1.544	2.266354	7.184	6.991424	28.82191	-23.104	-26.2995	12.7173
DR-2-2-143	22767	1.566	2.472885	1.925	1.713382	39.83576	-24.186	-27.3649	16.10902
DR-2-2-61	22768	1.537	2.040784	0.791	0.575275	44.82343	-23.509	-26.6983	21.96383
DR-2-2-43	22769	1.523	2.069085	1.712	1.49961	40.14562	-23.525	-26.714	19.4026
DR-2-2-94	22770	1.545	2.615706	3.732	3.526925	39.74421	-23.932	-27.1148	15.19445
DR-2-2-147	22771	1.529	2.652212	4.435	4.23247	38.47911	-23.918	-27.101	14.50831
DR-2-2-15	22774	1.559	2.02022	0.819	0.603377	37.9438	-23.484	-26.6736	18.78201
DR-2-2-96	22775	1.555	2.759648	3.366	3.159599	39.94504	-23.968	-27.1502	14.47469

DR-2-2-45	22776	1.599	2.060911	0.977	0.761949	39.65599	-23.843	-27.0271	19.24198
DR-2-2-102	22777	1.566	2.736119	5.376	5.176878	38.71045	-24.023	-27.2044	14.14794
DR-2-2-48	22778	1.594	2.025867	0.027	-0.19149	43.83009	-24.225	-27.4033	21.63523
DR-2-2-72	22779	1.551	2.406752	2.439	2.229243	41.5455	-24.64	-27.8119	17.26206
DR-2-2-27	22780	1.558	1.98584	-0.285	-0.50462	42.1241	-24.145	-27.3245	21.21223
DR-2-2-140	22781	1.555	2.472687	2.47	2.260355	39.22026	-24.556	-27.7292	15.86139
DR-2-2-49	22782	1.536	2.030357	0.199	-0.01887	43.71634	-24.09	-27.2703	21.53136
DR-2-2-159	22783	1.55	2.401934	6.225	6.028952	32.05433	-23.649	-26.8361	13.34522
DR-2-2-151	22784	1.555	2.491467	4.28	4.076909	35.45547	-24.186	-27.3649	14.23076
DR-2-2-70	22785	1.594	2.172076	1.514	1.300893	43.61378	-24.655	-27.8267	20.07931
DR-2-2-139	22786	1.578	2.526495	2.417	2.207163	38.36681	-24.305	-27.482	15.18578
DR-2-2-99	22787	1.558	2.602935	3.947	3.742703	37.15687	-24.171	-27.3501	14.27499
DR-2-2-56	22788	1.527	2.255277	1.419	1.205549	41.70994	-24.012	-27.1935	18.49438
DR-2-2-64	22789	1.521	2.375012	1.323	1.109202	41.10278	-24.232	-27.4102	17.30634
DR-2-2-104	22792	1.583	2.797459	4.505	4.302724	37.96115	-24.292	-27.4692	13.56987
DR-2-2-120	22793	1.543	3.432821	10.607	10.42682	33.59218	-23.819	-27.0035	9.785592
DR-2-2-170	22794	1.584	2.448703	6.763	6.5689	28.89637	-23.664	-26.8509	11.80068
DR-2-2-23	22795	1.565	1.857787	-0.909	-1.13088	41.82089	-24.182	-27.3609	22.51113
DR-2-2-33	22796	1.534	2.173896	-0.079	-0.29787	41.79427	-24.299	-27.4761	19.22552
DR-2-2-38	22797	1.528	2.259248	-0.875	-1.09676	42.73314	-24.31	-27.487	18.91476
DR-2-2-52	22798	1.527	2.272923	0.585	0.368529	44.4955	-24.356	-27.5323	19.57633
DR-2-2-131	22799	1.552	2.882242	4.82	4.618864	38.30102	-24.156	-27.3353	13.28862
DR-2-2-22	22800	1.561	1.862367	-1.357	-1.5805	41.38231	-24.092	-27.2723	22.22028
DR-2-2-11	22801	1.507	2.405782	1.399	1.185477	37.44998	-23.55	-26.7386	15.56665
DR-2-2-163	22802	1.581	2.420155	6.51	6.314984	28.52573	-23.957	-27.1394	11.78674
DR-2-2-109	22803	1.588	2.65717	5.034	4.833639	34.19971	-24.312	-27.4889	12.87073
DR-2-2-160	22804	1.589	2.433629	6.271	6.075118	32.72315	-23.768	-26.9533	13.44624
DR-2-2-51	22805	1.545	2.164627	0.376	0.158773	43.85353	-24.451	-27.6258	20.25916
DR-2-2-125	22806	1.59	2.711944	5.038	4.837654	38.51652	-24.218	-27.3964	14.20255
DR-2-2-85	22807	1.588	2.486777	2.382	2.172036	40.22924	-24.735	-27.9054	16.17726
DR-2-2-95	22810	1.532	2.637349	3.771	3.566066	37.47459	-24.295	-27.4722	14.20919
DR-2-2-67	22811	1.51	2.261048	1.417	1.203542	39.22977	-24.756	-27.9261	17.35026
DR-2-2-36	22812	1.553	2.168102	-0.287	-0.50663	41.59211	-24.299	-27.4761	19.18365
DR-2-2-135	22813	1.545	2.441392	4.837	4.635926	37.09305	-24.346	-27.5224	15.1934
DR-2-2-75	22814	1.551	2.437769	1.515	1.301897	42.5038	-24.941	-28.1083	17.43553
DR-2-2-88	22815	1.512	2.486839	1.952	1.740479	39.55031	-24.762	-27.932	15.90385
DR-2-2-130	22816	1.559	2.58009	3.442	3.235875	39.71724	-24.362	-27.5382	15.39374
DR-2-2-18	22817	1.6	2.021003	0.762	0.54617	38.13885	-23.599	-26.7869	18.87125
DR-2-2-86	22822	1.522	2.607874	2.567	2.089597	40.40098	-24.303	-27.9025	15.49192
DR-2-2-14	22823	1.587	2.030106	0.977	0.503951	37.36405	-23.163	-26.7753	18.40498
DR-2-2-87	22824	1.586	2.528475	2.091	1.6149	40.93385	-24.155	-27.7562	16.18914

