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THE MORPHOLOGY, SEDIMENTOLOGY AND PALAEOENVIRONMENTAL SIGNIFICANCE OF TWO PAN-LUNETTE CLUSTERS IN THE SOUTHWESTERN CAPE OF SOUTH AFRICA

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Dissertation presented to the
University of Cape Town
in fulfilment of the requirements for the degree of
Master of Science.

June 2003

Abstract

Two clusters of pans and associated lunette dunes are distinct landscape features in the Swartland and Agulhas Plain regions of the southwestern Cape of South Africa. While occurring in geographic proximity within the Winter Rainfall Region, each of the pan-lunette clusters is hosted by different substrates, subjected to different coastal climate regimes and exhibits different morphology, orientation of features, and sedimentological characteristics. Not only are geomorphic characteristics at variance between regions, but also the alignment of lunettes on the leeside of pans, parallel within the cluster, is at variance with predominant modern wind direction and seasonality of precipitation at both sites, although the difference is more pronounced at Agulhas. In order to elucidate the occurrence and formational processes of these features, a dual-scale approach was employed: a regional cartographic study coupled with detailed local sedimentological analyses. The geomorphic characteristics of these features were quantified using aerial photography and orthophotographic maps. Dry season palaeo-wind direction was inferred from the regional analysis; in Agulhas, winds must have been blowing from the WSW during the dry season, similar to modern wet season winds. The palaeo-winds in the Swartland were similar to the current dry season winds that blow for six months of the year, although with a slightly more southerly component to the current SSW direction. Sedimentological and geochemical analyses were applied to investigate the pan-lunette sediments at Voelvlei, in the Agulhas cluster, and at Droevlei East, in the Swartland cluster, in order to clarify the processes responsible for their formation. The characteristics of sediments in both lunettes indicate a primary control by parent material with little post-depositional diagenesis. Sedimentological characteristics of many of the lunettes suggest differences in timing of formation; radiocarbon dates confirm this. Although dunes within each cluster appear to have been initiated at different times, the dune-building activity at Agulhas was initiated, on average, prior to the activity in the Swartland. Radiocarbon dates obtained from gastropod shells within the lunettes indicate initiation of the Droevlei East lunette around 8000 BP: a time of low sea surface temperatures and a dry Holocene altithermal on the west coast. A date of roughly 11800 BP from a sample at Voelvlei suggests that the dune was initiated rather earlier. A younger palaeosol in that dune may be evidence for a more recent stable period of wetter conditions. Without further chronological constraints to elucidate the timing of dune-building periods, the lunettes may be seen as a cumulative product of at least the past 8000 years of windy arid season. Correlation with other arid periods in the southwestern Cape is difficult. The comparative relationships of the pan and lunette features in the Swartland and Agulhas do, nevertheless, offer important insights into the shifting palaeoenvironment of the Winter Rainfall Region of South Africa.

Acknowledgements

This dissertation could not have been completed alone. I am indebted to innumerable individuals and organizations on all sides of the globe.

Firstly, I would like to acknowledge my advisors in the Department of Environmental and Geographic Sciences, Peter Holmes and Mike Meadows, for their patient guidance, especially through the last frenzied weeks. Their efforts to provide me with exposure to relevant studies, in their individual ways, both at regional and international conferences and in the field have yielded invaluable experience.

I am grateful to numerous assistants who rolled up their sleeves to help me in the field. Those who saw action in the trenches include: Andy Carr, Keir Soderberg, Brett Smith, Danwell, Ann Barrable, Arthur Gaines and Jennifer Gaines.

John Rogers taught me to use the settling column and provided a veritable fount of knowledge throughout.

The NOSAMS facility at WHOI generously provided radiocarbon dates, free of charge.

This degree was funded by the US.ZA Education Initiative through Princeton in Africa.

The comments of my external reviewers have been meticulous and very helpful – a much appreciated final touch in a truly international effort.

Finally, I could not have completed this work without the support of both the other US.ZA fellows - my family in Cape Town - and my family on Cape Cod.

Contents

ABSTRACT

ACKNOWLEDGEMENTS

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

2 SETTING

3 THE FEATURE

4 PAN-LUNETTES AT A REGIONAL SCALE

5 PAN-LUNETTES AT A LOCAL SCALE

6 CHRONOLOGY OF THE FEATURES

7 DISCUSSION AND CONCLUSION

Figures

CHAPTER 1

CHAPTER 2

CHAPTER 3

CHAPTER 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

Tables

CHAPTER 4

CHAPTER 5

CHAPTER 6

Chapter 1: Introduction

1.1 THE QUATERNARY PERIOD IN THE SOUTHWESTERN CAPE

The Quaternary Period, essentially the past 2 million years of geologic time, has been a period of intense activity in southern Africa and the southwestern Cape of South Africa in particular. This activity occurred and continues to occur in a number of inter-related realms such as climate, biogeography, human evolution, and landscape evolution. The regional climate has been variable on a range of time scales, the current Mediterranean-type climate allegedly only of Quaternary origin (Linder *et al.,* 1992). The oceanic character of the region places it in a key position in the circulation of the earth's oceans, the global conveyor belt, which in turn drives climate around the globe (Broeker and Denton, 1989; Cohen *et al.*, 1992). Though it is contended to some extent, climatic fluctuation during the Quaternary may be directly responsible for the natural variety in the southwestern Cape, both the famous biological diversity of *fynbos* and the 'geo-diversity' of stunning regional geomorphology (Goldblatt, 1978). Also, speciation events in the evolution of modern-day humans are thought to have occurred in the region. A study of the Quaternary in the southwestern Cape is a study of the environmental origins of humankind, the land and climate that fostered them and their successors up to the present, including ourselves. The Quaternary history of the southwestern Cape is further important because of the current condition of land degradation in South Africa (Meadows, 2001). Additionally, despite the multiform importance, there is a dearth of information encapsulating the whole scientific state of knowledge about this time and place (Meadows, 2001). Not only is the Quaternary period in the region relevant, then, but also it is relatively unstudied.

Environmental change in the Quaternary has been investigated through a number of different kinds of evidence in South Africa. The proxies utilized are as numerous as the changes they monitor (Lowe and Walker, 1997). Researchers have approached the Quaternary record at archaeological sites through micro-mammalian fossils, charcoal, bones, human tools and speleothem (Avery, 1993; Esterhuysen and Mitchell, 1996; Roberts and Berger, 1997; Talma and Vogel, 1992). Vlei sediment and ocean core sediment have been scrutinised for pollen, shell, isotopic and textural information (Meadows and Baxter, 1999; Cohen *et al.*, 1992; Meadows and Asmal, 1996). Dune fields, ancient trees and landscape features have also been critiqued (Illenberger, 1996; Shaw *et al.*, 2001; Curtis *et al.*, 1978; Marker and Holmes, 1995). This study approaches the Quaternary of the southwestern Cape from a geomorphic perspective. The relict pan-lunette features studied here are potentially an additional source of evidence about the period.

Despite the range of proxies listed above, the evidence has been hard-won. Palaeoenvironmental studies in the southwestern Cape have been hampered by a lack of organic material and a general tendency of features to erode rather than accumulate. Geomorphology can thus provide an important proxy for study. In a region where glaciation did not occur, fluctuations in precipitation have had a greater influence than temperature on landscapes (Meadows, 1988). The influence of rainfall lies in the importance of precipitation to fostering vegetation, and hence altering geomorphologic conditions considerably. With recent advancements in quantitative chronological methods, geomorphologic proxies provide increasingly more attainable evidence about palaeoenvironments in the region, specifically, in this case, information about precipitation and wind.

1.2 QUATERNARY PALAEOENVIRONMENTS

1.2.1 SOUTHWESTERN CAPE, SOUTH AFRICA

Despite the wide variety of evidence interrogated throughout the southwestern Cape, a coherent palaeoenvironmental reconstruction for the late Quaternary remains elusive (Meadows and Baxter, 1999). Partridge *et al.* (1990) attempted to summarize the state of knowledge as shown in Figure 1.1. Incorporating a spate of more recent evidence, Meadows and Baxter (1999) suggested that the Last Glacial Maximum (18000 BP) was generally cooler and *wetter* (italics indicate contention) in the southwestern Cape. The first half of the Holocene (last 10000 yrs) was then drier and cooler before the Holocene altithermal (7000 to 5000 BP) when temperatures rose and there was a further *reduction* (micro-mammalian evidence indicates otherwise (Avery, 1993)) in available moisture until humidity increased and temperature decreased to current conditions (Meadows and Baxter, 1999). Further fluctuations continued to the present, however. Three well-established Neoglacial climate episodes occurred in the Southern Hemisphere between 4500 and 4000 BP, between 3000 and 2000 BP and during the past 1000 years (Jerardino, 1995; Illenberger and Verhagen, 1990). Temperature departures were of the order of 1-2°C and +/- 1-2m sea level (Jerardino, 1995).

Owing to the current complexity of environmental and biogeographical gradients between coastal and mountain environments, and over entire rainfall regions, it is reasonable to expect that palaeoenvironmental conditions during the late Quaternary were also spatially variable.

There is evidence to indicate that the southern portion of the Cape has responded to precipitation changes in phase with the summer-rainfall region, while the southwestern portion of the Cape is out of phase, indicating a potential difference in forcing mechanisms (Partridge *et al.*, 1990). For this reason, the regional palaeoenvironmental evidence for both study sites is considered separately below.

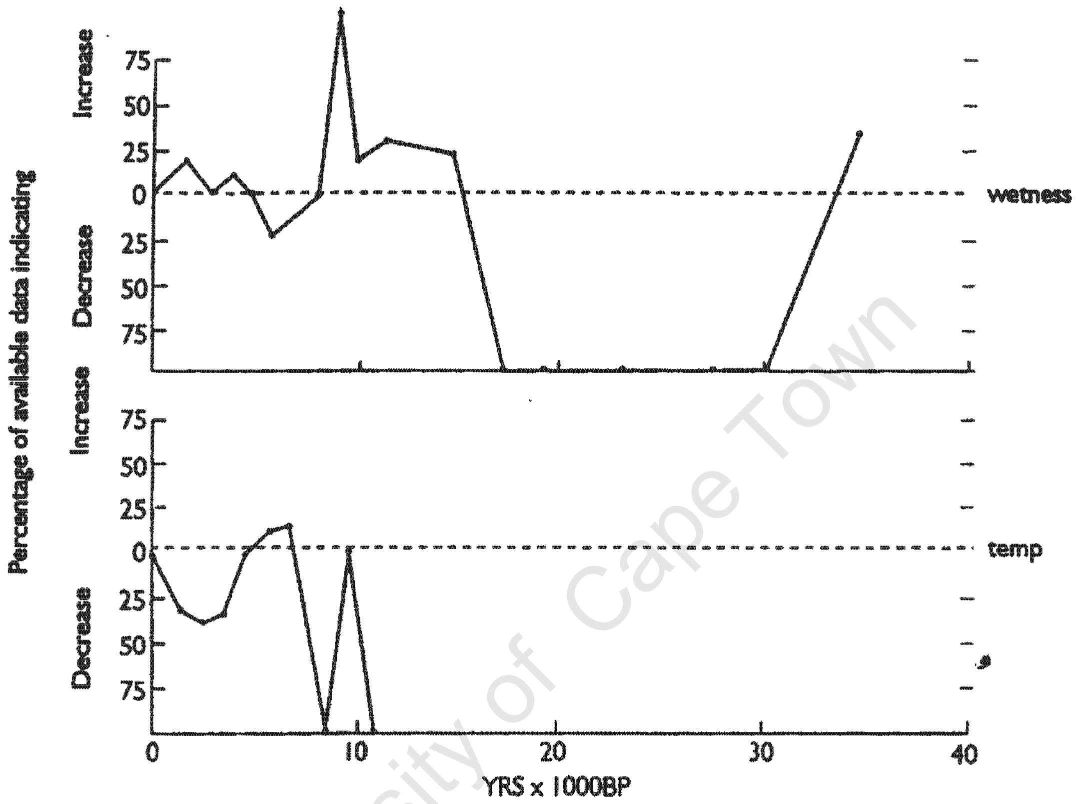

Figure 1.1: Regional synthesis of palaeoenvironmental data for the southwestern Cape (Partridge *et al.*, 1990)

1.2.1a West Coast

Evidence specifically from the western coast of the southwestern Cape comes primarily from archaeological evidence at Eland's Bay Cave (Figure 2.11) and palynology from Verlorenvlei (Figure 2.11). An occupational hiatus between 8000 and 4000 years ago (mid-Holocene altithermal) affects all west coast archaeological sites, indicative of a change in human behaviour or certain uninhabitable environmental conditions. Evidence from the Eland's Bay area, along the coast, indicates substantial aeolian sand transport and dune formation between 4000 and 2400 BP likely as a result of a drop in sea-level (Miller *et al.*, 1993). The west coast region of the southwestern Cape is solidly ensconced in the Winter Rainfall Region.

1.2.1b South Coast

The southern coast region of the Winter Rainfall Region, home of the Agulhas pan-lunette cluster, is climatically more variable than the west coast, verging on year-round rainfall. Based on micro-mammalian evidence at Byneskranskop (Figure 2.11), the grass component of *fynbos* vegetation, including restioid vegetation and grasses that indicate moderately warm wet winters, was dominant during the first half of the Holocene with particular dominance around 10300 BP and 7300 BP (Avery, 1993). Grass predominating by 6200 BP may indicate a greater proportion of summer rainfall, assuming annual rainfall remained over about 400 mm; a reduction in seasonality in the winter rainfall (Avery, 1993). However, the implication of 'grassy' environments has been interpreted in contradictory manners, both as a more humid and more arid climate, decreasing the utility of this evidence (Meadows and Baxter, 1999).

Isotopic shell records have been used to construct a record of the southern Benguela sea-surface temperatures off the coast of Agulhas. A cold period at 4200 BP indicates sea-surface temperatures 2.5-4°C colder than present (Cohen *et al.*, 1992). Sea surface temperatures decreased around 8700 and 6300 BP, as a result, in part, of increased easterly wind anomalies (Cohen, 1993). Cohen's ocean-atmospheric model (1993) indicates that these oceanic conditions are associated with increased rainfall over interior parts of South Africa, but drier conditions along the west coast.

Sediments and artefacts at Die Kelders (Figure 2.11), a coastal cave near Gansbaai, have provided the basis for generations of contentious archaeological and climatic conclusions (Tankard and Schwitzer, 1976; Avery, 1997). Tankard and Schwitzer (1976) identified a Layer 3, immediately overlying a Middle Stone Age (MSA) sequence, as archaeologically sterile because the cave mouth was blocked by an active dune, a dune that was active, they posited, because of the drier conditions during Isotope Stage 2 (24000 to 12000 BP). Avery's (1997) conclusion from subsequent findings was that the MSA sediments formed under cool and moist conditions.

1.2.2 CAUSES OF CLIMATE VARIABILITY

Many global climate oscillations are caused by the orbital-forcings of Milankovitch cycles. It has been established that climate change in the summer rainfall sub-humid climates of southern Africa are in phase with global-scale orbital-forcings as well as sub-Milankovitch scale climate oscillations (Meadows, 2001). The record from the Winter Rainfall Region of the southwestern Cape, however, does not slot easily into these fluctuations.

There is no scientific consensus explaining climate fluctuations in the southwestern Cape during the Quaternary, however researchers agree that answers lie in the circulation patterns of the Benguela and Agulhas currents, their role in global circulation, and hence sea surface temperatures (Tyson, 1986; Walker, 1990; Cohen *et al.*, 1992; Cohen, 1993; Jerardino, 1995). The oceanic thermohaline conveyor plays a prominent role in regulating climate globally (Broeker and Denton, 1989). However, ocean-atmosphere relations are complicated, at best. Cohen (1993: 82-85) proposed a conceptual model suggesting that strong westerlies arise from a weak Agulhas Current, advected Agulhas water causing warmer sea surface temperatures and simultaneous warming of the southern Benguela Current. Easterly wind anomalies across the Agulhas Current accompany and precede warm sea surface temperatures and increased rainfall (Walker, 1990). The extent to which temperature variations, zonal and meridianal wind components, and modulations by other southern hemisphere events affect southern African climates has still not been resolved (Tyson, 1986).

1.3 RATIONALE FOR PROXY

There are a number of motivations for using the Agulhas and Swartland clusters of pan-lunette features for a Quaternary investigation.

In a relevant study, Thomas (1999) combined regional studies of linear dune field alignment with detailed studies of individual sites in the Kalahari. He recommends two principal data sources for studies of palaeoclimate in low latitudes: *sand seas* which are useful for environmental reconstructions on account of their spatial extent, and *localized interactive systems* which contribute to more robust interpretations because aeolian deposits occur alongside deposits associated with other geomorphic processes. Pan-lunette features, when studied at regional and local scales are both localized interactive systems and provide a similar role to that of a spatially extensive sand sea. Although not continuous to the same spatial extent as sand seas, pan-lunette features may be the most effective feature for these purposes found in the southwestern Cape. For these two reasons, the feature was selected as a new proxy for Quaternary environmental change. Previous research on this kind of feature is discussed in Chapter Three.

The pans in Agulhas and the Swartland have been used for their salt, as runways, and as watering holes for livestock in the extensively agricultural regions, but less thoroughly for research purposes. In Agulhas, a lunette was dated with luminescence techniques by Thomas and Bateman from the University of Sheffield (Carr, personal communication). Currently Carr (University of Sheffield), is investigating the palynology of the pans as part of a greater study comparing humid (in pans and vleis) and arid (in dunes) chronologies from the Agulhas Plain and generally optimising on the dual deflational and aggradational nature of pans with an end to inform climate records of the region (Carr, personal communication). In the Swartland, Compton from the University of Cape Town looked at the weathering of rare earth elements into pans (Compton, personal communications). Subsequently, Smith did a geochemical survey of the brine and sediments of these pans (Smith, 2000). This prior work establishes a portion of the motivation behind addressing these pans in a more comprehensive manner.

The Swartland and Agulhas sites were selected because they are the only distinct clusters of pans and lunettes in the southwestern Cape area of the Winter Rainfall Region (Figures 2.1 and 2.2). Their proximity to Cape Town, where this research is based, provided relevant and accessible evidence. Their locations and differing morphologies is sustenance for both contrasts and parallels.

Depending on the age of the pan-lunette features under consideration, a variety of forces may leave their mark on these landscape features. In younger pan-lunette features there may be discernible records of land-use practices to complement extensive local archaeological records such as those at Die Kelders, where some of the earliest records of pastoralism in the Western Cape have been discovered (Sealy and Yates, 1994). Older features may preserve records of changing drainage courses, wind directions and rainfall regimes. A change in palaeowinds may have direct correlations to variations in the Agulhas and Benguela currents. Essentially, the morphology and sedimentation of these pan-lunette features could lend detail to the history of the Winter Rainfall Region in terms of human occupation and climatic timing, specifically in regards to direction of wind and amount of precipitation.

Whatever the cause, these features were active systems at one point and no longer are. Determining the changes that brought about this activation is a worthwhile endeavour when faced with the spectre of increasingly rapid and severe climate change. The oft-repeated mantra of the past as key to the present and future, even, is once again relevant.

1.4 OBJECTIVES

Bearing in mind this relevance and the aforementioned gap in the state of knowledge, the intentions of this research were to:

1. determine the spatial distribution and morphology of pan-lunette features in the Swartland and Agulhas Plain
2. investigate the formational history of pans in the southwestern Cape
3. elucidate climatic conditions, specifically, that would impact the development of the features
4. establish environmental changes, be they anthropogenic or climatic, documented by the formation of the pans and dunes

By documenting the geomorphic characteristics of the pan-lunette features in the Swartland and Agulhas clusters, a useful exercise in its own right, the formational history of the features was clarified. Once the formational history was determined, it could be decided how changing climate conditions would affect that formation and, as a result, what environmental changes have actually affected the features in the southwestern Cape.

1.5 STRUCTURE

This thesis is structured as follows. Firstly, this opening chapter serves as an introduction to the field of study and the context of the study, noting the aim and key objectives. Chapter Two provides the setting for each field site by describing the geology, geomorphology, soils, vegetation, climate, and land use both current and historic. A rationale for the sites chosen is provided. Chapter Three presents a literature review explaining the dynamics of the pan-lunette feature and the nature of prior research. Chapter Four discusses the first perspective of the research with a regional description of the pan-lunette features at each site. The regional view is a perspective that encompasses the whole cluster of features, describing the morphology and relationship between features and with the surrounding landscape. Chapter Four is methods, section I, the first perspective on the features. In Chapter Five, the local scale description of these sites is explained. The local perspective is a more intimate view of a number of individual features where sedimentological laboratory analyses were performed. Chapter Five is methods, section II, the second perspective on the features. The age of the features, both informed from this work and the work of other researchers, is considered in Chapter Six. The story presented by these features is found in a discussion in Chapter Seven and concluded at the end of that chapter.

Chapter 2: Setting

2.1 REGIONAL CHARACTERISTICS

Within a 200 km radius from Cape Town there are two distinct clusters of pan-lunette features punctuating the landscape. Both clusters of pans are located in coastal strips of land, the Swartland cluster to the north of Cape Town and the Agulhas cluster to the southeast of the city (Figure 2.1). Although the sites are relatively close together, they are situated on different substrates and different coasts of the southwestern Cape, and are thereby the product of different weather systems and weathering processes.

Figure 2.1: NASA space image of the southwestern Cape. The Cape Fold Belt Mountains are clearly evident marking the boundary of the coastal region. The pans in Agulhas and the Swartland are highlighted in white. Scale is approximately 1:2 500 000.

2.1.1 GEOGRAPHY

The southwestern Cape of South Africa is a geographically distinct region of southern Africa. It is distinguished from the rest of the country by winter rainfall (Figure 2.2) and a substrate that together host the uniquely diverse Cape Floristic Region, the smallest of six floristic kingdoms in the world (Meadows and Sugden, 1993). *Fynbos*, one of the globally richest plant communities in terms of plant species per unit area, is a characteristic vegetation covering 47% of the Cape Floristic Region (Richardson *et al.*, 1995). Renosterveld is another major vegetation formation of the region. A general description of the climate succeeded by a more detailed explanation of the geography and climate of each site follows.

2.1.2 CLIMATE

The southwestern Cape is subject to a Mediterranean-type climate, with cool wet winters and warm dry windy summers (Tyson, 1986). The climate at both sites is controlled and moderated by the proximity to dominant ocean currents (Figure 2.3). In brief, the cold Benguela current stabilises air masses and causes the summer aridity (Meadows, 1999). The winter rain is brought by westerly frontal depressions (Meadows, 1999). Precipitation gradients in the region are extreme, tending towards drier conditions to the north of the Swartland and to the east of Agulhas and wetter with altitude in both sites. In the southwestern Cape, annual rainfall varies from <200 mm in the inlands to about 400 mm on the coastal foreland, and up to 3000 mm in the mountains (Meadows, 1999; Deacon *et al.*, 1992). The change from winter-rainfall to non-seasonal rainfall in the eastern part of the southern Cape occurs abruptly at the Breede River, the boundary between the southwestern and southeastern Cape Floristic Region (Richardson *et al.*, 1995).

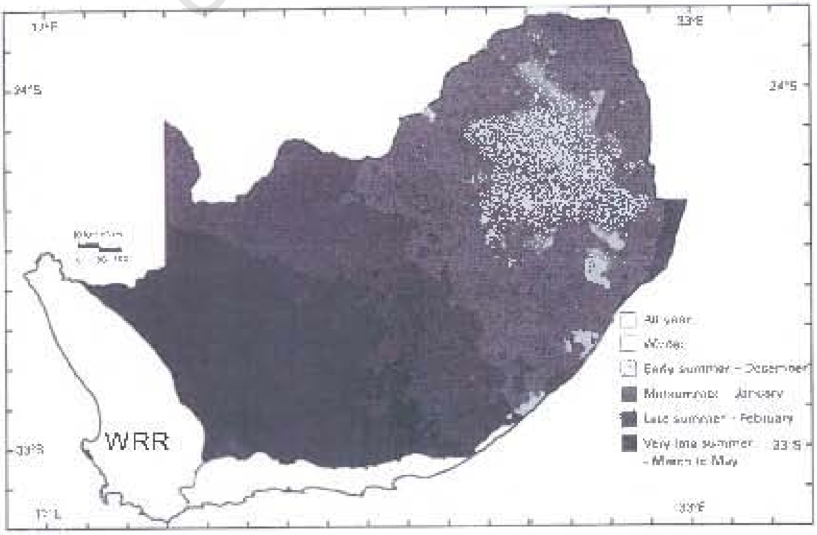

Figure 2.2: Southern Africa, showing Winter Rainfall Region (after Cowling, 1997).