DR-2 2 17	22825	1.542	1.829166	0.587	0.115019	42.35814	-23.382	-26.9918	23.15707
DR-2-2-103	22826	1.584	2.707836	5.56	5.074401	40.01008	-23.495	-27.1036	14.77567
DR-2-2-59	22827	1.551	2.083957	1.414	0.939754	43.76807	-23.954	27.5574	21.00239
DR-2-2-164	22828	1.539	2.368692	6.488	5.99986	32.13423	-23.755	-27.3607	13.56623
DR 2-2-74	22829	1.567	2.251694	2.517	2.039734	43.73365	-24.244	-27.8442	19.42083
DR-2 2-93	22830	1.597	2.620622	4.996	4.511945	39.52063	-24.009	-27.6118	15.08063
DR-2-2-137	22831	1.571	2.257268	4.192	3.710147	36.52084	-23.934	-27.5376	16.17922
DR-2-2-13	22832	1.567	1.917311	1.699	1.223974	36.69857	-23.257	-26.8662	19.14064
DR-2-2-12	22833	1.539	1.965963	2.234	1.757509	34.91466	-22.74	-26.357	17.75957
DR-2-2-166	22834	1.561	2.383219	8.073	7.58052	28.58091	-23.224	-26.8356	11.99257
DR-2-2-154	22837	1.585	2.18641	5.821	5.334686	32.64613	-23.309	-26.9196	14.93139

MODERN HYRAX PELLET ISOTOPE ANALYSIS RESULTS:

Sample Name	Analysis Number	Weight (mg)	%N	d15N/14N	Standard Corrected d15N/14N	%C	d13C/12C	Standard Corrected D13C/12C	C:N ratio
DR1-A	22630	1.517	1.564924	3.094	2.784256	49.17341	-23.989	-27.2893	31.42224
DR1-B	22631	1.587	1.829066	2.112	1.8021	49.7258	-23.987	-27.2776	27.18644
DR1-C	22632	1.536	2.145471	2.263	1.953124	47.67045	-24.49	-27.7676	22.2191
DR2 A	22633	1.522	1.610235	2.377	2.067142	48.44266	-24.402	-27.6818	30.08423
DR2-B	22634	1.573	1.616979	2.204	1.894114	49.57787	-24.346	-27.6273	30.6608
DR2-C	22635	1.505	1.930375	2.31	2.000131	48.60788	-25.414	-28.6676	25.18053

APPENDIX F: Linear age-depth examples

Depths and ages for Spitzkoppe Midden - Namibia (Chase, unpublished data)

Sample	Depth (mm)	Cal yr BP
SPZ-1-5-10.0	6.00	2421
SPZ-1-5-20.0	17.17	2898
SPZ-1-5-40.0	38.25	3455
SPZ-1-5-66.0	64.25	3908
SPZ-1-5-110.5	110.50	5402
SPZ-1-5-2	157.67	6870
SPZ-1-2-7.0	7.00	-7
SPZ-1-2-40.0	40	392
SPZ-1-2-78.0	72.00	851
SPZ-1-2-108.5	105.00	1279
SPZ-1-2-187.0	156.00	2339
SPZ-1-2-213.5	189.00	3064

Depths and ages for Zizou Midden - Namibia (Chase, unpublished data)

Sample	Depth (mm)	Cal yr BP
ZIZ-1-1-34.0	35.5	17073
ZIZ-1-1-89.0	90.5	19895
ZIZ-1-1-125.0	126	21383
ZIZ-1-1-187.0	188.5	29690
ZIZ-1-1-226	226	37500
ZIZ-1-3-top-8.5	8.5	9650
ZIZ-1-3-top-94.0	94	10715
ZIZ-1-3-top-185.0	185	10868
ZIZ-1-3-top-233.0	231.5	12096
ZIZ-1-3-top-356.0	355	13303
ZIZ-1-3-b-7.0	7	22678
ZIZ 1-3-26.5	26.5	26330
ZIZ 1-3-54.0	54	29820

ZIZ 1-3-106.	111	33210
ZIZ 1-3-136.	136.5	37590
ZIZ-1-3-5	147.5	39350