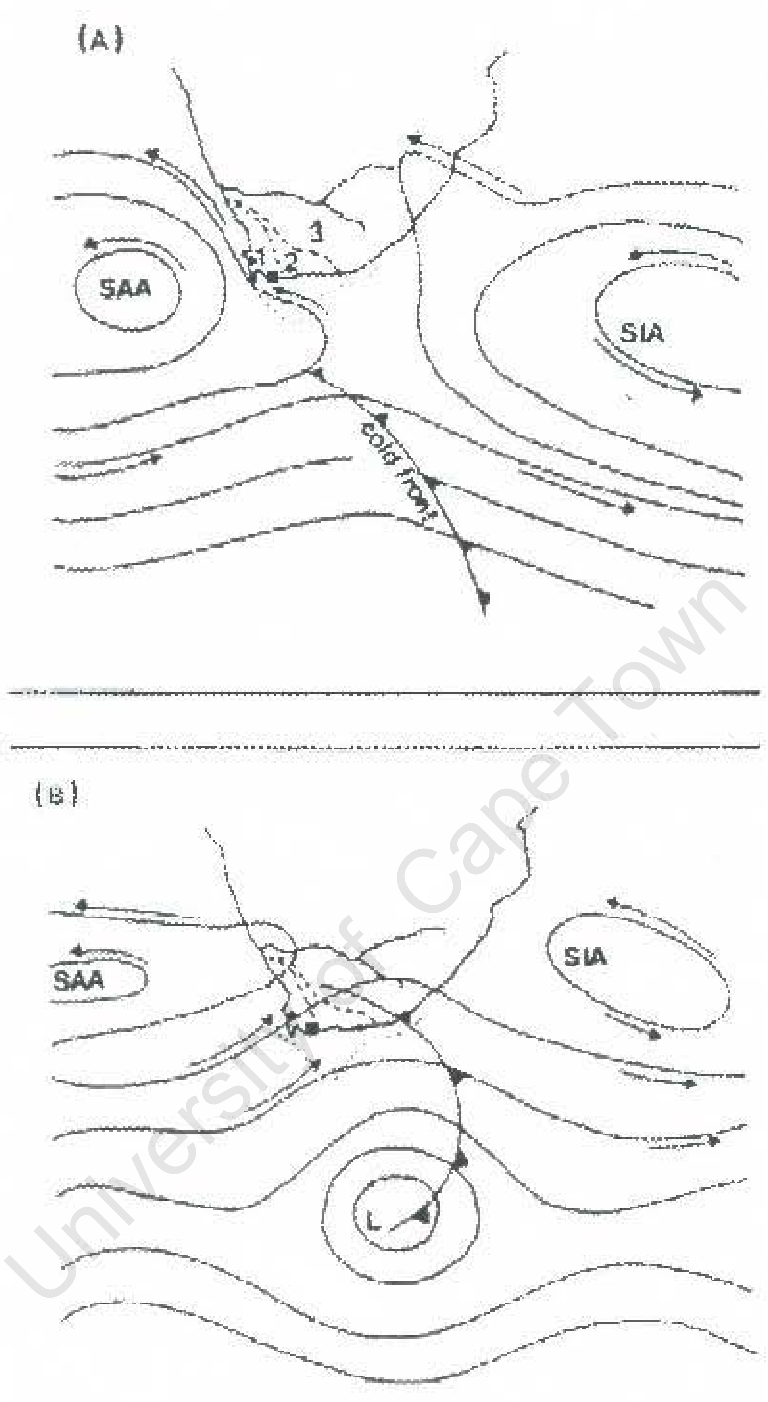

Figure 2.3: Basic elements in the seasonal air pressure distribution and wind direction (↑) over South Africa in summer (A) and winter (B). SAA and SIA are South Atlantic and South Indian Anticyclones (high pressure systems). In summer (A), southerly and south-easterly winds blow along the west coast causing cold water to upwell inshore. Easterly winds associated with anticyclonic ridging forces upwelling events along the south coast. The winter rainfall region (1) is dry during the summer (A) because low pressure systems, associated cold fronts and westerly winds are displaced southwards. The summer rainfall region (3) however receives moist air and hence rainfall from the South Indian high. In winter (B), the high pressure systems move north and westerly winds blow along the west and south coasts. Cold fronts stretch over the winter rainfall region bringing winter rain while the summer rainfall region remains dry. Region (2) does not exhibit strongly seasonal rainfall. The Agulhas (■) and Swartland (●) pan-lunette clusters are indicated. (adapted from Cohen, 1993)

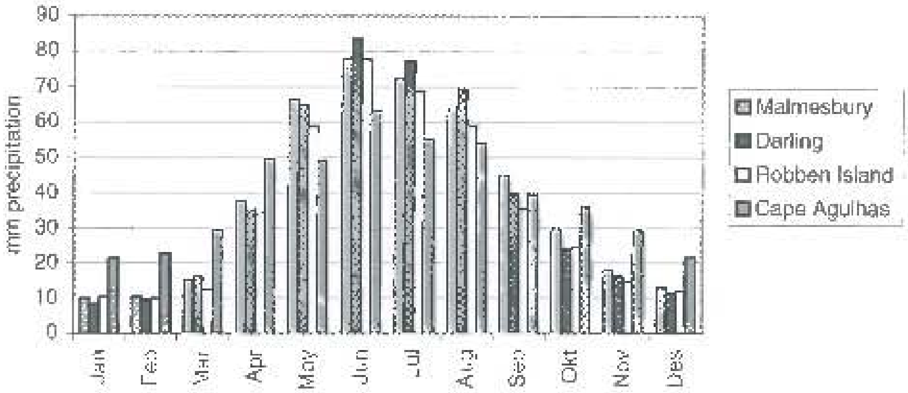

Figure 2.4: Histogram of monthly rainfall averages at coastal weather stations in the southwestern Cape (SA Weather Service).

As can be seen in Figure 2.2, the Winter Rainfall region of South Africa stretches from the southwestern Cape north along the coast to Namibia. As registered in monthly precipitation records from a number of weather stations of the southwestern Cape (Figure 2.4), the rains increase dramatically from April (>30 mm) to June (~70 mm) and persist until at least October, lasting the southern hemisphere winter. The summer months from November through March are drier. All of the stations graphed show this pattern, though the records from Cape Agulhas, a station situated on the border with the year-round rainfall region (Figure 2.2) show a less extreme seasonal effect.

The gross annual evaporation in the southwestern Cape coastal area is roughly 1270 mm while rainfall is only 380 mm, giving a net evaporation rate of 890 mm (Hugo, 1974).

2.2 AGULHAS

2.2.1 GEOGRAPHY

The Agulhas region of the southwestern Cape is a generally flat, extensively farmed plain stretching from the Bredasdorp Mountains of the Cape Fold Belt to the sea, at the southernmost point of Africa. Thwaite and Cowling (1988) coined the term "Agulhas Plain" to describe the regional geomorphic surface, most recently valley floodplains with many vleis and pans. Most likely, this surface was formed during the last interglacial when sea level was 7-9 m above present levels (Davis, 1981). On account of the vleis, pans and streams the area has been described as "the one area of South Africa where there is still an abundance of freshwater" (Davis, 1981, p.236).

The underlying geology is a mosaic of shale, alluvial sand, sandy clay, and clay. The shale is part of the Bokkeveld Group of the Cape Supergroup. The sandstone, which is commonly interbedded with shaley layers and quartzite, is part of the Table Mountain Group, also part of the Cape Supergroup. Older Malmesbury Group shales occur along the upthrust side of a number of fault lines. Much of the surface is young (<Tertiary) calcified dune sand of the Bredasdorp Group (Geological Survey, 1963). The sediments consist of a bisequal duplex profile with alluvial or colluvial topsoils over residual and transported clays. Numerous active dune fields occur along the coast.

2.2.2 PRECIPITATION

There is a strong rainfall gradient across the Plain from 480 mm per annum at Cape Agulhas to 540 mm at Gansbaai (SA Weather Bureau). It is a Mediterranean-type climate with between 65% and 75% annual precipitation falling in the winter (Thwaite and Cowling, 1988).

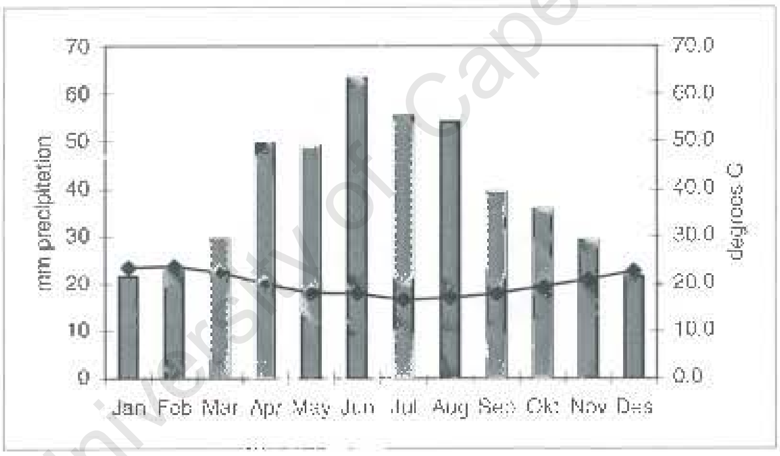

Figure 2.5: Monthly averages at the Cape Agulhas weather station. Precipitation records are from 1899-1999. Annual precipitation averages 470.9mm. Temperature records are from 1992-2002 (SA Weather Service).

Extreme precipitation events may indicate an amplification of the rainfall gradient in recent history. In a paper monitoring molluscan activity in the pans and vleis of the Agulhas region, Davis (1981) observed an eastward reaching aridity during the past century. Based on communications with local farmers, he stated that during the summers of 1969 and 1970 a number of the "lakes" in the Agulhas region dried entirely for the first time in 50 years. Soetendalsvlei, the largest water body in the region, was dry throughout a seven year drought, ending in 1973 (Davis, 1981).

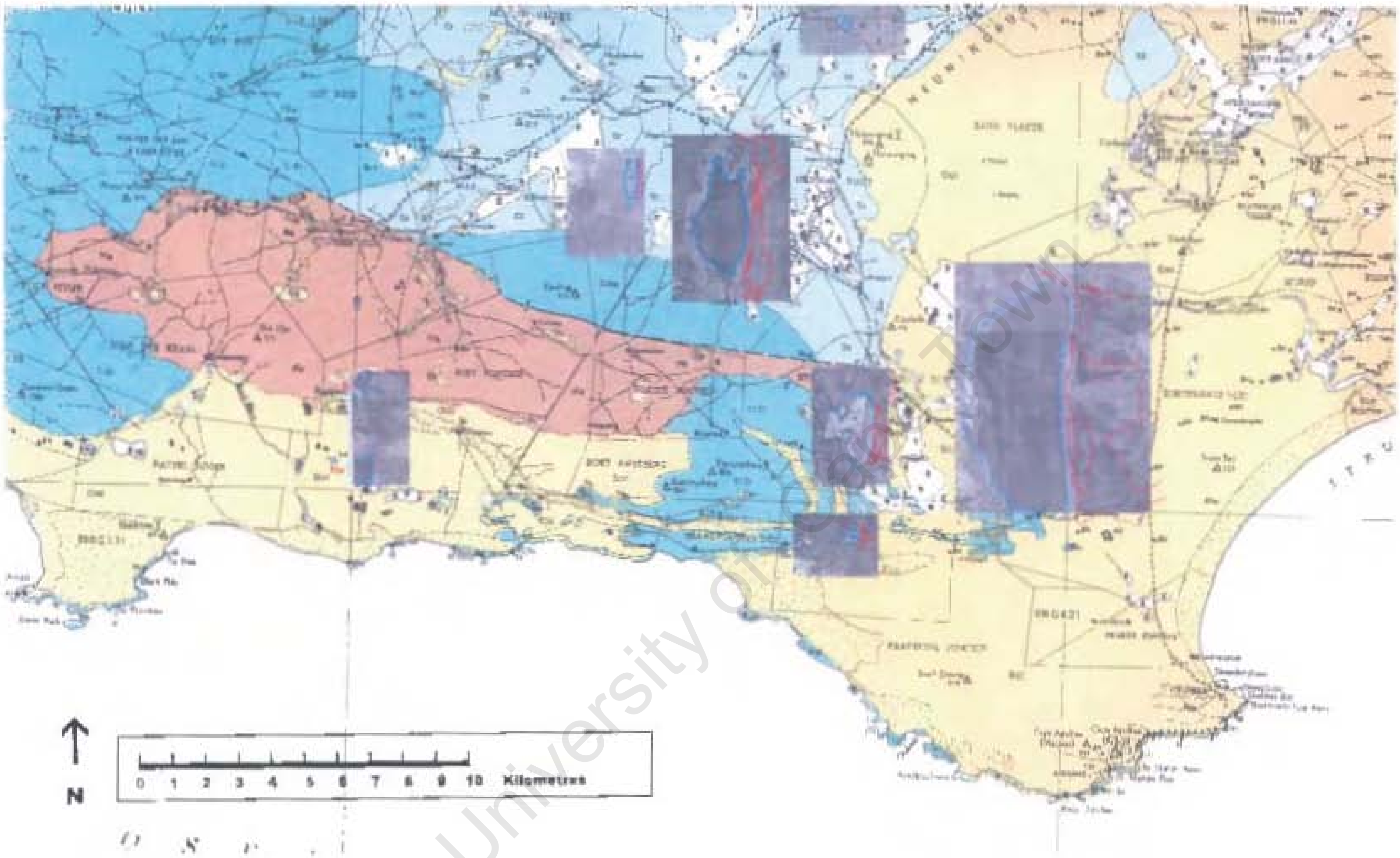

Figure 2.6: Geologic map (Geological Survey, 1963) of the Agulhas site overlaid with orthophotographs of pans (Directorate of Surveys and Mapping, 1981). In order of increasing age: the pale QQC is Bredasdorp calcified dune sand, the intermediate-toned C2 is Bokkeveld shale, the darker C1Q1 is Table Mountain Sandstone and the darkest region Ma, south of the shown fault-line is Malmesbury shale (Geological Survey, 1963). The outlines of pan-lunette features are the author's.

2.2.3 WIND

As evident in Figure 2.7, Agulhas[1] is subjected to a bimodal annual wind regime with calms for only 5.5% of the time. The wind, like the rainfall, is seasonal. For roughly 18% of the year, wind is blowing from the west, gusting greater than 8 m/s for 4% of that time. Likewise, for another 17% of the year, wind is blowing from the east and gusting greater than 8 m/s for nearly 5% of that time.

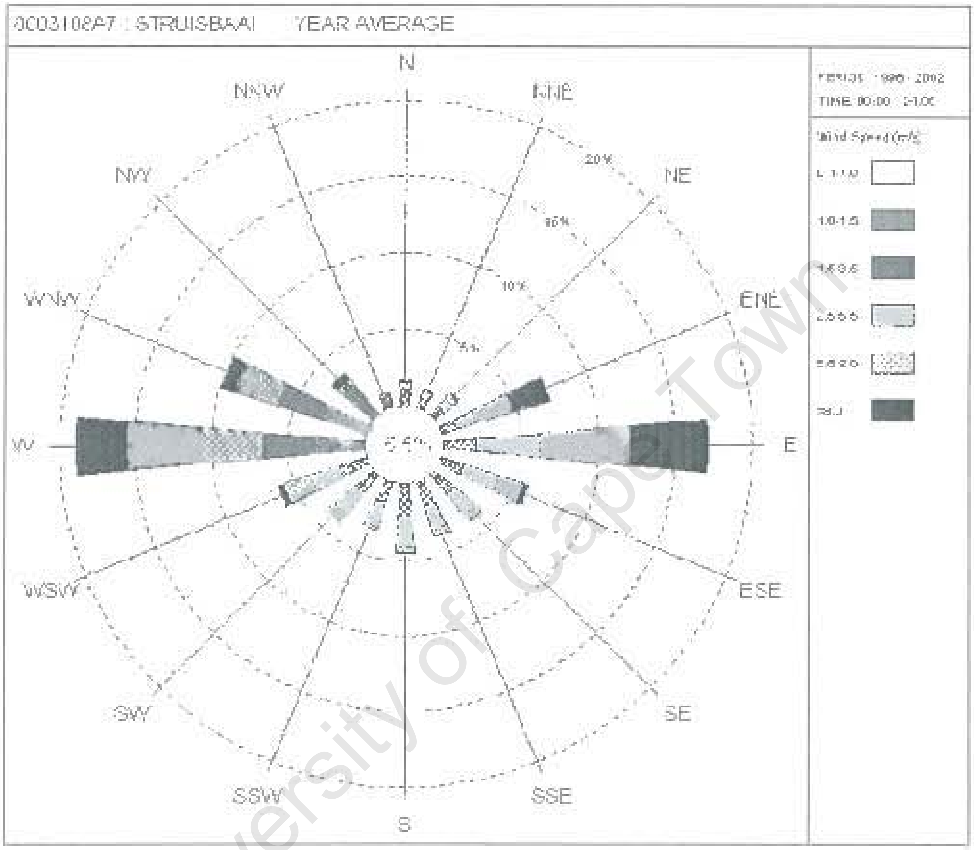

Figure 2.7: Annual wind averages for Struisbaai (34°48'S 20°04'E). Note arms point in direction from which wind blows. Percentage in centre indicates calm time (SA Weather Service).

2.3 SWARTLAND

2.3.1 GEOGRAPHY

The Swartland is a gently undulating plateau mantled by nutrient-rich soils. The Swartland region is inland from the more coastal sections of the region which are referred to as Sandveld; the Swartland site here occurs at a coast-wards extreme, bordering on the Sandveld (Talbot, 1947).

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[1] The Weather Bureau's station at Agulhas does not record wind data. The Struisbaai station is some 10 km east along the peninsula, and is likewise a coastal station.

The region is primarily underlain by the shales of the Precambrian Malmesbury Group. Near Darling where the pans occur, however, a number of different rock-types meet. The Precambrian coarse porphyritic Darling granite, of the Cape Granite Suite, intrudes into Precambrian Malmesbury Group meta-sediments and outcrops in a series of small rounded hills (Scheepers, 1995). The remaining geology of this particular part of the Swartland is Quaternary sand and loamy sand typical of the "hillocky veld" (Geological Survey, 1972)

2.3.2 PRECIPITATION

The Swartland receives a similar amount of annual precipitation to Agulhas but with a slightly more pronounced seasonal distinction, perhaps more noticeable because the Darling weather station is significantly further inland than the Agulhas stations which are at the coast.

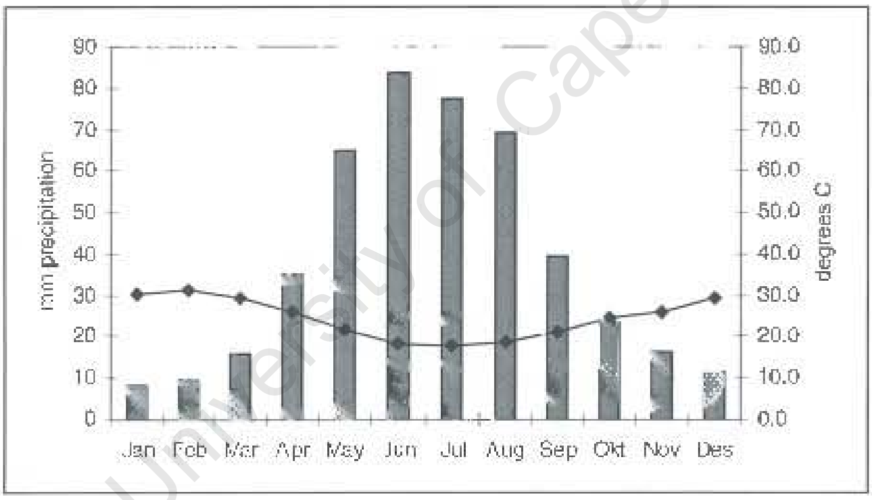


Figure 2.8: Monthly averages at the Darling weather station Precipitation data are from 1914-1999. Annual average precipitation is 455.4 mm. Temperature data span 1990-2002 (SA Weather Service).

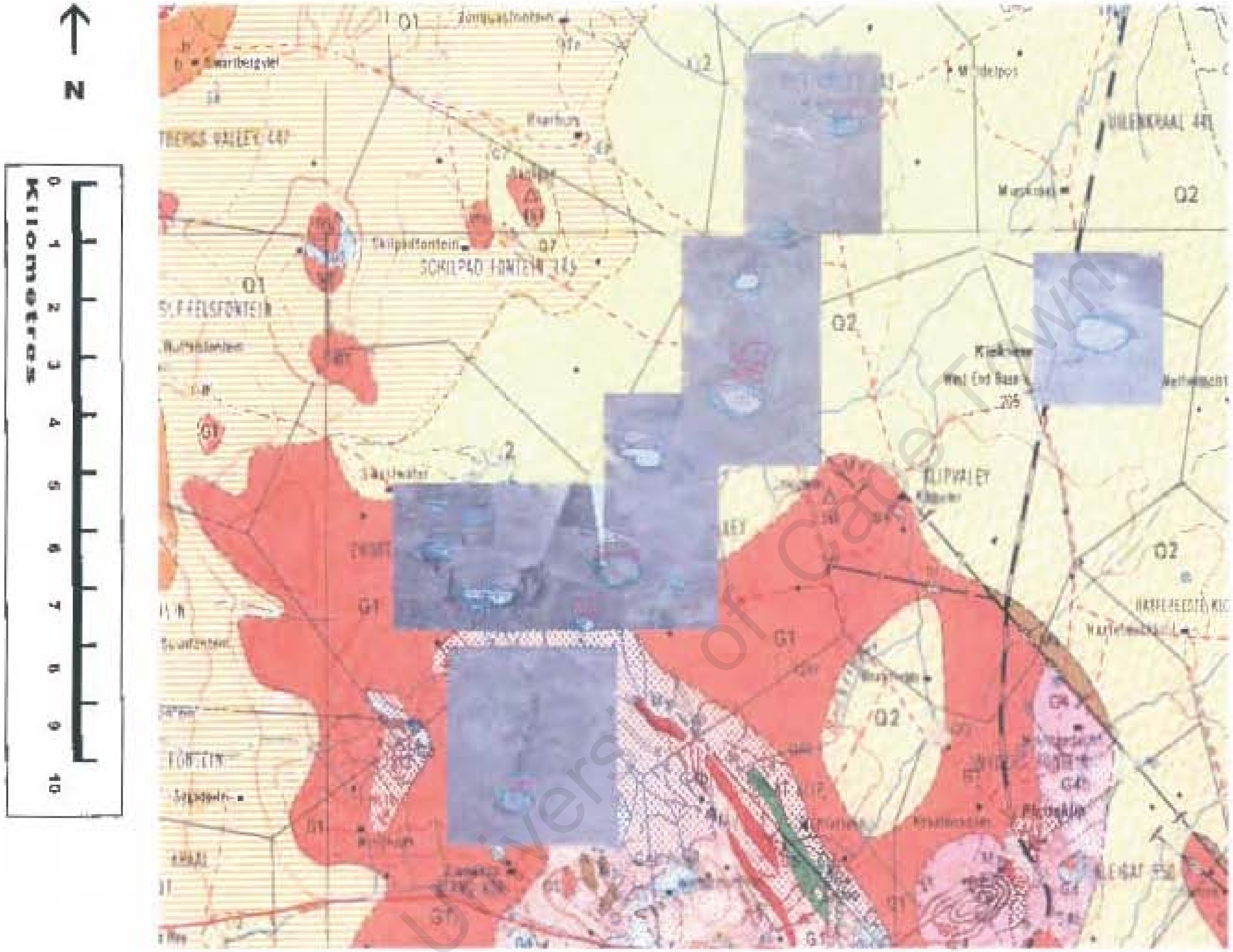


Figure 2.9: Geologic map (Geological Survey, 1972) of Swartland site overlaid with orthophotographs of pans (Directorate of Surveys and Mapping, 1981). In order of increasing age: Q2 is Quaternary sand and sandy loam, Q1 is Quaternary white to reddish sandy soil, G1and G1b are the Darling granite (Geological Survey, 1972). The outlines of pan-lunette features are the author's.

2.3.3 WIND

The Malmesbury weather station in the Swartland experiences a weak bimodal to unimodal annual wind regime with calm for 25.9% of the time. The wind blows from the southwest for approximately 14% of the time, 2% of that time gusting up to 8 m/s. The Swartland's strong winds are a known cause of aggravated soil erosion in an area with a history of soil degradation (Talbot, 1947).

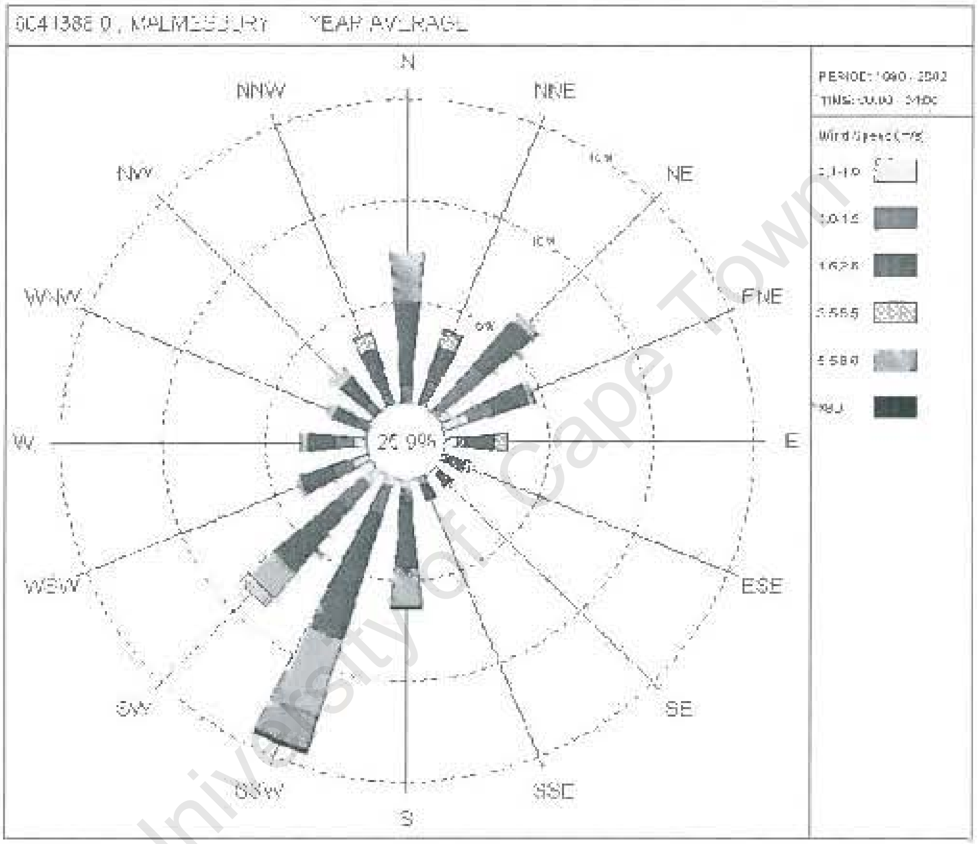


Figure 2.10: Annual wind averages for Malmesbury (32°58'S 18°10'E) (SA Weather Service).

2.4 CURRENT AND HISTORIC LAND-USE

Waves of human activity have left their mark on the landscapes of the southwestern Cape. The area has been inhabited by hunter-gatherer-fishing humans for the past two million years. Khoikhoi pastoralists have been raising stock for the past two thousand years. Jan van Riebeeck arrived in 1652 to establish a rest station for the Dutch East India Trading Company. English colonial spreading continued dramatically during the late 18th century from the epicentre of the "Mother City" of Cape Town. The land of the Swartland and

Agulhas Plain is currently used primarily for the cultivation of wheat and grapes and for raising livestock such as sheep, dairy cows, and ostrich. Less than 6% of renosterveld and 14% of fynbos in the western Cape lowlands remain untransformed (Richardson *et al.*, 1995).

2.4.1 ARCHAEOLOGICAL SITES

There are numerous archaeological sites in the southwestern Cape. In the Swartland, near the pan-lunette features, sites such as Saldanha Bay, Melkbos, Elandsfontein and Eland's Bay have been excavated (Jerardino, 1993, Deacon and Lancaster, 1988). Near Agulhas some sites are Stanford, Die Kelders and Byneskranskop (Avery, 1993; Deacon and Lancaster, 1988).

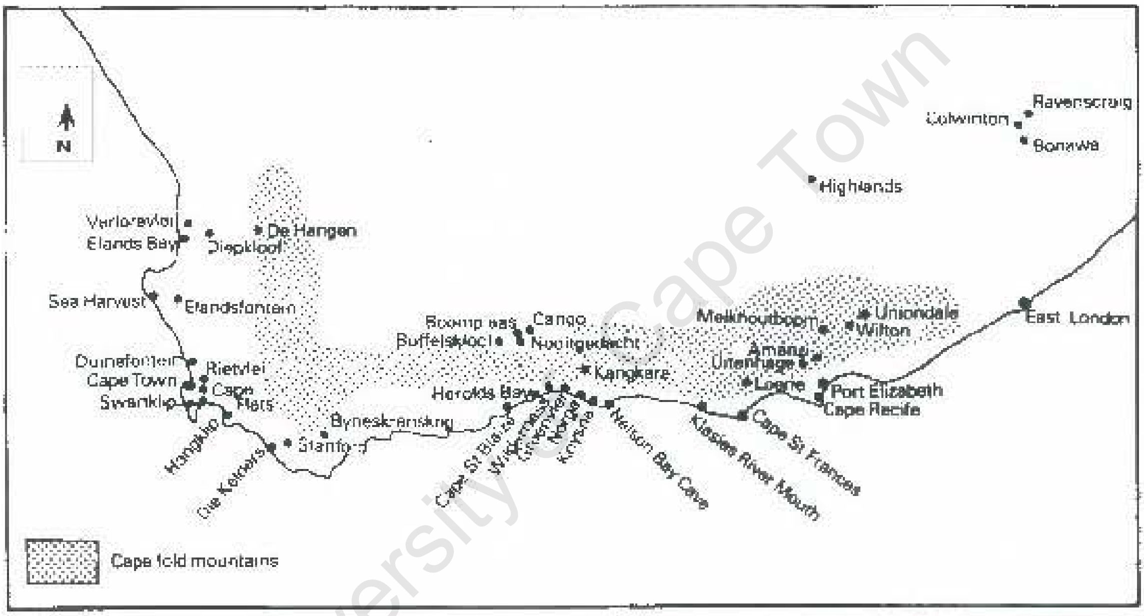


Figure 2.11: A number of archaeological sites in the western Cape (from Deacon and Lancaster, 1988). Scale is roughly 1:5 000 000.

After 1600 BP (Late Stone Age) the Cape landscape was altered by livestock kept by Khoikhoi herder-foragers. In one of the earliest southern sites, sheep appeared at Die Kelders between 1900-1600 BP (Smith, 1992). Avery (1997) found 342 sheep samples introduced between 2000-1500 BP (LSA), possibly in conjunction with pottery, but present a few hundred years before cattle. Cattle kept by the Khoikhoi appear in low numbers in the archaeological record of the southwestern Cape around 1300 BP (Smith, 1992). It was concluded that Middle Stone Age (MSA) peoples were less effective hunter-gatherers than successors (LSA), based on mammal, bird and tortoise remains found in the cave. Heydenrych (1999) identified Later Stone Age shell middens and fish traps along the coast also left behind by Khoikhoi pastoralists.

Although vegetation previous to the pastoralist economy has not been documented clearly for the southwestern Cape, there is little evidence to indicate that the seasonal migrations of the Khoikhoi and their herds between velds caused anything close to the magnitude of modern known 'environmental degradation', but rather that this transitory lifestyle was well-suited for sustainable livestock and veld condition (Hoffman, 1997). Other authors do argue, however, that resources such as nutrients, water, fuel, and fibre were scarce before the "substitutive technology" of the European colonialists, a system referring to the substitution approach to farming that relies largely on introduced plants and animals (Richardson *et al*., 1995).

Fire activity is a necessary force upon *fynbos* vegetation and the renosterveld vegetation endemic in these coastal strips (Le Maitre in Richardson *et al*., 1992). Seedling activity of these vegetation types is nearly confined to the period immediately following burning (Le Maitre in Richardson *et al*., 1992). Natural ignition is credited to lightning strike, but humans have been using fire as a tool to 'domesticate' the landscape through the course of their occupation. Early fire stick methods of burning were employed for the noticeably more fertile regrowth properties of the *fynbos*, but it was only the frequent burning by Europeans, which have been recorded, as detrimental (Hoffman, 1997).

2.4.2 SALT

Salt production may be the oldest human industry in South Africa. The Pretoria saltpan shows evidence of salt extraction before the arrival of Europeans (Beaumont, 1984). In the Western Cape, pans were first mentioned in the historical record by Leendert Janssen, commander of the survivors of the *Haarlem*, a ship from the Netherlands, which was wrecked near Bloubergstrand in March 1647 (Hugo, 1974). In 1649 Janssen recommended the founding of a refreshment station at the Cape, highlighting the presence of salt in abundance (Hugo, 1974). In May 1652 Jan van Riebeeck inspected a coastal saltpan near Bloubergstrand and soon initiated harvesting for both local inhabitants and passing ships (Hugo, 1974). In 1727 Kolbé reported the discovery of other pans "south of the Zondereind River near the sea", near Bredasdorp today (Hugo, 1974).

A number of pans in both Agulhas and the Swartland have been mined in the past 50 years (Spies *et al*., 1963; Visser and Schoch, 1973). Burgerspan South in the Swartland and Soutpan in Agulhas continue to be mined for salt today.

2.4.3 RECENT LAND-USE

2.4.3a Agulhas

The Agulhas area was first colonized by Europeans in the 18th century (http://www.lagulhas.co.za). The European settlers brought with them traditional wheat and sheep farming methods. Cape Agulhas lighthouse was built 150 years ago making it the second oldest lighthouse in South Africa (http://www.lagulhas.co.za). The lighthouse was a necessary addition as the earliest recorded shipwreck along the coast of Agulhas occurred in 1552 and they have continued to occur regularly into the present.

Two major transformative forces have been documented on the Agulhas Plain in recent history (Lombard, 1997). Firstly, cereals and pastures have been cultivated on more fertile shale-derived soils, which previously supported Coastal Renosterveld and Elim Fynbos. This land-use practice is responsible for the estimated loss of 34 693 ha (22.5%) of the area's indigenous veld (Lombard, 1997). Secondly, alien plants such as Australian wattles have replaced an estimated 17 470 ha (14.7%) of natural habitat reducing natural biodiversity, increasing fuel loads and the resultant wildfire hazards, and exhausting water supplies (Lombard, 1997). Lombard (1997) blames the overall regional fragmentation of native vegetation on the invasion of alien plants and agricultural clearing for pasture and cereal as described above and to lesser extents, urbanization linked with the development of coastal resorts, non-sustainable harvesting of indigenous wildflowers, and inappropriate fire regimes.

2.4.3b Swartland

Dutch pioneers first explored the Darling region of the Swartland in 1682, though the namesake of the village, Lt. Governor Charles Henry Darling, only established a farm there in 1853 (http://www.geocities.com/darlingvillage/history.html).

The regional economy moved from a stock-based system to the production of wheat, oats, barley, and rye during the late 19th century. By the end of that century, viticulture was beginning to replace the cereals as the international market opened. By the late 20th century after 1 000 000 years of fire stick farming, 2 000 years of stock raising, and 300 years of cultivation, farmers are beginning to struggle with the repercussions (Deacon *et al.*, 1992). Donga formation, accelerated by down-slope furrowing, water run-off, and wind erosion, is an increasing problem in the area. Since 1947 farmers have actively addressed the situation by growing lupins and building walls, with noticeably positive results (Morel, 1998). Currently as much as 75% of the land is cultivated (Macdowell in Meadows, 2001).

The name Swartland is derived from the dark-hued vegetation that greeted the first Europeans in the area. Indigenous Renosterveld is all but missing now except for the inaccessible scrubby heights of the Darling hills; the rest was ploughed up for wheat (Smith, 2001).

This research occurred amidst fields of wheat on farms in both the Swartland and Agulhas regions. This land-use has had a long-term effect on the development of the landscape. The topographic relief of the original lunette dunes may have been reduced by centuries of ploughing. Salt works cause chemical and physical changes. The farmed lands do clearly expose the pan-lunette features, however. In Agulhas, many of the features are now part of National Park land.

Chapter 3: Pan-lunette dynamics

3.1 DESCRIPTION OF THE FEATURE

The term 'pan-lunette' is a term used herein to describe pans bordered by lunettes. A pan is an ephemerally flooded closed basin water body found in arid zones and a lunette is a transverse dune composed of sediment ranging from sand to clay-sized on the leeside of the pan (Shaw and Thomas, 1997). The lunettes in Agulhas and the Swartland, as evident in Figure 3.1, are relict features and currently vegetated, in most cases even farmed. The pans never dry out entirely. The components and distribution of these pan-lunette features are described in more detail below.

Figure 3.1: Orthophotograph (Directorate of Surveys and Mapping, 1981) and photographs of the pan-lunette feature Slangkop. The top photo was taken under some of the driest conditions witnessed during this study (SMG, April 2002). Note figure on height of inner "lunette" for scale. The bottom photo was taken under water-full conditions (SMG, October 2002). The crest of the outer lunette can be seen at the middle horizon. The photos look westward. The orthophotograph is at 1:10 000.

3.1.1 PANS

Pans are commonly found in zones where annual evaporation exceeds precipitation, creating the saline water bodies. They occur on a range of different sizes and from a range of different origins. They exhibit ephemeral surface waters. Pans are labelled interchangeably worldwide as playas, salt lakes or sabkhas. In the southwestern Cape of South Africa, they are often referred to by landowners as vleis, indiscriminate to other water bodies. Usually clearly productive salt-pans, characterised by a crust of salt, are so called.

The distinguishing characteristics of pans include flat surfaces devoid of vegetation, their occupation of topographic lows, the lack of surface outflows, and ephemeral standing surface water caused by evaporation exceeding hydrologic input (Shaw and Thomas, 1997). In addition to a suitable sedimentary substrate, factors such as a tectonic or climatic drainage disruption, and geologic structures like intersecting fractures or basin-shaped sills encourage the initiation of pans (Shaw and Thomas, 1997). Pans are propagated by animal activity, surface deflation, and a lithology that is favorable to weathering in saline environments (Partridge, 2000).

The closed nature of pans is an important characteristic for many research purposes. According to Torgerson (1986), there are three assumptions that can be made to simplify the scenario if the basin is, in fact, closed. A closed basin means that (1) the pan sediments are controlled by water chemistry and depth within the pan, (2) a near equilibrium environment exists because of the fast response time of the surface water, (3) dry lakes cannot alter their own sediments or surface-waters in a simple manner. A closed basin is not an entirely closed system as it receives atmospheric inputs of chemical and particulate matter. Many of the so-called vleis in Agulhas have inflow channels, but no surficial organized drainage outflow. For the sake of this work, these vleis are considered to be pans, although technically they are not closed.

The distribution of pans in southern Africa has been described using 1:50 000 topographic sheets and aerial photographs (Goudie and Thomas, 1985). Pans in southern Africa primarily occur on the arid side of the 500 mm mean annual isohyet and the 1000 mm free surface evaporation loss isoline, occupying as much as 12% of the surface area, frequently along paleo-river courses (Goudie and Thomas, 1985). The distribution of pans in South Africa corresponds to rock and sediment types, usually shales and unconsolidated sands, such as Kalahari sands, Dwyka tillites and the Ecca shales in the Karoo Supergroup (Goudie and Thomas, 1985). The major regions of pan concentration are in the northern parts of the country with clusters in the western Free State, Northwest Province, and the Northern Cape Province (Figure 3.2).

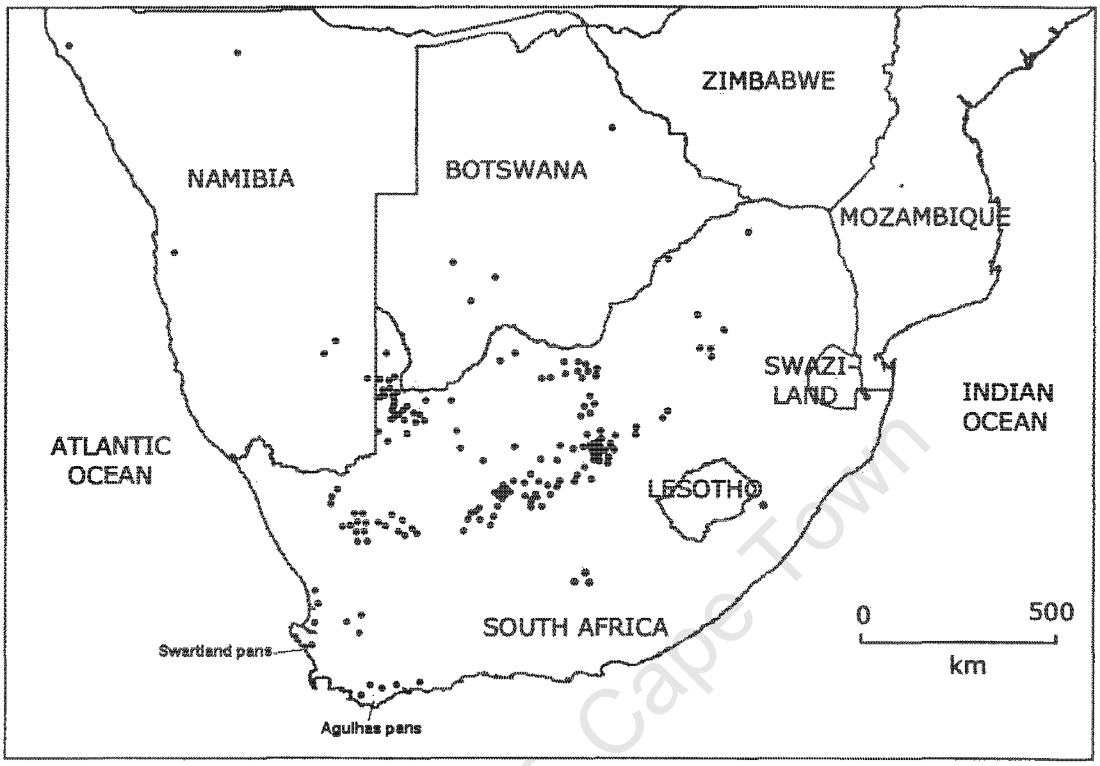


Figure 3.2: Distribution of pans in Southern Africa (adapted from Smith, 2000).

While the coastal regions of the southwestern Cape do not figure prominently in geomorphic reviews of pans throughout South Africa, much of the Swartland and the Agulhas Plain fall in what the Geological Survey of South Africa consider salt-pan regions. Although pans in the southwestern Cape are smaller and less densely distributed, they are of considerable economic interest.

Salt producers credit the presence of salt in the southwestern Cape with a combination of direct inundation of seawater into the pans by periodic flooding or gradual seepage, salts sunk into old marine sediments, and rainwater leaching salt from the dunes (Hugo, 1974). These theories are supported by chemical impurities in the salt that are the same as those found in seawater (Hugo, 1974). The replenishment of salt in these pans is not rapid enough to permit annual harvesting.

3.1.2 LUNETTES

The term lunette was coined in Australia by Hills (1940) to describe the lunate morphology of clay-rich pan-side dunes. Lunettes are defined as clay-rich transverse dunes on lake margins, meaning, firstly, that they have a clay loam composition and, secondly, that their horns face *into* the wind. Lunettes do occur in a range of textures and mineralogies in deserts around the world where mean annual precipitation is less than 700 mm (Goudie and Thomas, 1984). To clarify, it is common to label the lunette with its texture class: a clay loam lunette, for example. They range in height from a few meters to a few tens of meters.

In southern Africa, lunettes are common and well developed in the Northern Cape Province and Northwest Province (Goudie and Thomas, 1984). Lunettes of the Kalahari tend to be very sandy - up to 90.4% sand (Goudie and Thomas, 1984). Many lunettes in the region are calcretized, a process of post-depositional cementation with calcium carbonate (Goudie and Thomas, 1984).

A clay dune - composed of at least 20% clay - has a number of characteristics distinguishing it from its sandier cousins. This textural characteristic determines larger distinguishing characteristics. Clay dunes do not exhibit the cross bedding common in quartz sand dunes, but instead have a parallel bedding structure (Bowler, 1973). They form low-angle slopes, the steeper of which occurs on the windward side. Also, because they stabilize rapidly, they do not migrate from the original source, commonly the margin of a coastal lagoon or an inland saltpan. Not all clay dunes, however, are lunettes; only those dunes forming on salt lake shorelines are referred to as lunettes or fringing dunes.

Besides texture, lunette morphologies are also affected by wave action and shoreline drift in deeper pans, extent of aeolian activity often causing blowouts in clay dunes, and groundwater bevelling which serves to flatten the pan floor, often causing cliffs around the margins (Bowler, 1985).

Active clay dunes have been documented on the margin of coastal lagoons in Texas, on the west coast of Senegal, and inland on pan margins in Algeria. Clay dunes are actively forming in a wide range of climatic and environmental conditions (Bowler, 1973). Studies of these active systems have benefited theories of propagation.

3.2 PROPAGATION THEORIES

Although there is some contestation, it is generally agreed that lunettes form along pans in the following way (as described by Price, 1963):
During the dry season, the pan water table drops and the bare clay-rich shore and flats are exposed to rapid heating and drying, forming a clay crust. Because of the efflorescence of salts present, the crust flocculates into clay pellets of sand size. These pellets are then deflated by a predominant wind, accelerated across the pan floor, and deposited onto the leeward shore of the pan. During the ensuing wet season, on account of the hygroscopic nature of clays, the clay pellets are quickly stabilized into dunes in thin layers of clay, often preserved as individual laminae.

Clay dunes thus form in the presence of (1) a shallow saline water body that has (2) seasonally exposed mud flats and is subjected to (3) strong unidirectional winds during a (4) hot dry season (Bowler, 1973). *Salinity* is important for inhibiting plant growth on the pan floor, and for creating sand-sized clay pellets by efflorescence. *Water* is a necessary agent in this process, concentrating and distributing the salt and sediment supply. Seasonal *high temperatures* are necessary for high evaporation rates, which must lower the water table and desiccate clays rapidly. Necessarily high dry season temperatures may exceed 28°C (Bowler, 1973 as quoted in Lancaster, 1978). *Winds* during the mid to latter part of the dry season after the water table has lowered must be strong and unidirectional. Despite these limitations, modern clay dunes are forming in a range of climates, with local controls playing a more important role on hydrologic factors than regional controls.

The major issue of contention in regards to formational theories of lunettes deals with the presence of standing water in the pan. Hills (1940) theorized that droplets of water are wind-deposited from standing water in the pan to the downwind shore, there encouraging deposition and retention of the majority of dust. Hills then associated lunette propagation periods with humidity. Stephens and Crocker (1946) and many subsequent workers (including Price, above) stated the most important sediment addition was a product of dry-scouring of wind over an entirely desiccated lake bed, depositing sediment in a dune which is then self-propagating as wind is deflected over the dune crest and forced to deposit its particle load on the dune (Campbell, 1968). Stephens, Crocker and later authors connected dune building with arid climate phases.

Additionally, the importance of vegetated lunettes is contested. It has been argued that vegetation on actively growing dunes helps to catch and deposit air-blown dusts and actually provides a foundation to retain sediment on a steep windward slope (Campbell, 1968). Vegetation, then, in addition to the cohesion provided by high clay content would be responsible for the diagnostic steep windward slopes. In most analyses vegetation goes unmentioned.

An additional mechanism suggested is that the composition of the lunette is determined by the hydrologic environments during formation. Quartz-rich dunes are formed during lake-full conditions while clay or gypsum-rich dunes form when the basin is dry and the floor itself is deflating (Bowler, 1983). The sedimentary contrast thus reflects different origins.

In a number of examples, a series of lunettes with varying textures and orientations were identified along one pan shore and regarded as the product of different dune-building phases (Marker and Holmes, 1995; Lancaster, 1978; Bowler, 1985). In Australian examples, Bowler (1985) observed clay lunettes built stratigraphically above sandy lunettes as a result of a shift from surface water to groundwater-controlled basin hydrology, essentially a shift from standing water to arid halite-crusted pan basins. The southern Kalahari arcuate margin dunes in Botswana frequently have an inner dune ridge consisting of poorly sorted sediments, 12-20% silt and clay and 12-15% calcium carbonate (Lancaster, 1978). The outer dunes are composed of fine red quartz sands and have been interpreted as the product of initial deflation of the surface Kalahari sands during a dry period in the late Pleistocene. The age of the inner dunes has been assumed to be 9-10 000 BP, during post-glacial desiccation in the southern Kalahari (Lancaster, 1978). In the northeast Cape of South Africa, Marker and Holmes (1995) also identified a pan with a series of three marginal dune ridges, with textures ranging from silt and clay near the pan basin to fine sand in the dune furthest out. It was concluded that the sandy dune formed first, perhaps correlating with similar proximal sites, luminescence dated at roughly 20 000 BP. The smaller clay dunes were formed at the margin of a shrinking pan, under more arid post-glacial conditions.

3.3 PALAEOENVIRONMENTAL SIGNIFICANCE

In summary, clay lunettes require saline environments, seasonal flooding and evaporation, strong unidirectional winds, and a hot dry season during the windy times.

Despite the arid environment breeding the feature, dune formation requires at least the seasonal presence of water so that evaporation can exceed precipitation. Bearing this in mind, periods of dune formation are not solely indicative of arid periods.

Palaeoenvironmental inferences have been reached based on evidence in a number of pan-lunette features. These studies were first conducted in Australia (Hills, 1940; Campbell, 1968; Bowler, 1973; Bowler, 1983; Chen; 1995). Although there are pan-lunette features in the winter rainfall area of southeast Australia, the work there has focused on features in the summer rainfall regions. More recently studies have been done in southern Africa (Lancaster, 1978; Marker and Holmes, 1995, Thomas *et al.*, 2002).

The current study is one of the first of its kind in this part of South Africa. It is distinguished from other studies in the country by virtue of its locality in a winter rainfall region and its proximity to the sea. Additionally, no other regionally comparative studies were found. The work of this project does borrow heavily from previous techniques and approaches to the interpretation of these kinds of features, as this chapter indicates. The technical approaches to the pan-lunette features of the southwestern Cape are discussed in the following two chapters.

Chapter 4: Pan-lunettes at a Regional Scale

4.1 APPROACH

A perspective informed by a number of different proxies at various scales provides the best explanation of the history of the pan-lunette features. This work approaches the features from a regional scale, inspecting the entire cluster, and at a local scale, with detailed studies of two individual pan-lunette features.

At a regional scale, the spatial distribution of pan-lunette features can be morphometrically quantified using maps and photos. The map work utilizes orthographic photographs, topographic maps and aerial photographs to document characteristics such as the size, location, elevation, primary axial length and orientation of pans, and lunette orientation. Particular attention is paid to the relationship between pans and the surrounding landscape as well as the relationships between the pans themselves. Not all of the pans in the southwestern Cape have associated lunettes. Both the pans and the lunettes take many different forms. These variations are documented. The morphology of the modern landscape of the Swartland and the Agulhas Plain is studied in tandem with modern wind and precipitation data from the South African Weather Service. This work comprises the current chapter.

At a local scale, a number of different techniques are utilized to determine the sedimentary and geochemical nature of the interactive pan-lunette system. Sedimentary analyses on samples from the lunettes and pan floors specifically look at texture to determine clay fraction of the lunette, carbonate and organic components, and the clay mineralogy, pH and conductivity to consider weathering within the dune. This approach is described in the next chapter.

Finally, the age of the pan-lunette features and the relative timing of formation and dune-building is discussed in Chapter Seven. Radiocarbon dates obtained from gastropod shells are compared with geomorphologic evidence, ages measured in other studies of the area and the relative ages of related events in the southwestern Cape.

4.2 MAP WORK

The pans and pan-lunette features of the region were described generally using a number of different kinds of maps as well as Geological Society of South Africa (GSRSA) reports on salt in South Africa (Lourens, 1992).

4.2.1 RECOGNITION AS PAN-LUNETTE FEATURES

The first step in this work was to establish that the features under consideration are, in fact, pan-lunette features.

As discussed in Chapter Three, some characteristics of pans include flat surfaces devoid of vegetation, the occupation of topographic lows, the lack of surface outflows, and ephemeral standing surface water caused by evaporation exceeding hydrologic input. The basin floors of the southwestern Cape pans are free from vegetation. Maps indicate that the basin floors are flat. The water bodies do occur in topographic lows. Many of the shorelines are marked by a cliff or sharp break of slope. With the exception of Soetendalsvlei in Agulhas, based on map and fieldwork, all of these bodies of water lack organized surficial channels draining the basins in a network of outflow; they are essentially, thus, closed basins displaying endorheic drainage. The volume of standing surface water is ephemeral. In the two-year duration of this project in 2001 and 2002, particularly wet years for the southwestern Cape, none of the basins were observed at an entirely dry state (see Figure 3.1 for some extremes observed).

The dune features are less simply defined. Some characteristics of clay dunes were outlined in Chapter Three, but lunettes do form in a range of sediment texture and hence develop different overall morphology. There are a number of different origins besides the pan-lunette scenario that could potentially explain the current morphology: a gentle rise along one side of the pan margin, lunate in plan, steeper on the pan-side than the far side, which slopes gently away from the pan. What follows are other possible explanations for the current morphology, followed by the rationale for discrediting them. For example, the Pretoria saltpan is a crater formed by a meteorite impact (Partridge *et al.*, 1993). This up-thrown origin of the topographic highs at pan margins in the southwestern Cape can be discredited on account of the parallel one-sided orientation of all the lunettes in each cluster, the lack of impact breccia and similar geology, the morphology of each individual feature, and the fine-grained sorted sediments within them (described in Chapter Five). Likewise, a sea-level bench from previous high water levels does not explain the individual yet parallel morphology of each feature in the cluster. Detailed sediment analyses (described in Chapter Five) were necessary to definitively establish a wind-blown origin for the southwestern Cape 'lunettes', but no other explanation for origin proves satisfactory based on regional-scale evidence.

4.2.2 AERIAL PHOTOGRAPH STEREO PAIRS

Stereographic analysis of aerial photograph pairs was attempted in order to recognize those dunes not delineated at a 5 m contour interval on the orthophotographs. However, because of the low-relief landscape of each region this effort proved unsuccessful. Careful, magnified inspection of individual photos was more informative, and based on these, a number of dunes with a height smaller than 5 m were recognized and included in the maps in Figure 4.1 and 4.3.

4.2.3 CHARACTERISTICS OF THE FEATURES

4.2.3a Agulhas

There are ten principle pans on the Agulhas Plain (nine of the ten are shown in Figure 4.1). They range in size from 10 to 1495 hectares and occur at roughly 20 m elevation above mean sea level (see Table 4.2). The largest, Soetendalsvlei, cannot currently be considered a pan because of the organized outflow drainage there, but previous arid conditions, when surface water was less prevalent, may be responsible for the apparent dune. Of these ten pans, 50% feature a clam-shaped morphology, a circular shape, flattened along one side and narrowing on the opposite side. The other 50% display a more regular oval shape. The features occur on shale and sand (Figure 2.6) although much of the Plain surface is occupied by marshy vleis. The oval morphology is more common on shale (3/4) while the clam morphology appears on the sandier substrates.

Half of the pans (5/10) are accompanied by lunettes, all of which occur on the eastern margin. The recognized lunettes are from 3 m to 17 m in elevation above the pan floor. The 5 m orthophotographic contour reveals a fragmented morphology to many of the dunes, especially those at Soetendalsvlei and Voelvlei (Figure 4.1). Many of these dunes are also characterized by an erosional cliff on the pan-side. Other dunes follow exact lunate morphology; Soutpan and Renosterpan are examples of these. There is no apparent correlation with underlying geology or pan morphology for the occurrence or morphology of a lunette. However, as shown in Figure 4.2, there is a good positive correlation between the size of the pan and the height of the dune, indicating that the sediments in the dune are derived from the pan basin, not just accelerated across the floor surface.

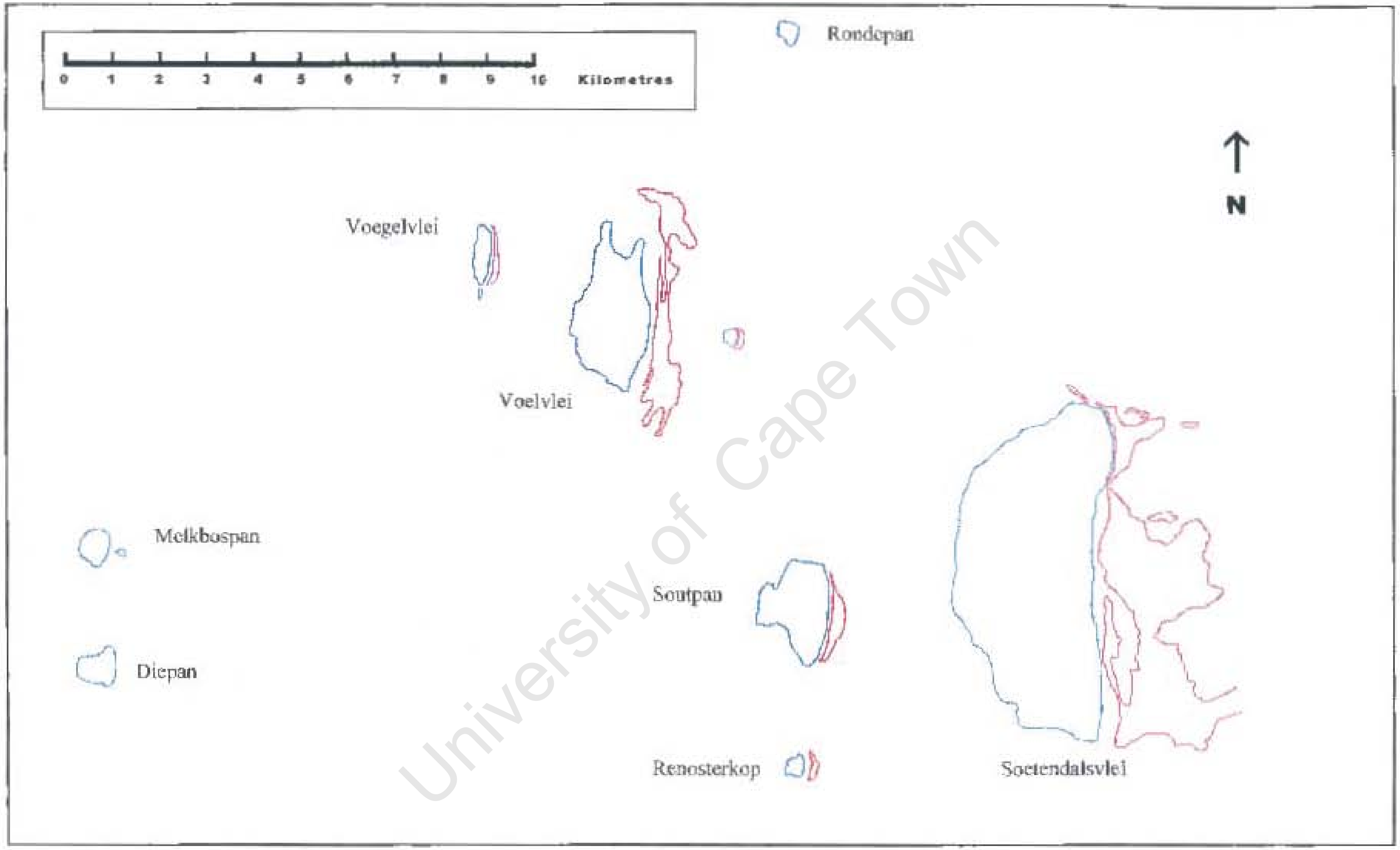


Figure 4.1: Primary pans and pan-lunette features in Agulhas drawn from Figure 2.6. The dunes outlined in red were drawn from orthophotographs. The pink pans were drawn from aerial photographs and represent an elevation of less than a 5m.

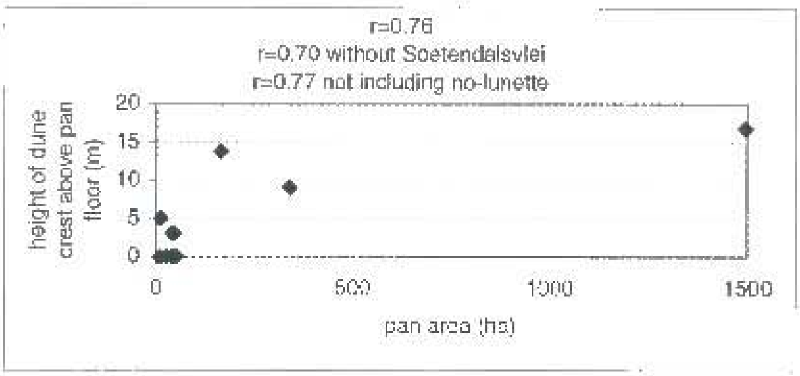


Figure 4.2: Correlation between pan area and height of dune in Agulhas. Points on the x-axis indicate pans without dunes. A correlation coefficient was calculated both with and without Soetendalsvlei because of its extreme scale. In both cases a good positive correlation (r=0.7) exists.

4.2.3b Swartland

There are twelve primary pans in the Swartland (Figure 4.3). (Two additional Swartwater pans are included in Figure 4.3 but are not discussed further because of their indistinct nature in map and fieldwork; their presence however is noted.) The pans range in size from 5 to 18 hectares and sit at around 60 m elevation (Table 4.1). The morphology of 75% (9/12) of these pans is clam-shaped. The remaining 25% (3/12) are round. The Swartland pans are situated at the base of the granitic Darling hills. The substrate hosting the pans is granite and sand (Figure 2.9). There is no apparent correlation between pan shape and underlying geology. The geologic contacts, of course, do not limit the shifting of overlying sediment.

The pans that Smith (2000) described as brine-type based on their salt chemistry display a cliff or sharp change of slope at the margins. This kind of drop would be expected as a result of dissolution or ground water bevelling, two processes that occur in salty ground water controlled pans (Bowler, 1983). There does not appear to be a correlation with the underlying geology; Smith (2000) credits the saline environments of some of the pans as a result of through flow of coastal rainwaters along the base of the granite underneath surficial sands. The reader is referred to her work for a more thorough analysis of the groundwater chemistry and hydrologic character of these pans. These pans do not, however, show any more favourable predilection to the formation of lunettes. These cliffs in the front face of the dune, identified elsewhere where information about salt chemistry is unavailable, are also created by wave action during high water levels in the pan.

Other pans occur nearby at Ysterfontein, but these coastal pans are of a different nature, occurring in the Sandveld and generally influenced by the sea, as flooding during coastal storms is common. They are therefore not included in this discussion.

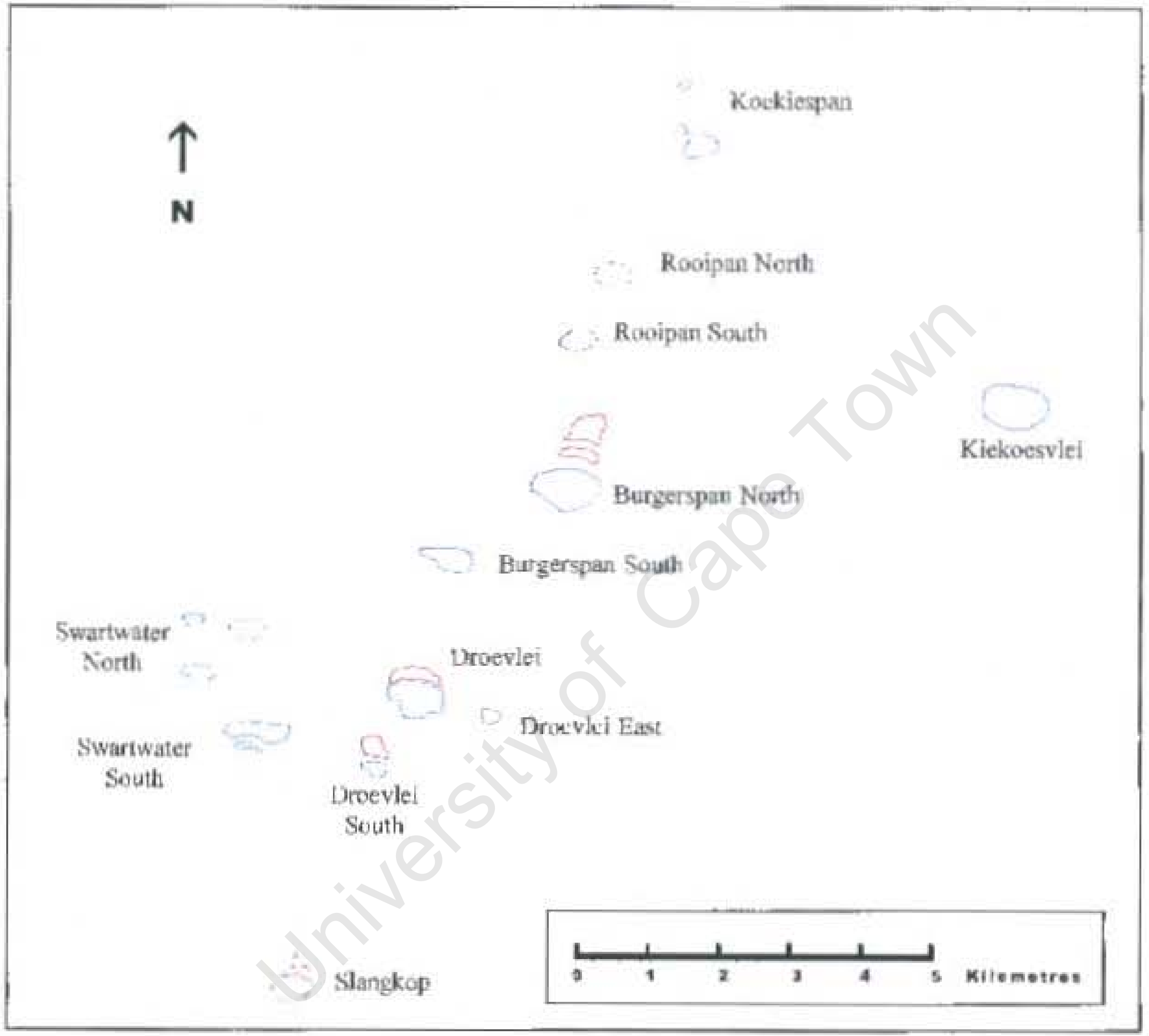


Figure 4.3: Primary pans and pan-lunette features in the Swartland taken from Figure 2.9. The dunes outlined in red were drawn from orthophotographs. The pink pans were drawn from aerial photographs and represent an elevation of less than a 5m contour.

Roughly 60% (7/12) of the pans are accompanied by lunettes which range from 5 m to 10 m in elevation. Lunettes in the Swartland cluster occur on the northeastern shore of the pans. Based on 5 m contour interval lines from orthophotographs, the lunettes of the Swartland are one of two forms: a lunate morphology with narrowing hooked limbs, or a simple rounded rise sitting on the north margin of the pan. In the field, all discernable lunettes do have recognizably narrow pan-hugging horns. Of the five pans mapped on granite, four have lunettes; a majority of the Swartland pan-lunettes (4/5) occur on granite. Otherwise the morphology (including size) of the Swartland pans is not a determinate of lunette propagation. Unlike the Agulhas cluster, which is composed of much larger pans, the Swartland pans do not show a significant correlation between pan area and lunette height (Figure 4.4).

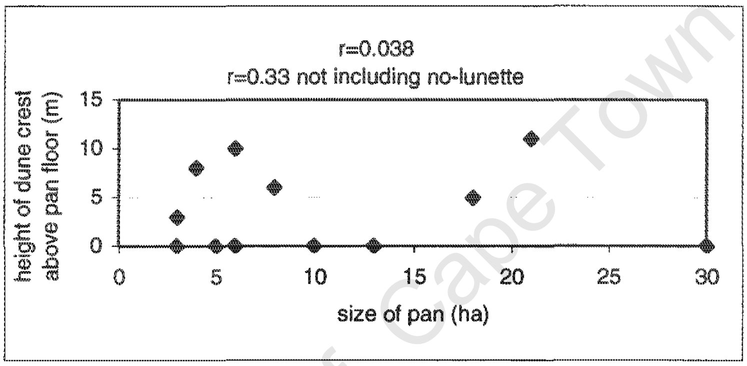


Figure 4.4: Correlation between pan area and height of dune in the Swartland. Points on the x-axis indicate pans without dunes. There is essentially no correlation here (r=0).

Table 4.1: Major characteristics of the pan-lunette features in either cluster.

	Swartland	**Agulhas**
Number of pans	12	10
Size of pans	5 to 18 ha	10 to 1495 ha
Morphology of pans	Clam (75%) and round (25%)	Clam (50%) and oval (50%)
Elevation of pans	55 to 105 mamsl	15 to 25 mamsl
Substrate hosting pans	Sand and granite	Shale and sand
% with lunettes	60%	50%
Size of lunettes	3 to 11 m above pan floor	3 to 16.8 m above pan floor
Rough orientation of lunettes	Northeast pan margin	East pan margin

Table 4.2: Swartland pans

Pan name	Chemistry (Smith, 2000)	Substrate	Size (ha)	Long axis (m)	Short axis (m)	Elevation (mamsl)	Lunette elevation	Elevation change	Shore	Morphology
Burgerspan South	brine	sand	12	650	490	60-65	---		topo low	round
Burgerspan North	brine	sand	21	670	240	62	73	11	cliff	clam
Droevlei	brackish	granite	18	700	450	70-75	75-80	5	---	clam
Droevlei East	---	granite	3	235	150	70-75	70-75	3	---	clam
Droevlei South	---	granite	4	300	180	75-80	84	8	---	clam
Koekiespan	brine	sand	7	280	160	57	---	---	cliff	clam
Kiekoesvlei	brackish	sand	30	800	620	55-60	--	---	---	clam
Rooipan South	brine	sand	7	380	260	60-65	70-75	10	topo low	round
Rooipan North	brackish	sand	2	330	220	60-65	---	---	---	clam
Slangkop	brackish	granite	7	400	225	100-105	111	6	---	round
Swartwater South	brine	granite	10	660	80	71	---	---	topo low	clam
Swartwater North	brine	sand	5	310	180	70-75	---	---	topo low	clam

Table 4.3: Agulhas pans

Pan name	Substrate	Size (ha)	Long axis (m)	Short axis (m)	Elevation (mamsl)	Lunette elevation	Elevation change	Shore	Morphology
Melkbospan	sand+shale	42	810	620	29	---	---	topo low	clam
Die pan/ Vispan	sand+shale	51	900	730	5-10	---	---	topo low	clam
Voegelvlei	shale	43	1330	340	20-25	24	3	---	oval
Voelvlei	shale	340	3560	1680	8	17	9	cliff	oval
Renosterkop	sand	12	550	470	10-15	15-20	5	---	clam
Soutpan	sand+shale	167	1650	1360	9	22.8	13.8	cliff	clam
Langepan	shale	26	1080	350	15-20	---	---	topo low	oval
Rondepan	shale	10	450	320	21	---	---	---	clam
Soetendalsvlei	sand	1495	3800	2570	2	18.8	16.8	---	oval

4.3 DYNAMICS OF SEDIMENT TRANSPORT

4.3.1 DUNE PROPAGATION: APPLICATION FOR CLAY LUNETTES

The direction of dune propagation is not determined by wind direction and force alone, but rather by sand moving effectiveness. Fryberger (1979) established models for sand roses in quartz sand seas based on wind vectors and drift potential. Fryberger's work (1979) defines wind regimes that are characteristic of certain dune types. His sand roses, introduced in the 1979 work, have been used by many subsequent arid zone geomorphologists to indicate direction of sand movement. The sand rose differs from a wind rose because the arms of the rose are vector quantities representing drift potential whilst the wind is blowing in the given direction thereby producing a resultant drift potential. Force of wind is not the sole determinate of drift potential; calculations of drift potential are complicated by the effects of shear velocity, namely grain diameter, surface roughness, vegetation and moisture (as expressed by the Lettau equation cited in Fryberger, 1979).

In dynamic environments like those of the southwestern Cape, where surface roughness and vegetation are highly variable through millennia, moisture is seasonally variable, and grain size is partially dependant on the flocculating activity of salts in different clays, calculations of drift potential are practically unattainable. 'Sand moving potential' must necessarily be referred to as 'sediment moving potential' as much of the sediment moved is actually sand-sized clay pellets. Bearing this in mind, wind data from the South African Weather Service weather stations have been used alone as indication of modern direction and force of wind, an approximate 'sediment moving potential'.

The 'Fryberger method' has been applied to calculate sand moving potential from winds by discounting those winds below the 5 m/s threshold and resolving the remaining wind vectors. This approach was not utilized here for two primary reasons. According to more recent work by Wiggs (1997), wind with velocities as low as 20 cm/s is capable of moving grains. The 5 m/s figure is less of a 'threshold' perhaps than previously considered; using that figure as a cut-off point would ignore winds with sediment moving potential. Also, the average wind speeds in either region studied here are below 5 m/s, in the case of the Swartland site, significantly below that limit (Figure 4.5 and 4.6). Excluding those winds would leave few remaining gusts, and oversimplify the scenario. An alternative, more appropriate approach to resolving the wind data and suggesting sediment moving potential is applied in the following section.

The surface-wind data are not without inaccuracies. There is a significant problem of observer bias; the observer is much more likely to take note of extreme weather conditions than more subtle average ones. Major variations also occur in the actual method in which the data are gathered, for example the height at which a wind meter is mounted (it should be a standardized 10 m) and surrounding topography will vary. A third common inaccuracy comes with the data summary where data is condensed from 36 to 16 directions and the resolution of statistics is thereby coarsened (Fryberger, 1979).

4.3.2 METHODS FOR DETERMINING LUNETTE ORIENTATION

Despite the problems inherent (irregular grain diameter, surface roughness, vegetation and moisture) in applying Fryberger's (1979) method to environments like those in the southwestern Cape, it is useful to note that he associated transverse ridge dunes (barchanoid dune types) with wind regimes characterized as narrow unimodal, wide unimodal, or acute bimodal with one mode much stronger than the other. Barchanoid dunes occur in areas with a variety of wind energies or drift potential. Of all dune types Fryberger (1979) studied (barchanoid, linear, star), the barchanoid dunes are associated with the least variability in wind direction over a large range of drift potentials.

The formation of a pan-margin transverse dune is a different process from the formation of a transverse dune in a uniform quartz sand sea. To begin with, there is a limited position and extent possible for a structure that derives its sediment from the pan floor and margin. Despite the limitations, however, a lunette still requires a minimal amount of wind and a well-directed sustained force in order to develop its indicative arcuate morphology. Based on this argument, this work proceeds with Fryberger's (1979) conclusion that unimodal and imbalanced acute bimodal wind regimes in a range of strengths are the most ideal winds for lunette propagation and the generally supported conclusion that clay lunettes develop when some pan floor is exposed during the drier times of the year.

Because of the seasonally unimodal (annually averaged bimodal) winds and seasonally arid/humid climate of the southwestern Cape (see Figures 2.5, 2.7, 2.8, 2.10), this work will heretofore take the assumption that during the dry period (the period of greatest sediment moving effectiveness, currently the southwestern Cape summer specifically from December through February), the wind regime is actually unimodal (Figures 4.5 and 4.6).

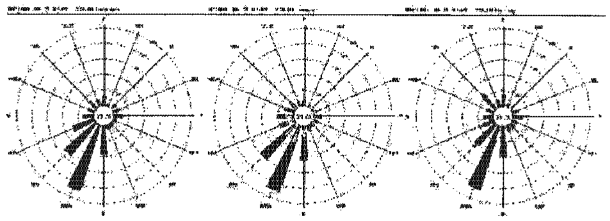


Figure 4.5: Unimodal Malmesbury wind regime during the three driest months of December, January and February. (See Figure 2.4). The average wind speed during this time is 3.20 m/s with calms for 19.05% of the time. The annual average wind speed is 2.64 m/s with calms for 21.33% of the time (all data from SA Weather Service from 1986 to 1988).

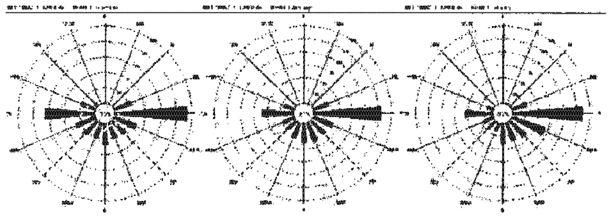


Figure 4.6: Unimodal Struisbaai wind regime during the three driest months of December, January and February progressing from imbalanced acute bimodal to unimodal. (See Figure 2.5). The average wind speed during this time is 4.78 m/s with calms for only 1.49%. Annually, the average wind speed is 4.57 m/s with calms for 2.29% of the time (all data from SA Weather Service from 1988 to 1998).

There have been a number of means of identifying the orientation of lunettes and hence wind direction. Bowler (1983) stated: "The axis of symmetry which also intersects the lunette at its highest point reflects the direction of the controlling wind regime". His statement here reinforces the above assumption that a unimodal wind is responsible for lunette growth. However, in the case of sand lunette orientation, Bowler (1983) comments that the development and orientation of sandy beaches determined by a complicated interaction between wind, waves, and sediment transport in the lake is also important. Lancaster (1978) measured the alignment of dunes by the "perpendicular bisector of a line joining the upwind arms of the dunes" and then assumed wind direction from that azimuth. For the purpose of this work, Lancaster's (1978) perpendicular bisector approach was employed as, in virtually all cases, no highest dune point is easily recognizable.

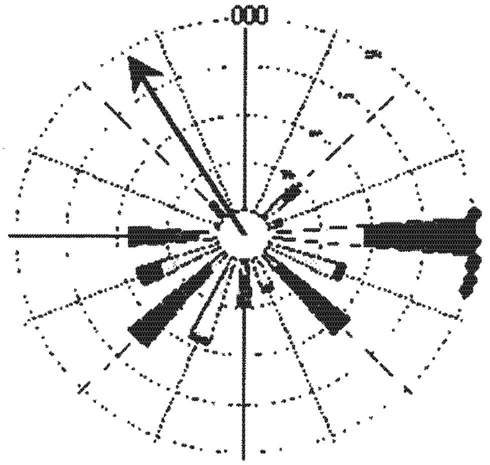


Figure 4.7: Lunette orientations in Agulhas against predominant dry-season winds. The month's wind has been divided into 16 even divisions on the 360 degree plot. The arrow indicates the direction of the resultant drift potential, and the expected lunette orientations. Each dot on the outer ring represents the orientation of a lunette in the Agulhas cluster.

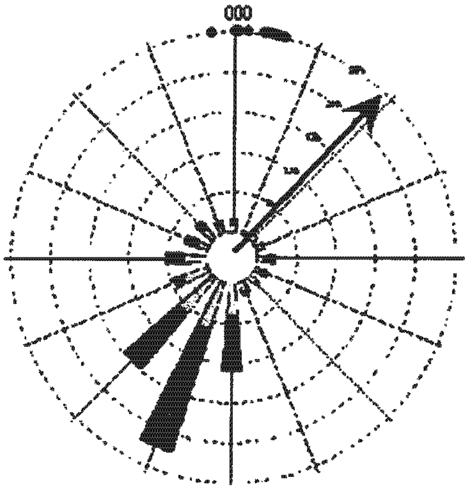


Figure 4.8: Lunette orientations in Swartland against predominant dry-season winds. The month's wind has been divided into 16 even divisions on the 360 degree plot. The arrow indicates direction of the resultant drift potential, and the expected lunette orientations. Each dot on the outer ring represents the orientation of a lunette in the Swartland cluster.

In both cases, the January wind regime, the middle month of the three driest months, was used as a basis to determine the unimodal wind responsible for sediment movement. Although January is not likely to be the absolute driest time of year on the pan floor, it was selected as a middle-ground representative of the dry summer season to avoid the variable wind and rain extremes of the season. For example: although April was a dry month in 2002, it was drier in the Swartland than in Agulhas, and downright wet in other years. January was chosen as a mid-summer point, which in terms of rainfall, at least, is a standard annual low throughout the southwestern Cape (Figure 2.4).

The component wind vectors representing more than 5% of the average January winds were resolved to give one vector of effective wind and hence resultant drift potential. This calculation yields a resultant drift direction of 331 degrees in Agulhas and 044 degrees in the Swartland. The orientation of the Swartland dunes is on average 11% (40°) off the resolved modern January wind (Table 4.4). The orientation of the Agulhas dunes is on average 33% (119°) off the resolved modern January wind direction (Table 4.5). Although the modern wind resultant is more similar to the modern lunette orientation in the Swartland cluster, neither of the resultant drift directions in Agulhas or the Swartland, as calculated, would yield the lunettes.

The resultant drift potential may change if the wind vector is recalculated using only those winds capable of moving sediment (not such an easy task for complications discussed in 4.3.1). In terms of grain moving potential, particles between 0.04 and 0.40 mm (sand-sized) are most susceptible to entrainment or movement by wind, with velocities as low as 20 cm/s threshold shear velocity (Wiggs, 1997). Smaller, clay and silt sized particles actually require higher velocities to counteract their forces of cohesion, tendency to retain moisture, protection by larger particles and position in the still (zero-velocity) bottom layer of airflow (Wiggs, 1997). Of course, this shear velocity does not translate directly to the wind speed measured at weather stations, the lowest of which is only 0.5 m/s (50 cm/s). So, depending on the relationship between the measured wind speed and the shear velocity, every wind measured by the station, assuming ideal grain-moving conditions, is capable of sediment transport. By using the 5% mark, the data set of monthly wind vectors has been simplified without seriously altering the resultant.

Table 4.4: Orientation of dunes in the Swartland cluster and difference from resolved January wind direction (blowing from 224).

Pan	Angle connecting horns	Lunette orientation	Wind that built lunettes	Difference in lunette-building and modern wind orientations	Percent difference (out of 360 degrees)
Slangkop	280	010	190	034	9%
Droevlei	270	000	180	044	12%
Droevlei E	273	003	183	041	11%
Swartwater	271	001	181	043	12%
Burgerspan S	277	007	187	037	10%
Burgerspan N	281	011	191	033	9%
Rooipan S	278	008	188	036	10%
Rooipan N	264	354	174	050	14%
Mean		004	184	040	11%
Median		005			
standard deviation		5.4			

Table 4.5: Orientation of dunes in the Agulhas cluster and difference from resolved January wind direction (blowing from 154 degrees).

Pan	Angle connecting horns	Lunette orientation	Wind that built lunettes	Difference in lunette-building and modern wind orientations	Percent difference (out of 360 degrees)
Langepan	004	094	274	120	33%
Voelvlei east	009	099	279	125	35%
Soutpan	007	097	277	123	34%
Voelvlei	001	091	271	117	33%
Soetendalsvlei	355	085	265	111	31%
Renosterpan	005	095	275	121	34%
Mean		094	274	119	33%
Median		095			
standard deviation		4.5			

A more thorough comparison of modern wind orientation and lunette orientation to determine the wind regime during dune formation would include the analysis shown in Table 4.4 and 4.5 for each month of the year. Despite producing numerical values, this approach would not necessarily sustain a more critical analysis of changing wind regime. The resolved wind directions above are already a rather gross representation of the actual wind regime. The statistical exercise could be performed, but a precise reconstruction of ancient wind regimes is neither in the scope of this research nor substantially more informative than the above analysis and the discrimination of the human eye with the unaltered wind roses. Finally, the orientation of lunette dunes, unlike other transverse dunes, is ultimately determined by the orientation of the pan from which it springs in concert with wind directions. Wind reconstructions do not encapsulate all motivations for lunette orientations.

4.4 DOUBLE LUNETTES

In Section 3.2, the occurrence of double lunettes with different textures was discussed as a proxy for two environmentally distinct periods of dune building. Three potential examples of this double-lunette morphology have been identified in the two study sites. Although the dunes have not been sampled thoroughly for textural comparison of the pairs, the general morphology, both from aerial photographs and field surveying, indicates two sets of dune ridges.

At Slangkop, the most southerly pan of the Swartland cluster, a small bare crest is clearly evident within the larger vegetated lunette (Figures 4.10 and 4.13). This ridge is not large enough to appear on the 5 m contour intervals of orthophotographs. Slangkop is unique among these pans in the way it is eroding into the cliff of the southern Darling hills which are underlain and outcropped with granite (Figure 4.11). Salt was harvested at Slangkop in the 1960s, so there is some doubt as to whether the inner ridge is a result of human manipulation in order to deepen the basin for the salt works (Figure 4.11). The volume of sediment moved, however, would represent major earthworks, and the general eroded morphology of the ridge is similar to that of lunettes in the eastern Cape (Holmes, personal communications). In the hope of elucidating the formational history of this feature, the site was surveyed and the inner "dune" sampled (Figure 4.9) and analysed by wet sieving for texture (Figure 4.12). The outer dune was surveyed (Figure 4.13) but not sampled on account of the impenetrable nature of the densely packed clay sediment.

A basic textural analysis discriminating only between course and fine, using 63 microns as the division, reveals a generally courser texture at the Slangkop inner "dune" than that of other lunettes. Although the limited number of samples taken from each pit necessarily limits interpretations of trends, there is a general relationship of equivalent to coarsening texture at depth, the opposite trend to the fining seen at depth in the other lunettes. However, this analysis and sampling strategy is not extensive enough to be significant.

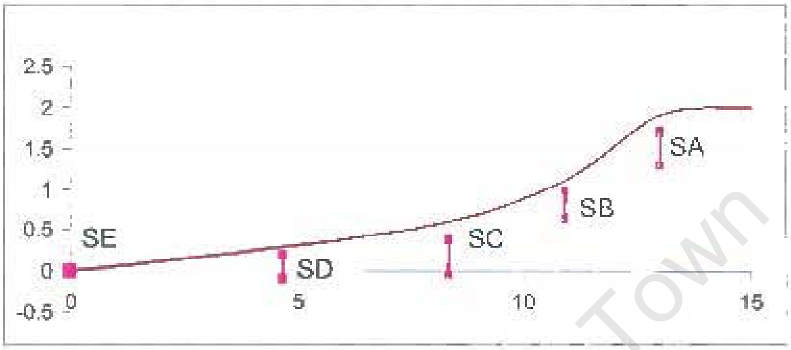


Figure 4.9: Sampling at the inner lunette at Slangkop. Units in meters. Two times vertical exaggeration. (0,0) represents the waterline. (26 April 2002).

Figure 4.10: Sampling at Slangkop. View towards the west. Note low water level and cliff at left side of photo (SMG, 26 April 2002).

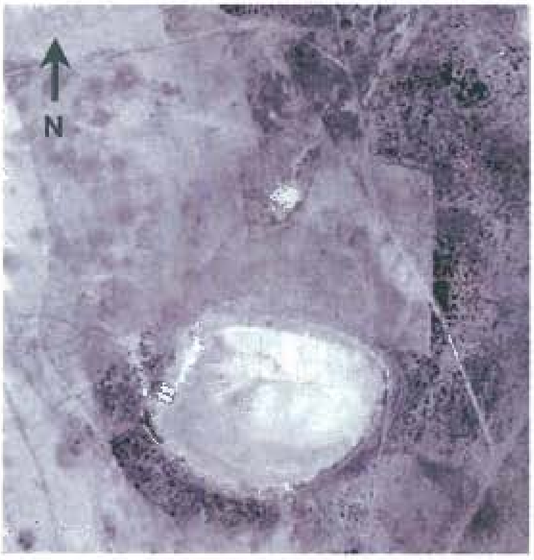


Figure 4.11: Aerial photograph of Slangkop. Note salt works. Approximately 1:14,400 scale. (Directorate of Surveys and Mapping, 1960).

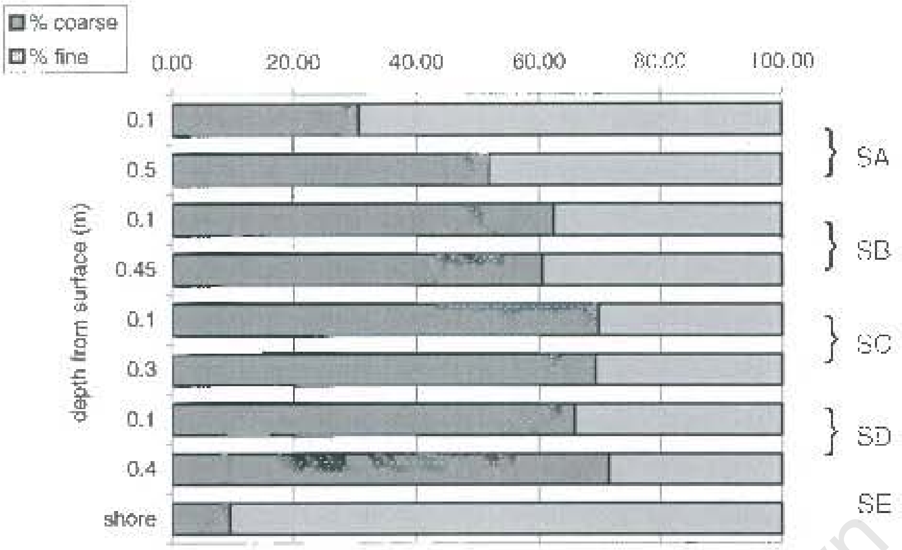


Figure 4.12: Texture of inner "lunette" sediments. The coarse/fine fraction divide is 63 microns (wet sieved), both the clay and silt of the more detailed analyses.

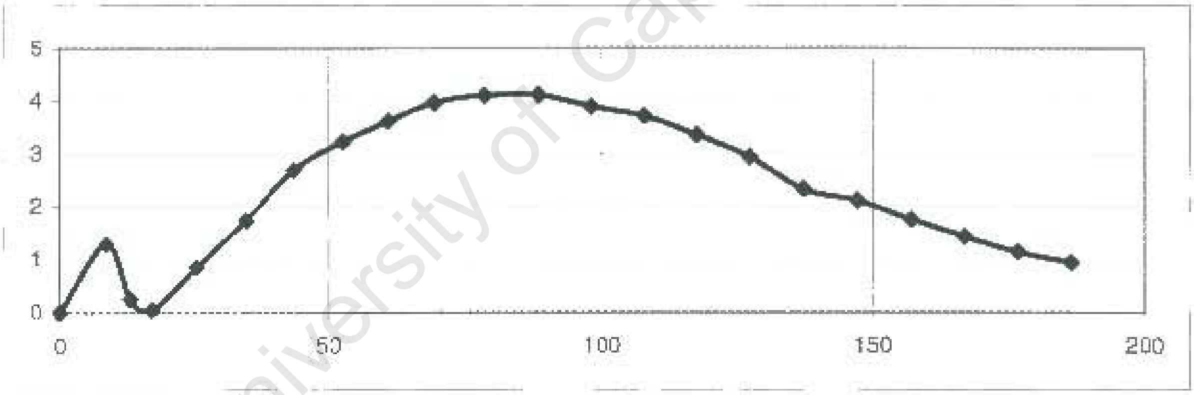


Figure 4.13: Profile of Slangkop. Note 10 times vertical exaggeration (01 September 2002).

Burgerspan, a loamy sand-based pan further to the north in the Swartland cluster, is actively mined for salt today (Figure 4.14). The pan is surrounded by a 5 m cliff that follows a small inflow stream to the pan from the northwest (Figure 4.15). There are two sets of ridges, 10 m above the pan floor with a 5 m drop between them. There is a road currently running between the two ridges, but there is no evidence to indicate the presence of the road is the cause of the valley between the ridges. No sediment sampling was performed at Burgerspan because of the scale of the feature, the considerable extent of modification by salt works and agriculture, and the limitations of time.

Figure 4.14: Burgerspan North looking north towards the first lunette to the north. Note crystallized salt along the shore (SMG, 26 April 2002).

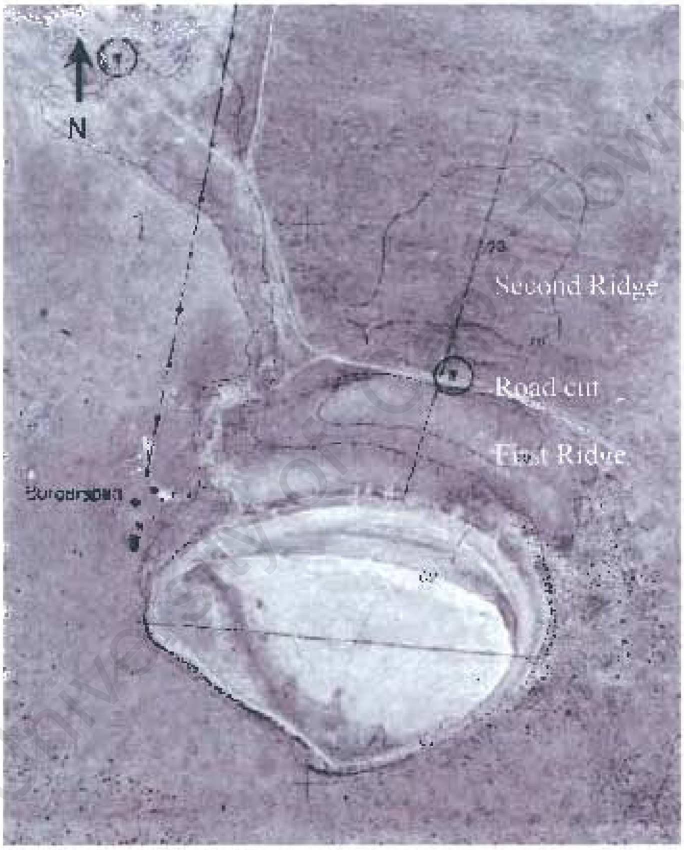


Figure 4.15: Orthophotograph of Burgerspan. Approximately 1:10,000 scale (Directorate of Surveys and Mapping, 1981).

Voelvlei is the only pan in the Agulhas cluster with clear evidence of a double lunette. Voelvlei is surrounded by a 5 m topographic cliff. In the field it can be seen that the western margins of this cliff consist of a more gentle, vegetated slope by comparison with the eastern shores where the cliff is a sheer vertical face. Walking from the top of this cliff further eastward, the land surface dips into a hollow before climbing the steep face of the primary dune. This hollow is more prominent closer to the horns of the lunette. In the orthophotographs it appears as two separate fingers along the 15 m contour line that delineates the main lunette (Figure 4.17). As can be seen in Figure 4.16 there is yet another rise behind the ridge of the primary dune. There is no evidence that Voelvlei was ever mined for salt, nor does it currently have a particularly salty nature, as the water levels are kept high by an inflow channel through a vlei at the northernmost part of the pan. Voelvlei is developed in shale. The sediments of the top two layers of the cliff are chemically and texturally similar to the sediments in the top two layers of the crest gully (see Chapter Five). The similarities in the texture of the top 0.50 m at the shoreline cliff and at the crest would indicate they are part of the same dune.

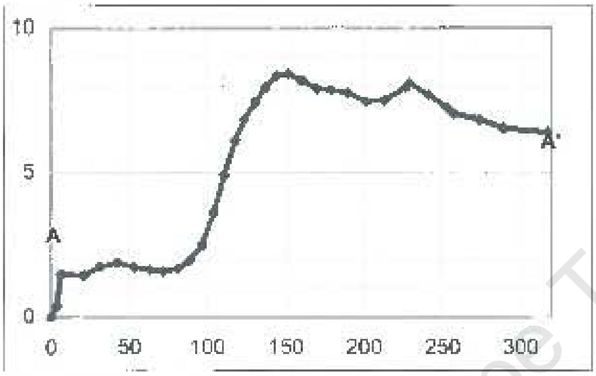


Figure 4.16: East to West transect A to A' of the Voelvlei lunette. Units are in meters. Note 20 times vertical exaggeration.

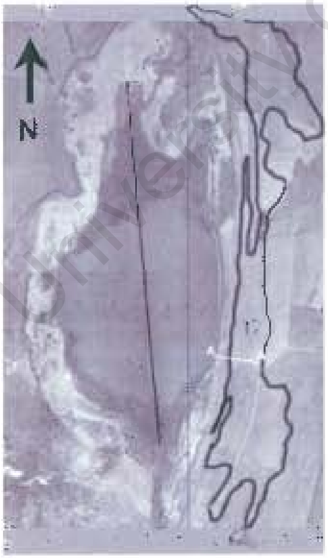


Figure 4.17: The 15 m contour of the lunette at Voelvlei (5 m contour interval). The transect was done above the north edge of the road gully. Approximately 1:46 000 scale.

At this point, without detailed sedimentology of these features, it is impossible to say whether the general morphology is the product of a set of lunettes. Although the topography does indicate two dunes at these three sites, the paucity of sites and information about those sites does not provide the evidence necessary to take these observations further. Although more comprehensive analyses were conducted on the sediment at Voelvei, the analyses focused on one profile at the crest of the dune, along the transect line, with only two samples taken from the shore-line cliff. Detailed sediment analyses and major excavations, beyond the scale of the current research, are necessary.

In the next chapter, Voelvlei and Droevlei East, where extensive sedimentology was performed, will be discussed in detail, the work there comprising the local-scale aspect of this research.

Chapter 5: Pan-lunettes at a Local Scale

5.1 INTRODUCTION

Because of the limited extent of this work, a number of major assumptions were necessary to proceed with a local-scaled investigation. Although multiple pan-lunette features at each site were observed and sampled briefly between September 2001 and October 2002, one feature at each site was sampled and analysed intensively. With this sample limitation in mind, one feature is taken as roughly representative of the cluster at each site. The features selected at Droevlei East in the Swartland cluster and Voelvlei in the Agulhas cluster were chosen for their clear pan-lunette morphology, accessible size and central location in the respective cluster. For purposes of interpretation, this decision assumes that all the pan-lunette features in each cluster evolved synchronously under similar conditions. Of course, based on the morphological differences and the age determinations discussed in the following chapter, conclusions may determine otherwise.

5.2 SAMPLING

5.2.1 DROEVLEI EAST

The lunette at Droevlei East in the Swartland cluster was sampled using a backhoe. Two pits were excavated (Figures 5.1 and 5.6). One pit (DV), 2.5 m in depth, was excavated through the vegetated front face of the dune. The second hole (DL) was penetrated through the ploughed, albeit unvegetated, crest of the dune to a depth of 1.5 m. There was evidence of recent calcrete and ferricrete addition for agricultural purposes in the field at the crest of the dune, and shallow furrows were present. Both sections lacked a clear stratigraphy through the homogenous clay layers (Figures 5.3 and 5.6). Only the basal sample in the crest pit (DL) exhibited distinctions, being both sandier and yellower than overlying sediment. Soil samples were taken every 0.15 m to 0.30 m. Agricultural practices have significantly disturbed stratigraphy to at least 0.5 m depth, and inferences from samples taken at less than 0.5 m depth are avoided, where possible.

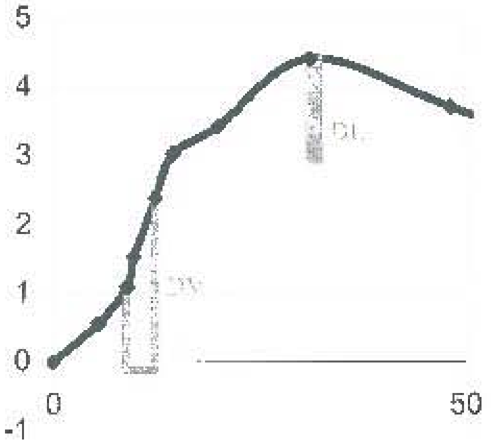


Figure 5.1: Profile of Droevlei East lunette including sample pits (in grey). Units are in meters. Note 10 times vertical exaggeration. The graphed zero is the pan floor. 70m elevation above mean sea level. Measured 4 June 2002.

Figure 5.2: Aerial photograph of Droevlei East with a general outline of the lunette and the transect graphed in Figure 5.1 (Directorate of Surveys and Mapping, 1960).

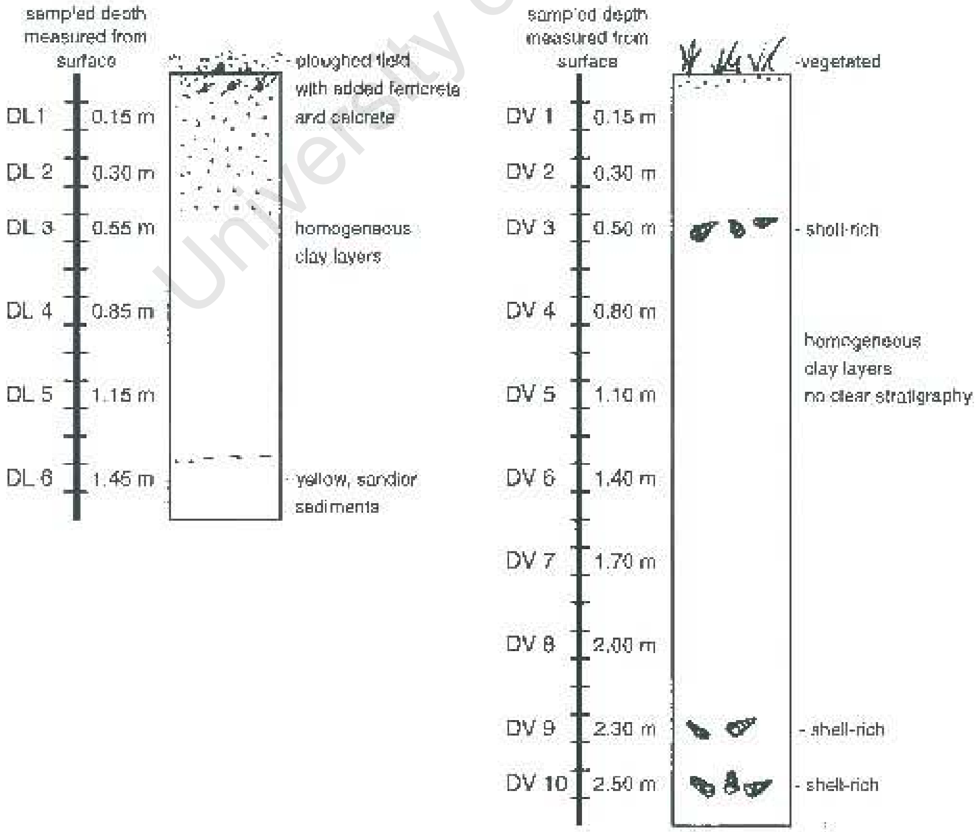


Figure 5.3: Measured, logged profiles at pits DL and DV in Droevlei East lunette.

The double-pit sampling strategy (Figure 5.1 and 5.2), necessary in order to gain depth in the dune while at the same time revealing the structure, causes some complications. The sampling strategy provides information both vertically and laterally across the dune. By sampling in this way, it should be possible to determine if sedimentation has occurred in a series of laminar parallel beds or with bedding that conforms uniformly to the topography of the dune form in successive stages of clay dune growth (Bowler, 1983). Using the relationship of the two pits, the surveyed profile of the dune and sample sites, the sediment data which follows is graphed continuously, starting first with the shoreline sample and then from the crest of the dune (DL1, depth=0 m) extending down to the bottom of the lower pit (DV10, real depth in the hole=2.5 m). This approach is purely a practical way to simplify graphical representation of characteristics within each dune (one dune, one graph); it is not intended to indicate that the layers are cumulative. In all cases the samples are labelled by depth and pit in order to maintain distinctions between the pits.

Figure 5.4: Back-hoe excavating lunette face. Furrowed fields in foreground. View facing eastwards (SMG, 4 June 2002).

Figure 5.5: Back-hoe excavating lunette crest. Photo facing south, across the pan to the Basson farmhouse (SMG, 4 June 2002).

Figure 5.6: Sampled pit (DV) in front face of dune. Heap of soil from upper pit (DL) on horizon. View looking north from the pan shoreline (SMG, 4 June 2002).

5.2.2 VOELVEI

The lunette at Voelvlei was sampled from the face of a road cutting that runs transversely across the dune (Figures 5.7 – 5.10). The cutting was cleaned with a shovel and extended to a depth of 1.9 m below the height of the crest (VL1-VL7). Further excavation by hand was impossible due to the hardness of the clay. Additionally, a number of samples were taken from a cliff at the edge of the pan (VS1, VS2); samples were taken roughly every 0.30 m. A more distinct stratigraphy is evident at Voelvlei. A red-brown layer extends from 0.50 m to 0.90 m with well-defined contacts between overlying and underlying layers. The clays here form columnar and angular peds throughout. A number of shell-rich layers exist, most obviously at 1.45 m and 1.88 m.

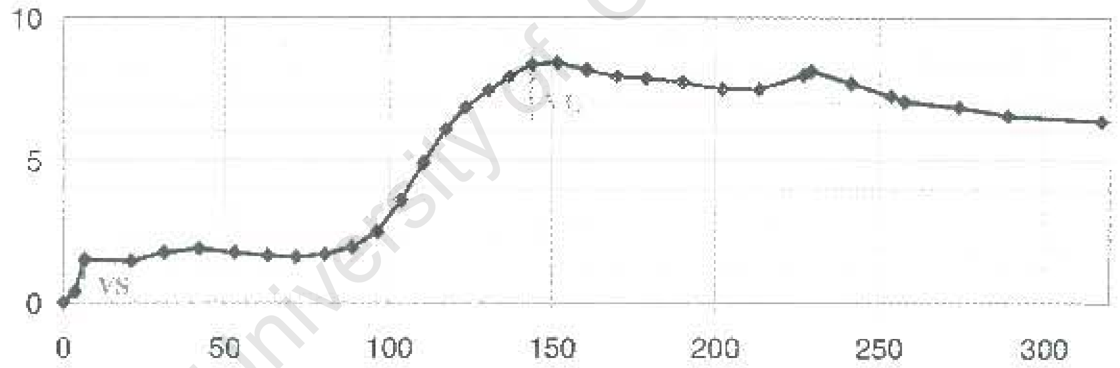


Figure 5.7: Profile of Voelvlei lunette including sampling (in grey). Units in meter. Note 10 times vertical exaggeration. The graphed zero is the pan floor, 20 m above mean sea level. Measured 12 October 2002.

Figure 5.8: Orthophotograph of Voelvlei with a general outline of the lunette and the transect graphed in Figure 5.7

Figure 5.9: Photograph of the south side of the gully sampled at Voelvlei (profile VL). (SMG, 5 October 2001).

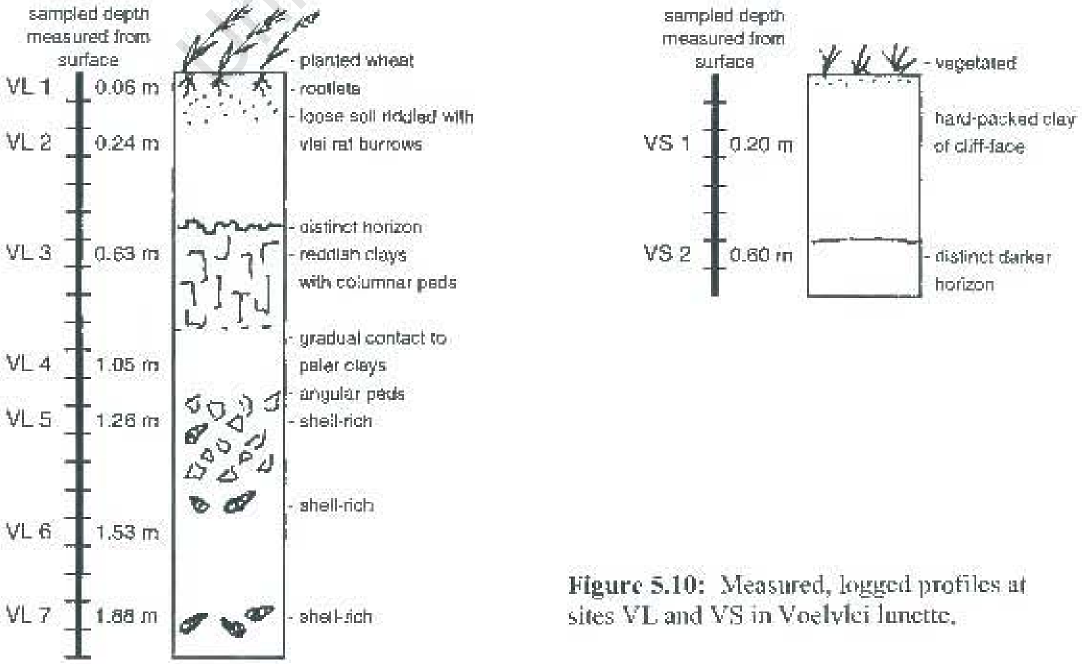


Figure 5.10: Measured, logged profiles at sites VL and VS in Voelvlei lunette.

5.3 SEDIMENTOLOGY

The sediments comprising the lunettes are typical neither of sand dunes nor of soil profiles, though traits of both are relevant to interpretations. The sediments in the lunettes are the product of at least three phases of weathering transportation: the erosion of sediment from parent rock, the aeolian transport across the pan floor, and the deposition and subsequent *in situ* alteration in the dune. A study of the sediment attempts to verify and unravel the details of this process.

There are many factors at play in determining the current characteristics of the lunette sediments. A sediment is defined as transported material, while a soil forms in place, although a gradation between the two is possible (Retallack *et al.*, 1984). The lunette sediments represent transported material that has since undergone a degree of soil formation; the term sediment with be used primarily in this discussion. Soil is a three-dimensional "material at the surface of a planet or similar body, altered in place by physical, chemical or biological agencies, or by a combination of them" (Retallack *et al.*, 1984, p.7). Jenny (1941) defined the factors of soil formation as climate, organisms/vegetation, parent material, topography, and time. By scrutinizing a number of different qualities of the lunette sediment, both physical and chemical, the influential factors of sediment and soil formation may be isolated.

Processes of soil formation are dependent upon proximity to the atmosphere. The known processes for soils that develop in unconsolidated sediments (Birkeland, 1984), processes that the procedures enumerated in brackets attempt to uncover, include:

- chemical weathering (such as decalcification)
  [pH, carbonates, XRD]
- downward leaching of soluble minerals, including weathering products
  [pH, conductivity, carbonates, XRD]
- precipitation of soluble salts in near-surface horizons because of evaporation
  [conductivity, pH]
- incorporation of decomposing organic matter
  [organics]
- disturbance of soils (by biological or physical processes)
  [field descriptions]
- downward movement (eluviation) of clay and redeposition (illuviation)
  [particle-size, XRD]
- reduction of brown, yellow or ferric iron minerals to more soluble grey ferrous compounds in waterlogged conditions
  [colour]

5.3.1 PHYSICAL CHARACTERISTICS

The physical properties of colour, particle size, and the collective characterization of texture are presented here. Soil structure was mentioned in the site description above. The methods used to characterize the samples are presented in detail in Appendix A. The rationale and results of analyses are presented here; a more detailed discussion of the implications of the results follows in Chapter 7.

5.3.1a Colour

Colour is the most obvious visual characteristic of a sediment, and is a potentially useful parameter as it can also provide an initial index of other properties such as mineralogy, parent material, formational conditions, particle-size and weathering history. The colour of soils was quantified using the Munsell Soil Colour Charts (Munsell Colour, 1994).

The sediments, when observed in profile, are generally light grey to brown excepting a red horizon (Figures 5.9 and 5.10) in the Voelvlei lunette. These pale greys and browns are the expected hues of deposits derived from light-coloured bedrock sources high in silicic minerals such as the feldspar-phenocrystic Darling granite. Upon further consideration, using the Munsell system, it was observed that samples in the uppermost half meter of both the Voelvlei pit and the pan-side Droevlei East pit have hues closer to red than the other samples (Table 5.1, 5.2). Red hues are frequently the result of the oxidation of iron minerals, and are one common characteristic of palaeosols (Retallack, 1990). As there are many factors affecting soil formation, these observations and possible explanations require additional quantitative proof, and are discussed further once other evidence has been presented.

Table 5.1: Voelvlei Munsell colours of samples VL1 to VS2.

sample	depth from surface (m)	Munsell colour (dry)	Description
VL1	0.06	10YR 5/3	brown
VL2	0.24	10YR 7/3	very pale brown
VL3	0.63	10YR 4/4	dark yellowish brown
VL4	1.05	2.5Y 6/3	light yellowish brown
VL5	1.26	2.5Y 7/2	light grey
VL6	1.53	2.5Y 6/2	light brownish grey
VL7	1.88	2.5Y 6/2	light brownish grey
VS1	0.2	2.5Y 6/2	light brownish grey
VS2	0.6	2.5Y 5/2	greyish brown

Table 5.2: Droevlei East Munsell colours of samples DV shoreline to DV10.

sample	depth from surface (m)	Munsell colour (dry)	Description
DV shoreline	0	Mottled	--
DL1	0.15	2.5Y 5/2	greyish brown
DL2	0.30	2.5Y 5/3	light olive brown
DL3	0.55	2.5Y 6/2	light brownish grey
DL4	0.85	2.5Y 7/3	pale yellow
DL5	1.15	2.5Y 6/3	light yellowish brown
DL6	1.45	10YR 7/2	light grey
DV1	0.15	10YR 5/2	greyish brown
DV2	0.30	10YR 6/2	light brownish grey
DV3	0.50	2.5Y 6/2	light brownish grey
DV4	0.80	2.5Y 6/2	light brownish grey
DV5	1.10	2.5Y 6/2	light brownish grey
DV6	1.40	2.5Y 6/2	light brownish grey
DV7	1.70	2.5Y 6/2	light brownish grey
DV8	2.00	2.5Y 6/2	light brownish grey
DV9	2.30	2.5Y 6/3	light yellowish brown
DV10	2.50	2.5Y 6/2	light brownish grey

5.3.1b Texture

The texture of sediments in each of the sampled pan-lunette features was analysed in order to investigate the history of the feature, namely the source, the means of sediment transport, and the age of the material. Grain sizes were determined utilizing laboratory techniques reliant on Stokes' law of settling (see Appendix A). The sorted rate of settling, and hence grain-size portions, was first measured using a soil hydrometer, which quantifies the buoyancy over time of a deflocculated sample. The dried coarse fraction was then timed through a settling column in order to determine the silt to clay ratio. Each trial was repeated multiple times. This classic approach to grain size analysis was considered sufficiently accurate for the general classification and comparative nature of the work. Modern laser and sieving techniques were either unnecessary. Texture was characterized using the Udden-Wentworth grade scale for grain sizes (Wentworth, 1922). Each of these methods are means of determining approximate texture and cannot be taken as an accurate breakdown to the percentage point.

As stated above, the sediments were treated with a deflocculant before the grain size analysis was carried out. This action reduced the clay and sand pellets to individual constituent grains.

Because of the cohesive nature of clays, the sediments in the pan have a tendency to form pellets which are transported and subsequently reorganized, likely in a process of deflocculation. The textural characterization of these dunes does not necessarily indicate the textural activity during pan-lunette formation. Current clay fraction sizes *in situ* in the field would need to be measured by the creation of thin-sections for microscopy. Instead the hydrometer method used here on deflocculated samples provides a basic characterization of the grain-sizes present in the dunes without elucidating the pelletal-sizes that may have been deflated and redeposited.

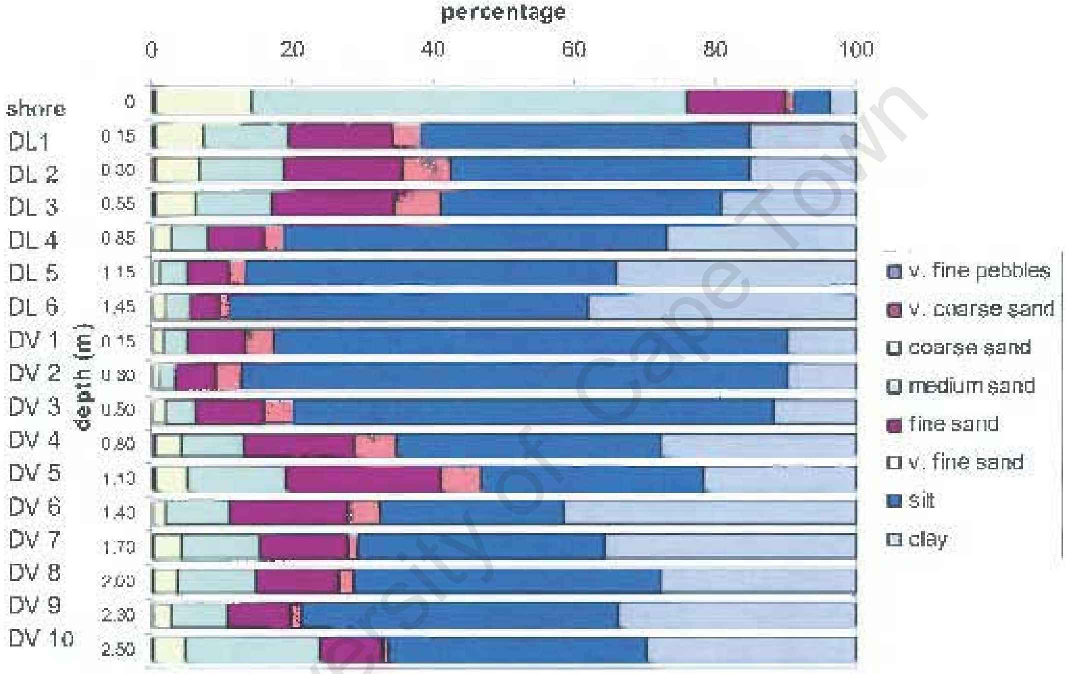


Figure 5.11: Grain size of sediments from Droevlei East lunette.

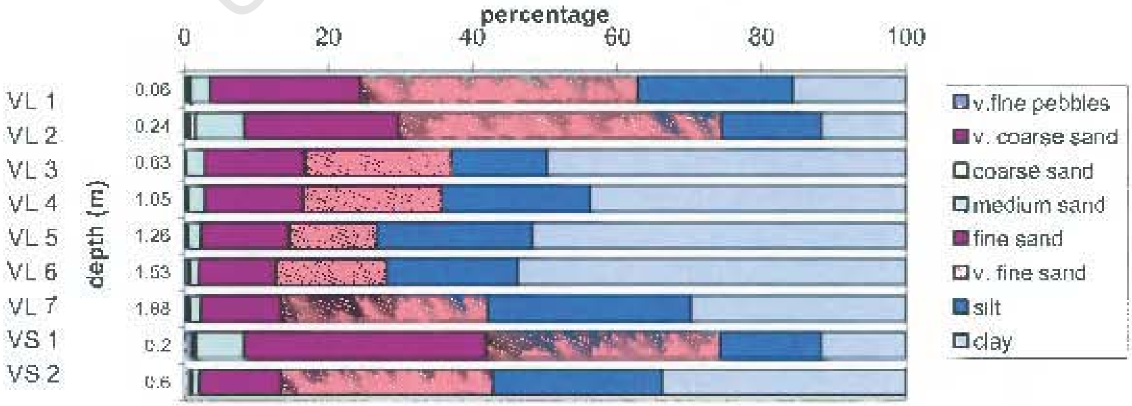


Figure 5.12: Grain-size of sediments from Voelvlei lunette.

The dune at Droevlei East (Figure 5.11) shows a trend of textures fining with depth from the surface. In the upper pit the sampled sediment is a series of increasingly clay-rich strata with depth. From 0.15 m in the lower pit, the texture again is increasingly fine with depth. There is a slight reversal in the trend, with the appearance of coarser textures, at 1 m to 1.5 m.

The texture of the Voelvlei dune exhibits similar trends with increasing clay proportions at depth down to around 1.5 m where clay levels are near 50%, below which there is a slight reversal to coarser textures (Figure 5.12). The samples from the cliff face (VS) have similar textural proportions to the samples at equal depth in the crest (VL), indicating parallel bedding structures.

The trend of fining textures with depth in all pits could indicate a number of different situations. More rapid dune propagation with time (less time spent subjected to surficial weathering processes) or increasingly wet conditions (and sand portions) would yield similar trends. Older soil particles tend to be more weathered and hence finer-grained at the surface on account of leaching processes (Jackson and Sherman, 1953). Reduced *in situ* weathering through time would result in fewer fine surface particles. The lunette environment may not display the characteristic of old weathered surface sediments, however, because leaching, requiring humidity, is not the main weathering function of the environment and dunes may grow quickly, the variation of humidity through time causing various weathering signatures.

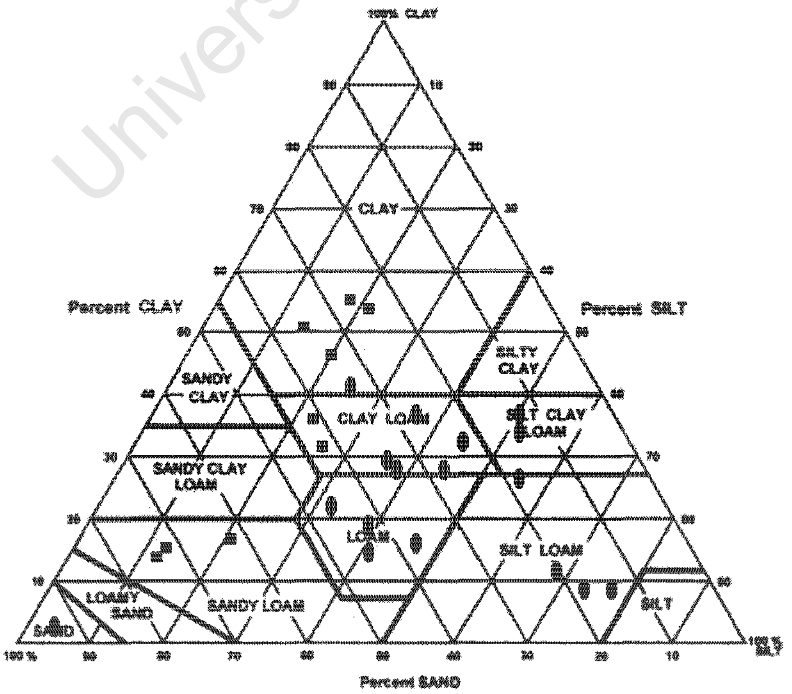


Figure 5.13: Texture pyramid of sediments in Voelvlei Lunette (squares) and Droevlei East Lunette (ovals).

As can be seen in Figure 5.13 the samples from the Droevlei East Lunette are characterized as silt loam to clay loam. The samples from the Voelvlei lunette are texturally more varied ranging from a sandy loam to a clay loam to clay. Following Bowler's (1973) definition of a clay lunette having at least 20% clay composition, not a texturally-defined clay (more than 50% clay), both of these dunes could fit into the category of clay dunes, depending on the depth sampled. Overall, the Droevlei East lunette is finer grained than the Voelvlei lunette. This trend may be a result of age, weathering or source material and is further discussed in Chapter Seven. These textures, however, are based on measurements of dispersed samples, but texture as relating to wind erosion is that of an aggregate. The statistical sorting values can be used to clarify the source of this fining trend.

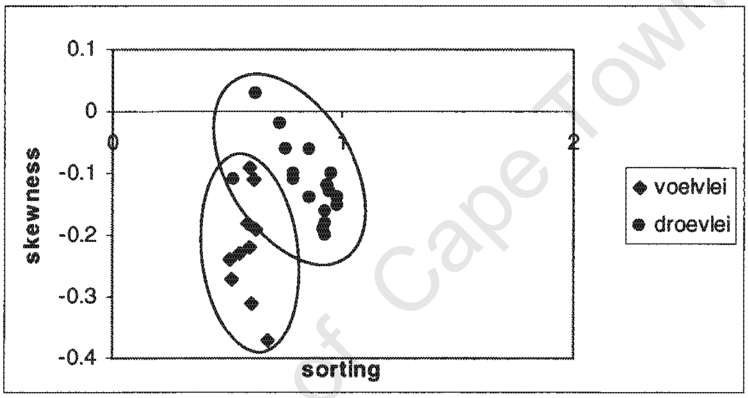


Figure 5.14: Skewness vs. Sorting (Standard Deviation): statistics for settling of lunette coarse fraction. Both axes are expressed in phi units. Increasing values on the y-axis represent finer grain sediment. Increasing values on the x-axis indicate less sorted samples.

The statistics reflect the Gaussian distribution (log-normal scale) of the coarse fraction (>63 microns). The graphed comparison of skewness and standard deviation (sorting) of these sediments can be used as a diagnostic feature of the environment represented (Lewis and McConchie, 1994; Meadows and Asmal, 1996). The cluster of the statistics for the lunettes is graphed in the sector expected for beach environments. As these statistics represent only the coarse fraction (half the story) this is not a surprising relationship; the sands in a humid pan are subjected to beach-like wave energies and sorting. The pan environment at Voelvlei is more beach-like than Droevlei East with extended pan-full hydrologic conditions and considerable wave activity forming sandy beaches and cliffs. Figure 5.14 indicates that this difference may extend into the palaeoenvironmental record.

This kind of statistical interpretation is problematic. Primarily, comparing the particle size distribution of a sample to the log-normal Udden-Wentworth scale (1922) assumes that the distribution is, in fact, regularly logarithmic. Sediments frequently display two or more particle-size distribution modes. It is also possible that the sample is a product of several formational episodes, and not a single event, so that interpreting the statistics as one environment ignores the potential composite origin (wave-transport and wind transport for example).

Generally, it can be seen from Figure 5.14 that the coarse-fraction of the Droevlei sediments is both finer and less well sorted than the Voelvlei sediments.

5.3.2 CHEMICAL CHARACTERISTICS

The pH, electrical conductivity, organic matter percent by mass, and the calcium carbonate equivalent by mass were measured on each sample. The results are graphed in Figures 5.15 through 5.22. As before, the methods used are presented in detail in Appendix A. Rationale and results of analyses are presented here; a more involved discussion of the implications of the results follows in Chapter 7.

5.3.2a pH

The pH of a soil is the negative logarithm of the hydrogen ion activity. It is one of the most frequently measured characteristics of soil and a critical determinant of plant growth (McBride, 1994). The pH of a soil is the primary determinant of ion exchange, dissolution and precipitation, reduction and oxidation, adsorption and complexation reactions. The pH of a soil, young soils in particular, is determined primarily by parent material (Birkeland, 1984). The pH was measured here using a probe and a saturated soil extract.

Calcareous soils tend to have a high pH because of the release of OH^- in a process known as *carbonate hydrolysis*:

$$CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^- \qquad \textbf{[Eqn 5.1]}$$

Although calcium carbonate is only slightly soluble, in equilibrium situations with atmospheric carbon dioxide, the reaction in Eqn 5.1 can produce a soil pH as high as 8.3 (Foth, 1990). The free OH^- ion tends to react with any H^+ formed and maintains an alkaline environment. Soils containing the more highly soluble Na_2CO_3 can have a pH as high as 10 by the same reaction, with sodium carbonate replacing calcium carbonate (Foth, 1990).

In a calcareous soil, carbonate hydrolysis dominates the system maintaining a pH of between 7.5 and 8.3. Weathering of other rocks and minerals, including aluminosilicate clay minerals, tends to have an alkaline effect. Mineralogy and pH of soils, when undisturbed by human activity, should remain relatively unchanged over time.

The development of more acidic conditions requires the leached removal of carbonates. In more acidic environments, mineral weathering increases, releasing more major cations, and in turn, creating more acidic environments. Acidity in soils can also be traced to root respired carbon dioxide reacting with water to form carbonic acid, the mineralization of organic matter, and the natural reaction of precipitated water with carbon dioxide. These kinds of leaching and reacting environments require humidity; in arid environments these reactions have a minimal effect.

Although calcium carbonate makes up less than 30% by mass of the soils at Droevlei East (Figure 5.17), the fluctuations in soil pH, ranging from mildly to very strong alkaline (Figure 5.18) vary parallel to the variations in calcium carbonate. The shoreline of the pan, where calcium carbonate (barring gastropod shells) is nearly non-existent, is the primary divergent sample from this relationship with a pH (KCl) of 8.25. The same relationship does not exist at Voelvlei where the soil pH is much lower ranging from very strongly acidic in the cliffs adjacent to the shoreline, to mildly alkaline at the base of the pit.

By measuring pH in KCl as well as water, an attempt is made to mask variation in salt concentration resulting from fertilizer residues, irrigation water and microbial decomposition of organic material (McBride, 1994). The expected difference is 1 to 2 pH units. Clay, which is negatively charged, can cause junction potentials with the K within the pH electrode (the pH electrode is filled with KCl), reading a decrease in pH (McBride, 1994). By determining pH in both water and KCl, it is possible to determine the net charge of colloids in solution. Low colloid charges are found in low-clay environments and high salt materials (which causes flocculation, keeping colloids out of solution). A positive net charge indicates iron oxides; a negative net charge indicates silicate clay minerals. As expected, all of the samples measured a negative net colloid charge except VL3 and VL4, the red layers in the Voelvlei dune, likely so coloured on account of iron oxides.

5.3.2b Organic Matter

Soils are composed of inorganic mineral soil, composing the majority of the actual soil, and organic matter, which plays a disproportionately important role in soil physical and chemical reactions (van Loon and Duffy, 2000). Organic matter is primarily the remnants of plant tissue and litter, found in varying stages of decay through the soil profile. The biomass of soil micro-organisms and small soil dwelling animals provides an additional, small (0.05 to 0.5% by mass of the top 0.15 m) component of the organic fraction (van Loon and Duffy, 2000).

In an area with little biomass, currently or historically, such as the Agulhas and Darling sites, low soil organic matter would be expected. The organic component was measured by mass difference after combustion.

5.3.2c Carbonates

Calcite ($CaCO_3$) and dolomite [$CaMg(CO_3)_2$] are the principle carbonate minerals found in soil (Sposito, 1989). Often, pedogenic calcite is formed as a weathering product. Carbonate-rich horizons in arid to semi-arid regions are the result of a shifting carbonate-bicarbonate equilibrium which is forced by factors such as pH, presence of water, temperature and CO_2 pressure (Birkeland, 1984). Biogenic calcite is also found in the lunettes in the form of pan-origin gastropods (discussed in detail in Chapter Six).

The carbonate measured here is actually a 'calcium carbonate-equivalent' based on the assumption that only the calcium carbonate in the sediment will react with acid (Gale and Hoare, 1991).

5.3.2d Electrical Conductivity

The electrical conductivity (EC) of a soil is a measure of the charged species, a measure of the total ionic concentration of a soil solution (van Loon and Duffy, 2000). Electrical conductivity was measured using a probe in a saturated soil extract. The measurement is inversely proportional to the resistance measured across a set distance between electrodes.

Typically the electrical conductivity is interpreted as reflecting the concentration of ionisable salts. Colloids, whose characteristic property is that they do not dissolve in water to form solutions, will not affect electrical conductivity (Sposito, 1989). Electrical conductivity values closely mirror clay content in these environments, because salt concentrations are the drivers of clay flocculation that permits aeolian deflation of the flocculated pellets.

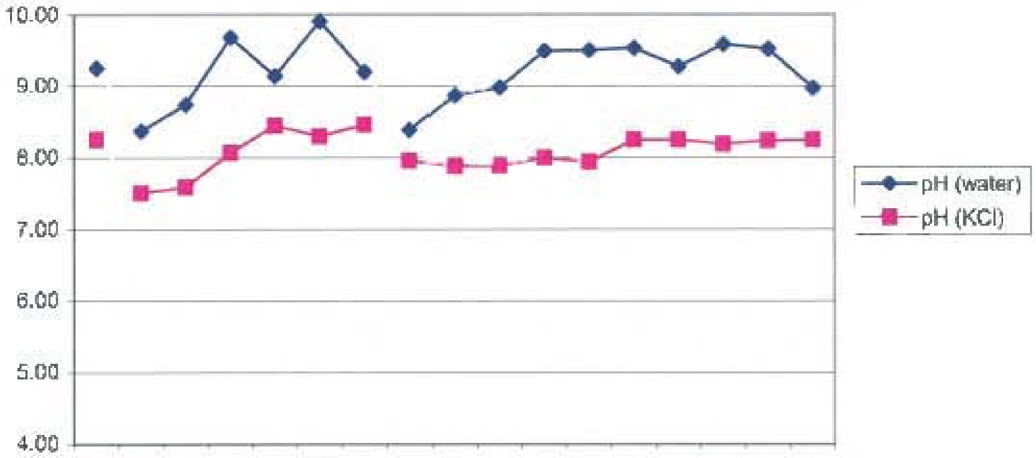


Figure 5.18: pH of Droevlei East lunette.

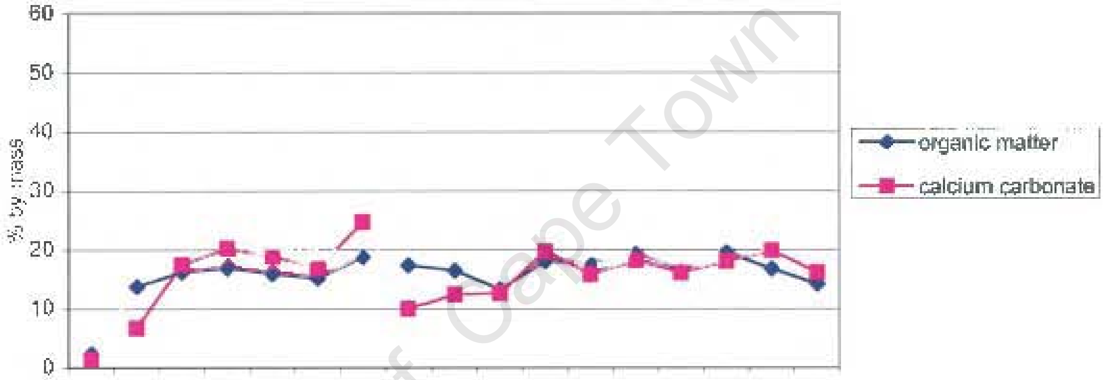


Figure 5.17: Organic matter and Calcium carbonate of Droevlei East lunette.

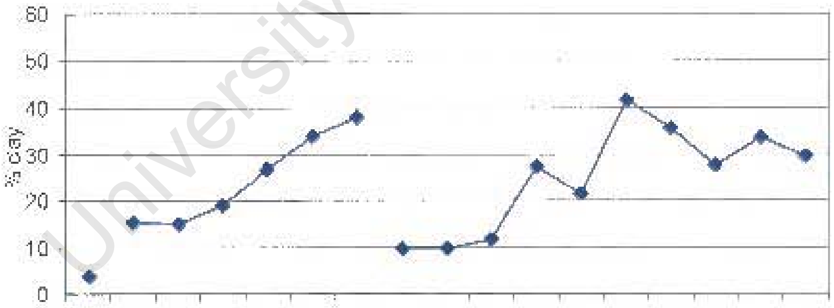


Figure 5.16: % Clay in Droevlei East lunette.

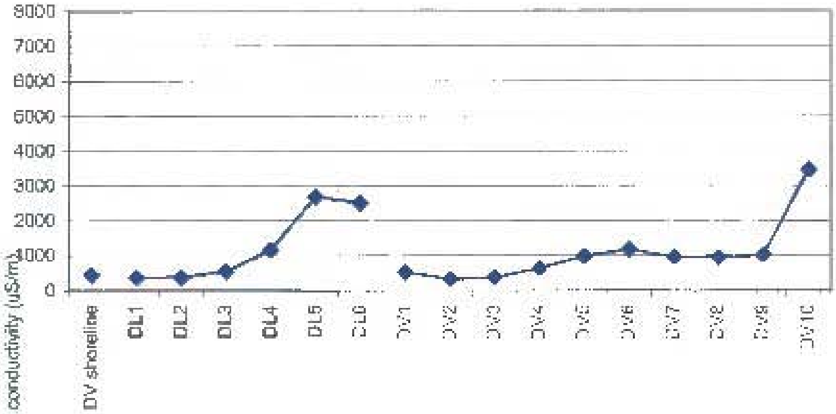


Figure 5.15: Conductivity in Droevlei East lunette.

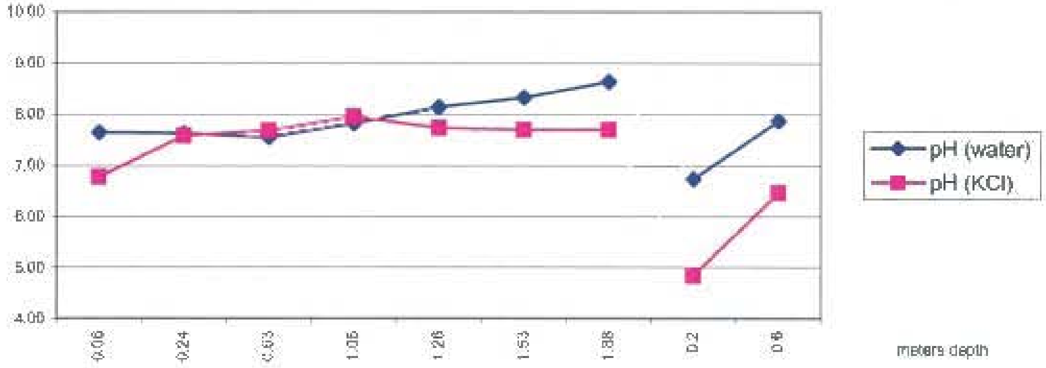


Figure 5.22: pH of Voelvlei lunette.

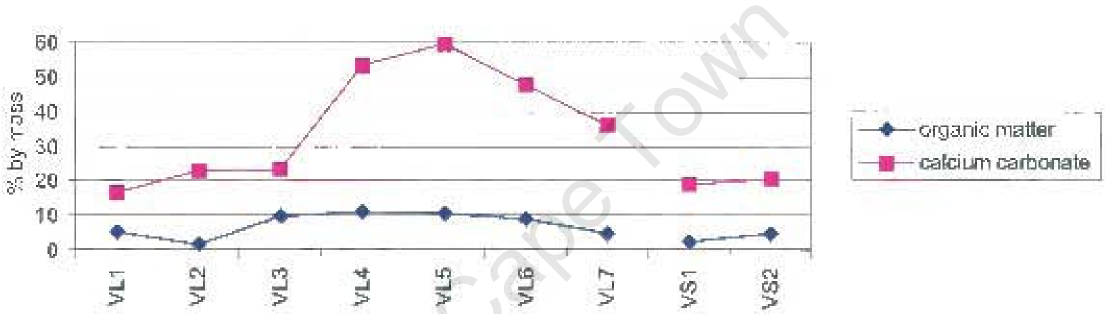


Figure 5.21: Organic matter and Calcium carbonate of Voelvlei lunette.

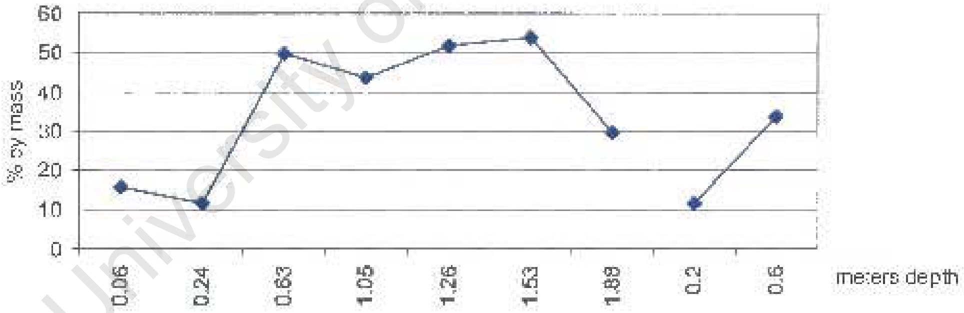


Figure 5.20: % Clay in Voelvlei lunette.

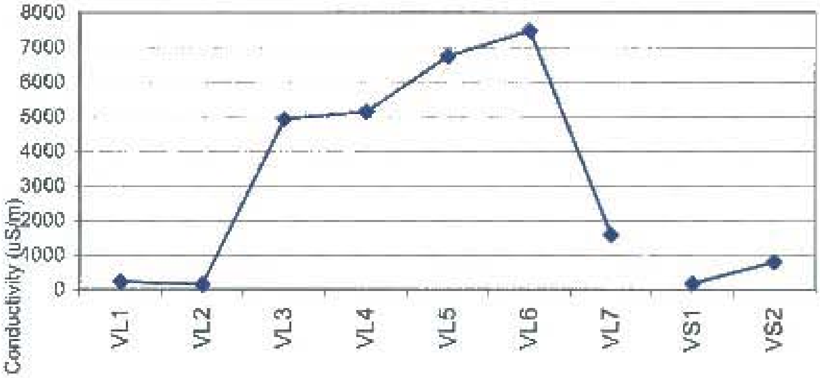


Figure 5.19: Conductivity in Voelvlei lunette.

5.3.2e Clay Mineralogy

The minerals in a soil are the primary control on both the physical and chemical properties of that soil. The minerals of the clay fraction (<40 microns) play an especially important role because of their large *specific surface*, defined as the surface area per unit mass of soil (Klute, 1986). The extent of weathering of primary minerals to form secondary clay minerals depends on soil climate, age and the geological nature of the parent material (Evans, 1992).

The mineralogy of a soil can help elucidate the source of the soil and the degree of weathering. A number of potential weathering pathways exist, as shown in Figure 5.21. Fine-grained mineral particles weather differently to coarser-grained particles because the specific surface is large enough to accelerate the weathering process (Jackson and Sherman, 1953). The successive stages of weathering (*weathering sequence*) of clay-size mineral particles are shown in Table 5.3.

Table 5.3: Weathering sequence of clay-size mineral particles (Jackson and Sherman, 1953)

Stage	Mineral	
1	Gypsum	Least stable stage
2	Calcite	(first to weather)
3	Olivine-hornblende	
4	Biotite	
5	Albite	
6	Quartz	↕
7	Muscovite	
8	Interstratified 2:1 layer silicates and vermiculite	
9	Montmorillonite	
10	Kaolinite	
11	Gibbsite	
12	Hematite	(last to weather)
13	Anatase	Most stable stage

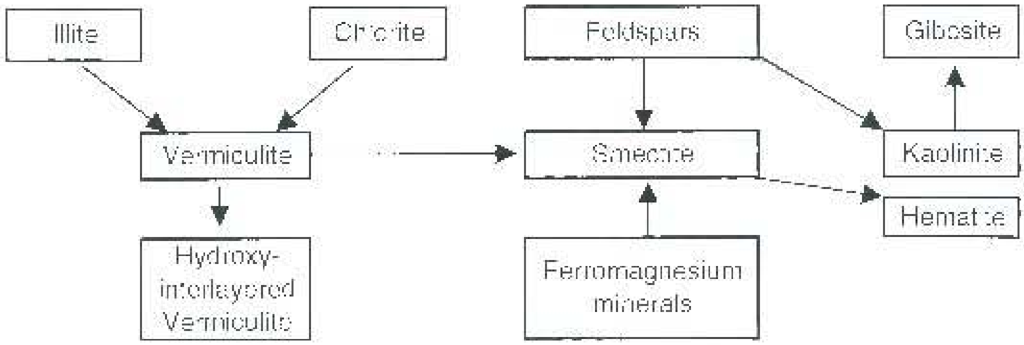


Figure 5.23 Some possible weathering pathways of minerals (adapted from Evans, 1992).

X-ray diffraction can be used to determine the mineralogical composition of a soil. The mineralogy of the clay fraction of ten samples was measured by X-ray diffraction at the Institute for Soil, Climate and Water (ISCW) in Pretoria, South Africa. The samples were chosen to be roughly representative of the profile, avoiding the top half-meter where agriculture has disturbed the soil.

Figure 5.24: Clay mineralogy of selected samples from Voelvlei lunette (VL).

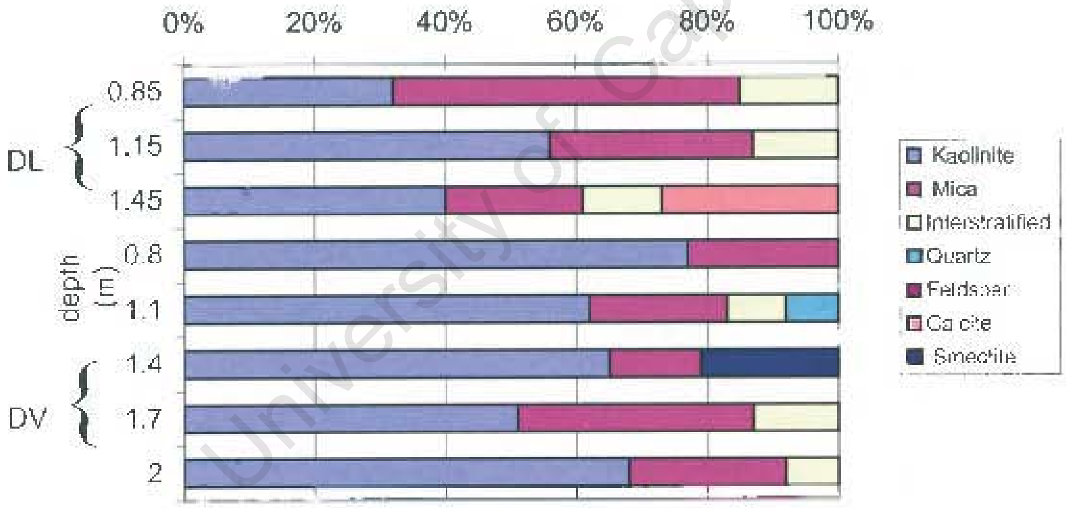


Figure 5.25: Clay mineralogy of selected samples from Droevlei East lunette.

When clays build up in soils as a product of time, the profile is termed a chronosequence (Birkeland, 1992). In order to interpret chronosequences, soil forming factors must have remained constant through time so that each subsequent soil experienced similar pedogenic pathways. Soils older than early Holocene are most likely polygenetic (variation in soil forming factors through time) products, hence complicated for pedological interpretations (Birkeland, 1992). When a chronosequence does exist, the expected clay mineralogy would be more weathered at depth. The most common vertical variation is when the amount of silica and bases in the weathering product increases with depth, usually forming kaolinite (Birkeland, 1984). Figure 5.26 shows the frequency of mineral occurrence in terms of the weathering stages from Table 5.3. It shows that mica, an intermediate weathering product, and kaolinite, a heavily weathered mineral, are the most common in these samples. There is no clear trend in Figures 5.24 or 5.25 of increasingly weathered minerals at depth.

The appearance of feldspar (11%) at 1.45 m depth in the Voelvlei lunette and smectite (21%) at 1.45 m depth in Droevlei East lunette are anomalous. The presence of feldspar may indicate that the soil has not been leached extensively, or that it has been leached out of overlying sediments (Sposito, 1989). The calcite (27%) at 1.45 m depth in the top pit at Droevlei East is not from gastropod shells. Calcite low in the profile conventionally suggests decalcification from overlying samples, a product of weathering.

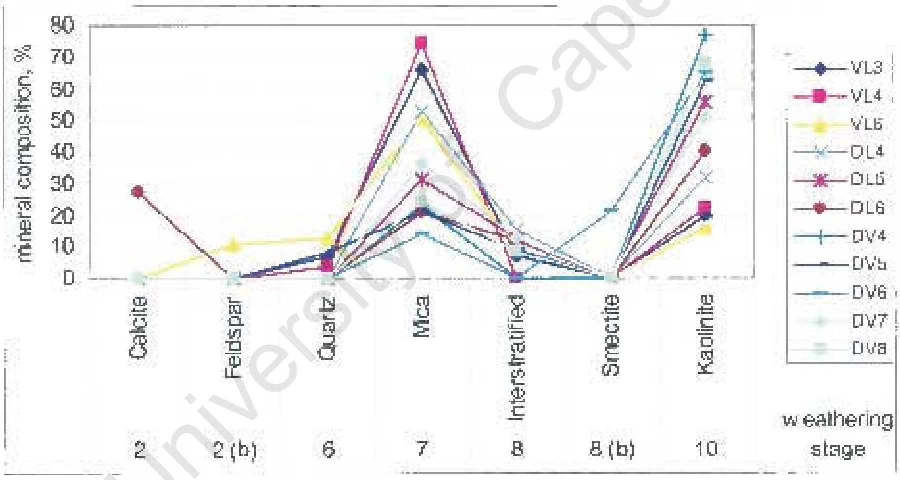


Figure 5.26: Mineral composition in order of weathering sequence for all samples analysed for XRD.

When a clear chronosequence does not exist, as in this case where there is not a more weathered clay mineralogy at depth, the clay mineralogy must be explained based on other soil forming factors besides time. The clay in these dunes was transported from the pan floor as clay: the weathering to clay minerals occurred out of the parent material into the pan, so weathering sequence and clay mineralogy would be primarily determined at that stage of formation, by parent material, assuming the dunes are relatively young. In a similarly complicated scenario, Bühman (1994) warned that interpretating the weathering sequence within sediments derived from Karoo shale parent material was no simple process as they themselves are the product of previous cycles of weathering and diagenesis.

Shales, such as the Bokkeveld shale that underlies Voelvlei, tend to weather to micas first and then smectites (Birkeland, 1984). Feldspathic granite, such as the Darling Granite, weathers to feldspar or muscovite and then kaolinite (Evans, 1992). These general weathering pathways from parent material to clay, support a parent material determinate for the clay mineralogy in the lunettes.

Other determinates of clay mineralogy that may take place in the dune, altering the primary clay material originally moved from the pan floor, include the acidity of the soil and the weathering between clay minerals.

A general inverse relationship between pH and kaolinite has been documented in previous studies. Both low pH and high kaolinite proportions have been used separately as indicators of weathering; a strong negative correlation between the two has been used as a more definitive indication of weathering (Jackson and Sherman, 1953). The nature of the weathered kaolinite is also dependent on the soil pH (Evans, 1992). The primary source of confusion arises from discrepancies in the measured pH values (such as the inverse relationship between pH(KCl) and pH(H_2O) (Figure 5.27, 5.28)), as well as limitations in the sample size at Voelvlei for statistical methods. In this comparison, the pH(H_2O) is generally used. In the case of these samples, Droevlei indicates a good positive correlation, hence little weathering, and the sample size at Voelvlei is too small to definitively cite the negative correlation between pH and kaolinite as a sign of weathering.

Chapter 5 continues

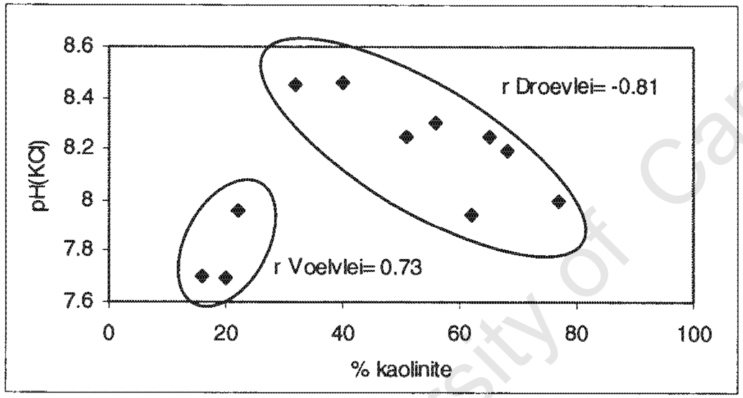


Figure 5.27: Correlation between % kaolinite and pH(KCl)

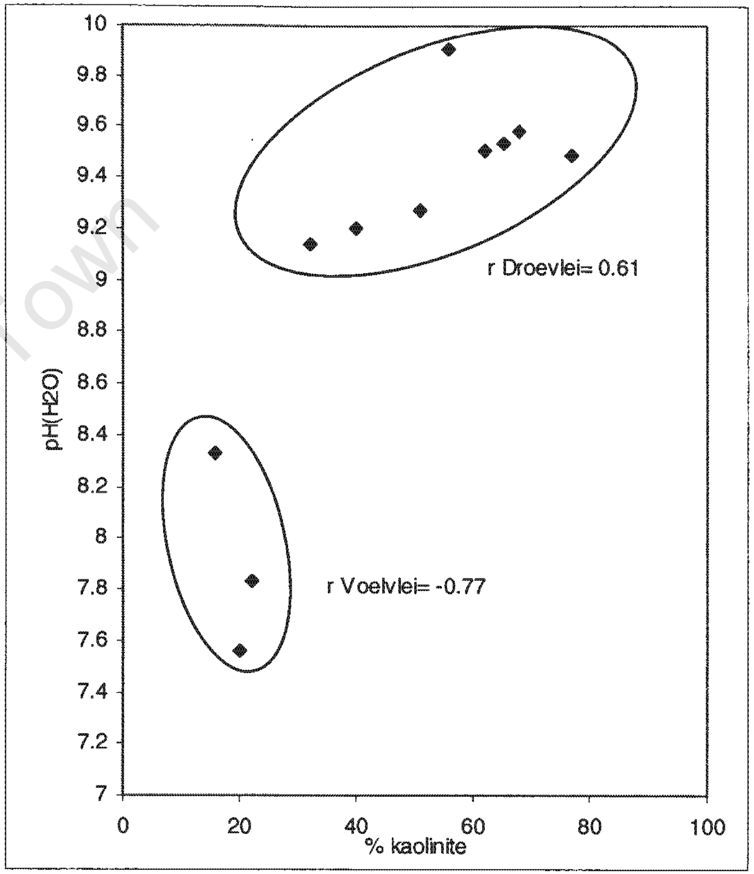


Figure 5.28: Correlation between % kaolinite and pH(H_2O)

In another measure of weathering, 2:1 layer type clay minerals such as mica and smectite often will break down to 1:1 layer type clay minerals like kaolinite, forming secondary clay minerals which have a simpler structure. This process may be occurring at Droevlei East as recorded in the good negative correlation between the 2:1 layer type clay minerals and kaolinite. Kaolinite changes down-profile indicate that the kaolinite is secondary, a product of weathering.

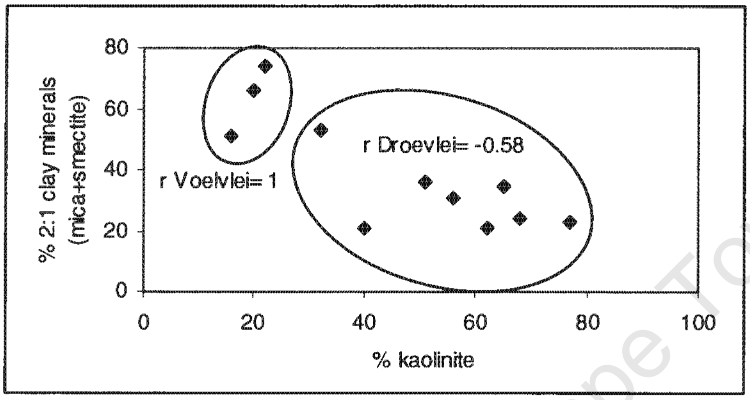


Figure 5.29: Correlation between 2:1 and 1:1 levels of clay minerals.

Although conclusions based on three data values are speculative at best, a general picture emerges from the clay mineralogy of these samples, one that appears to reflect differences between the two sites. The clay mineralogy at Voelvlei is generally less weathered (stage 7 in the weathering sequence) than Droevlei East (stage 10 in the weathering sequence), though both dunes have the weathered mineralogy expected from the underlying substrate. The kaolinite at Droevlei East could be the product of secondary weathering of 2:1 layer clay minerals, potentially suggesting more highly weathering conditions (humidity, time, etc).

These relationships will be discussed within the context of the other sedimentology characteristics described in this chapter and the morphology described in the previous chapter in Chapter Seven. The question of age and timing of these features, one determinant of weathering, will be discussed in the next Chapter.

Chapter 6: Chronology of the features

6.1 MORPHOLOGICAL INDICATION OF AGE

In all landscape studies and particularly those concerned with palaeoclimate interpretation, the question of timing, both in terms of initiation and evolution of structures, is a crucial one. In Quaternary Science, a field itself defined in terms of time, an accurate grasp on the ages represented in a chronology is fundamental. Although many comparisons and conclusions can be made without a precise chronology, a quantitative number, in this case a set of radiocarbon ages, provides a starting point, albeit not without its own complications.

These numerical dates represent a few finite points in a feature that is the product of reoccurring cycles of accumulation and erosion. The material present in the modern feature is the current status of that cycle, and provides solid evidence for only half the history. Dates from the dune can only be interpreted as the age or timing of activity of the dated section of the dune. Regular interpolation through the profile is impossible. Ages of the undated sediments rely on relative-age methods to compare characteristics between layers and correlated-age methods to demonstrate equivalence to independently dated features. The "age of a dune" can only be discussed as periods when the dune was known to be active; an "older dune" is recognized if it exhibits earlier periods of activity. Dune building was likely synonymous at both sites during some stages.

The morphology of the entire pan-lunette feature reflects age and timing of formation. Pans, when following a hydrologic evolution or aging within one hydrologic regime, exhibit certain indicative characteristics (Bowler, 1986). Lunettes are constructed and then deconstructed by natural weathering processes at variable rates and with variable morphologies depending on composition and time. Changes in climate or land-use may alter the rate and extent of this process, making it an inaccurate method, at best, of identifying age.

Simply observed, as a body the pans at Agulhas are larger and deeper than the pans in the Swartland. The dunes at Agulhas, in plan view, have a more dissected appearance, possibly in response to erosion over time. Bowler (1983) also observed a morphological variation resulting from differences in scale: larger complexes tend to have a more irregular gullied form than those found at smaller basins. The size of the pan itself is indicative of age; the large pans at Agulhas have been deflating sediment for a longer period than the smaller pans in the Swartland. The initial interpretation from these types of observations is that the pan-lunette features in Agulhas represent an older collection of landforms than the pans in the Swartland. In both clusters, however, there is a variety in structure between features that likely represents a difference in the timing of the initial formation of individual features.

The overall elevation of the cluster is potentially indicative of age. Altitudinal variations in the western Cape have been identified as Cenozoic marine-cut surfaces at 180m, 90m, 60m, and 30-20m which are progressively younger with lower altitude (Marker, personal communication; Rogers, personal communication). This chronology could be used to support a younger age for the Agulhas cluster (15-25 mamsl on average) than the higher Swartland cluster (55-105 mamsl on average). Although this is a distinct morphologic relationship, it is not corroborated with the majority of other age evidence. The age of the surface, alone, does not determine the age of the pan.

The characteristics of the dune sedimentology also contain information about the timing of the dune formation. Regular down-profile changes are due to weathering as a product of humidity or time. Non-systematic changes, such as the appearance of unstable clay minerals at depth, are due to parent material vulnerability and control. Distinguishing between products of time versus products of humidity is the primary complication. Both dunes studied have the mineralogy expected for weathering products of the parent material. Droevlei East in the Swartland, however, shows signs of heavier weathering in the stage of clay mineralogy and calcite accumulation at depth. These observations could indicate either heavier weathering (more humid conditions) or older features in the Swartland. The finer texture of Droevlei East would support a generally arid climate, and therefore an age-control on the weathering of clay minerals.

The age of similar features and events (arid conditions) in the southwestern Cape can augment the story of the timing of development here. The conclusions of this chapter will be placed in a regional context of the chronology of similar events in the following chapter.

6.2 PREVIOUS CHRONOLOGIES

The work of a number of previous researchers does shed light on the age of these features. In Agulhas, a 1.5 m hole in the crest of the lunette at Soutpan was dated at 92.5 +/- 9.4 K years before present based on Optically Stimulated Luminescence (OSL) (Shfd97048) (Carr, personal communications). Ongoing research is working on getting OSL dates for more than twenty aeolian structures and vlei cores from around the Plain. The ages currently suffer from inconsistent Inductively Coupled Plasma Mass Spectrometry (ICPMS) results for dose rates (concentrations of Ur, Th, K), but some of the more feasible age determinations are included in Table 6.1 (Carr, personal communications). Although none of these dates are from basal samples, indicative of the age of the dunes, they do indicate that the pan-lunette features were active roughly 80 000 years before the present and again 17 000 years ago, it is unclear from these dates whether the activity was continuous. Based on this initial data, the dunes at Soutpan and Voelvlei, both in Agulhas, are of different ages (80 ka vs. 17ka).

In the Swartland, Smith (2000) estimated an age of the pans from 4-10 ka based on salt concentration calculations. She also decided that the pans are of different ages, decreasing to the north with Slangkop being the youngest.

Table 6.1: Dates obtained during current and previous research.

	Site	Depth	Age (BP)	method	researcher	O-isotope stage
Agulhas	Soutpan lunette	1.5 m	85-95 K	OSL	Thomas and Bateman	5
	Soutpan lunette	0.85-3.48 m	60-70 K	OSL	Carr	4
	Voelvlei lunette	1.08 m	17 K	OSL	Carr	2
	Voelvlei lunette	1.53 m	12 K	C14	Gaines	1
Swartland	various pan waters	Surface	4-10 K	[Salt]	Smith	1
	Droevlei E lunette	4.5 m	8 K	C14	Gaines	1
	Droevlei E lunette	2.5 m	0.3 K	C14	Gaines	1

Based on these ages, the Agulhas cluster is older than the Swartland cluster. It is possible that the youngest pan-lunette features in Swartland were initiated at the same time as the oldest features in the Agulhas. The reversal of ages at depth in Agulhas is most likely a product of the different dating methods utilized to produce those dates, and is not a great cause for concern.

6.3 GASTROPODS

As a part of this research the radiocarbon ages listed in Table 6.1 were obtained from gastropods. The gastropods were hand-picked from the dry soil samples wherever they were obvious, and for dating purposes represent the average of a few inches of sedimentation.

6.3.1 DESCRIPTION

Gastropods are abundant in a distinct number of layers in both the Voelvlei and Droevlei East lunettes. They have been identified as *Tomichia ventricosa* (first documented by Reeve in 1842), a gastropod common in ephemeral southwestern Cape saltpans and occurring in quantities up to tens of thousands under favourable conditions (Herbert, 2002).

A number of other species of *Tomichia* are found in wetlands in the southwestern Cape (*T. zwellendamensis, T. differens*). Morphologically the species are very similar, but the physiognomies differ substantially. Of these, *T. ventricosa* live in the broadest range of environments from shallow rivers to coastal wetlands to inland pans. They are the only species hardy enough to survive the hydrologic cycle of the saltpans. They can survive the annual drying of the pan and salinity fluctuations (from 8-10‰ when wet to >160‰ during dry spells) that come with precipitation variability by burrowing below the surface to moist areas in modes of amphibious behaviour and aestivation (Davis, 1981). Many individuals do die off during the dry season because of stranding or desiccation by osmosis when waters reach a salinity of 130 to 160‰ as observed in Ysterfontein (Davis, 1981). With the first rains, the surviving individuals reproduce at a high rate. *T. ventricosa* is one of the most resilient gastropods to changes in salinity and water availability.

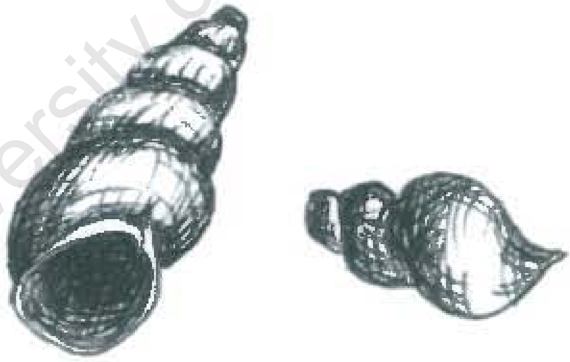


Figure 6.1: *Tomichia ventricosa*. The large specimen is approximately 3mm in length (SMG).

Davis (1981) identified *T. ventricosa* during two field expeditions in the Western Cape during 1977 and 1978. Some of the field sites where he collected *T. ventricosa* include Ysterfontein (Swartland), Rhenosterkop (Agulhas), Rondepan (Agulhas), Langepan (Agulhas), and a number of other small pans and streams in the region.

Smith (2000) likewise identified modern individuals of the same species in many of the Darling pans. She recognized a strong enough correlation between the presence of *T. ventricosa* and the pan chemistry to use their occurrence as a distinguishing characteristic of her so-called 'small brackish to saline inland pans' (2-64 g/kg total dissolved salt, equivalent to 2-64‰). Pans of higher salinity, 'small brine pans' (168-531 g/kg total dissolved salt), were detrimental to *T. ventricosa* propagation.

This environmental adaptation is not a recent occurrence. The modern species of *Tomichia* in South Africa have been evolving since the mid-Miocene, potentially in response to increasing aridity (Davis, 1981).

> "The coastal vleis and pans so common from Ysterfontein across the Cape Flats to Agulhas have probably had annual cycles of drying from the Pliocene onward, a period of about 5 million years during which *T. ventricosa* and *T. tristis* became adjusted to their current ecological situations."
>
> (Davis, 1981, p.237)

Besides excessive aridity and the resultant salinity, calcium availability and the actions of people are the biggest limiting factors on the distribution of *Tomichia*. In terms of calcium deficiency, *Tomichia* habitats are limited to a series of thin coastal strips, characterized by calcrete deposits. Detrimental human interference includes pollution of all kinds as well as the disruption of natural hydrological cycles by, for example, the modification of pans for salt works.

6.3.2 CLIMATE IMPLICATIONS

These gastropod shells can be used as climate indicators in a number of ways. On the coarsest level, the type and degree of physical weathering is indicative of the age and treatment of the shell. When living, the shells are an orange colour, but with *post-humus* etching or bleaching they fade to a grey-white. There is also recrystallization evident on some shells. Shells from deeper levels (Figure 6.5) were mostly fragmented and smaller than the more robust samples from the modern shoreline (Figure 6.2). It is not evident from inspection of the shells whether the snails moved themselves or were blown by the wind to their current position. In the case of marine molluscs in a shifting coastal dunefield, Illenberger and Verhagen (1990) commented that it takes thousands of years for an average mollusc to be broken to 1mm diameter fragments. From an initial macro-scale perspective, the Voelvlei shells look either older or more roughly treated since the death of the organism.

It is also clear from modern studies that *T. ventricosa* prefers particular conditions. Although they are flexible habitants of a range of environments, they are most prolific in pans during brackish to fresh water-full conditions. Large populations of *T. ventricosa* in the record can be interpreted, then, as more humid periods when pan basins retained standing water throughout the year, as they do currently. In Australia, accumulations of a similar gastropod, *Coxiella*, has been used as an indication of arid periods in lunettes (Bowler, 1983).

Figure 6.2: Sample Modern Shoreline

Figure 6.3: Sample DV3

Figure 6.4: Sample DV10

Figure 6.5: Sample VL6

6.3.3 RADIOCARBON DATING

The most quantitative Quaternary method for dating these gastropods is the radiocarbon analysis of the ^{14}C found in the calcite of their shells. Four samples were dated at the National Ocean Sciences Accelerator Mass Spectrometer Facility (NOSAMS) at the Woods Hole Oceanographic Institution (WHOI) in Woods Hole, MA, USA.

The author performed the sample preparation, namely sonnicating the sample shells in milli-Q water to clean them thoroughly, removing any residual soils from the shell coils. Because of the thinness of the shells, they were not etched in dilute acid to clean them further. They were dried in an oven at 50°C and homogenized before an analysable sample was separated. The shells were homogenized to reduce error resulting from age differences between individuals. Even on modern shorelines, individual molluscs display age differences as great as 500 years. In order to measure this potential source of error, one modern sample from the shoreline of Droevlei East was analysed. By crushing three individuals from each sample into a carbonate powder, this individual age variability was muted as much as practically possible. The staff of NOSAMS then hydrolysed the resultant carbonate in a vacuum and combusted the carbon dioxide produced over an iron catalyst to form graphite. This graphite was then pressed into targets and run through the AMS.

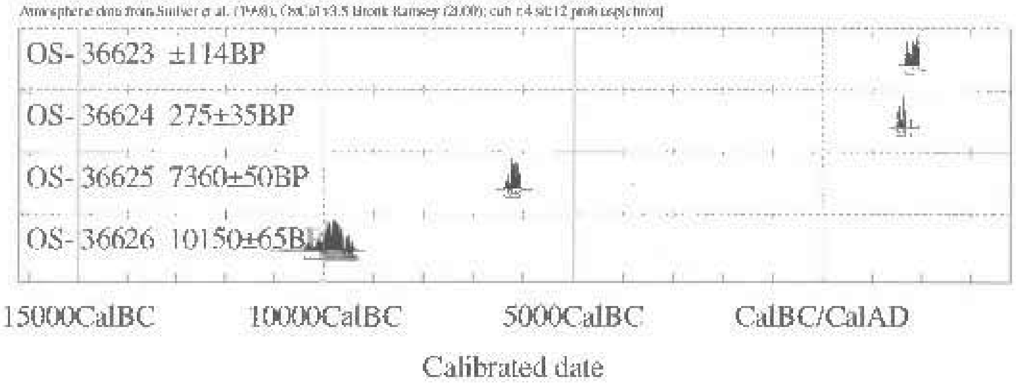
Table 6.2: Radiocarbon Analysis results

NOSAMS Accession #	Submission label	d13C (per mil)	F Modern	Fm Error	Age (yrs)	Age Error	D14C
OS- 36623	Modern shoreline	-5.67	1.1210	0.0052	>Mod	114	
OS- 36624	DV3	7.29	0.9663	0.0045	275	35	-39.8
OS- 36625	DV10	-7.53	0.4001	0.0024	7360	50	-602.4
OS- 36626	VL6	-5.75	0.2832	0.0024	10150	65	-718.5

The reported age of the samples in Table 6.2 includes a correction for natural fractionation that was based on the measured values of δC13. NOSAMS calculates the total error margin for the sample processing, AMS instability, and this correction at 0.48% (http://nosams.whoi.edu/). Other sources of error are discussed later in this chapter.

The radiocarbon ages were calibrated using a number of programs (Table 6.3) but the dates from CALIB are the primary dates cited because the simple format of the program produces ages that are in accord with the other programs. The ages do fall within the range calculated through other calibration programs.

Table 6.3: Relative CALIB calibrated ages of samples (Stuiver, 1993).



To avoid confusion, the calibrated date is reported in regard to 1 and 2 sigma (σ) variation, 68% and 95% confidence level respectively (Talma and Vogel, 1993). Because the radiocarbon is from the southern hemisphere, a further 41 +/- 5 years must be added to the calibrated dates (Vogel *et al.*, 1993).

Table 6.4: Calibration of radiocarbon ages. See Appendix A for more detail.

Sample	radiocarbon age	CALIB- University of Washington			OXCAL- Oxford University	
		Calibrated Age	1 sigma (max - min)	2 sigma (max – min)	1 sigma (max - min)	2 sigma (max - min)
Modern Shoreline	>Mod +/- 114	0 BP	255 - 0 BP	291 – 0 BP	270 - ...BP	290 - ...BP
DV3	275 +/- 35	306 BP	420 - 294 BP	433 - 157 BP	481-331 BP	511 - 201 BP
DV10	7360 +/- 50	8173 BP	8187 - 8055 BP	8327 - 8025 BP	8280 - 8040 BP	8330 - 8020 BP
VL3	10150 +/- 65	11893, 11863, 11746, 11713, 11700 BP	12091 – 11577 BP	12318 - 11343 BP	12000 - 11400 BP	12350 - 11300 BP

6.3.4 SOURCES OF ERROR

There are a number of potential problems with using these gastropods as indicators of climate or timing of dune-building phases.

Firstly, *T. ventricosa* burrow as a survival strategy. The author could find no research to indicate the extent of their burrowing, although bearing in mind the intent - to reach wetter sediment beneath the surficial crust - it is likely to be on the order of only 10 cm. The burrowing behaviour could mean that shells are younger than the sediments from which they were collected. Shells have been discovered cemented into calcrete aeolianites in Agulhas, the product of a long-standing process. If the gastropods are burrowing extensively, they have been doing it for a while.

Burrowing gastropods, notwithstanding, would yield apparent young radiocarbon ages, although should retain relative ages between dates.

In regards to this also, there is the question of taphonomy. Some vagueness exists as to the means by which the gastropods arrived at their current position. Based on the fixed nature of lunette dunes and the current topography, it is unlikely that the layers the shells were extracted from represent a former shoreline. Additionally, the texture of the surrounding sediments is not that of a shoreline. The gastropods must have moved from the shoreline of the pan to the dune crest. It is unlikely that the snails moved themselves that distance from their water sources while alive- tens of meters at least horizontally- so it is reasonable to assume that the shells were deflated to the dune along with other sediment after the death of the gastropod and desiccation of the shells. Burrowing is less of a concern then, unless the gastropods were deflated while alive and then burrowed into the dune crest. Gastropods found in Australian lunettes were assumed to be the product of aeolian transport from the pans (Bowler, 1983). No shells were found in modern dune-crest sediments. Although the shells do not show clear evidence of aeolian transport, a shell which survives intact when buried under meters of sediment for several thousand years, can surely survive a few tens of meters of deflation without major damage.

Nevertheless, the shell calcite is relatively fragile and susceptible to post-depositional chemical weathering. There is slight evidence of physical weathering and fragmentation (see Figures 6.1-6.4). The variation in C^{13} isotopes (Table 6.2), however, does not show an age relationship indicative of isotopic fractionation and chemical weathering with time. Namely, the C^{13} isotopes are not getting progressively more or less concentrated with age.

Finally, a source of error when determining authenticity of all radiocarbon ages is the consideration of the reservoir effect, the result of radiocarbon-dead carbonate from which a specimen derives its carbon. Gastropods make the calcite of their shells by incorporating carbon from their food sources. *T. ventricosa* eats algae which derives its carbon from atmospheric CO_2. The carbon in gastropod shells is then ultimately modern atmospheric CO_2 ($\delta C^{13} = 0‰$). As stated in Davis (1981) the distribution of *T. ventricosa* is limited by carbonate distribution, mainly in the form of calcrete. It is possible that some of this carbon is incorporated into shell production via dissolution in bicarbonate-rich waters ($\delta C^{13} = -7‰$ which at equilibrium conditions with the atmosphere yields a $\delta C^{13} = 0‰$) and uptake in algae. This carbon, derived from carbonate-rich rock ($\delta C^{13} \approx -20‰$), is radiocarbon dead. The measured δC^{13} values from –5 to -7‰ indicate a primarily atmospheric source with some rock-input. Also, the dates obtained do not indicate a dead-carbon reservoir effect from calcrete influence. It is concluded, then, that the question of a reservoir effect is not a primary concern for this particular environment.

Bearing these sources of error in mind, the ages of modern, 306 BP, 8173 BP, and between 11700 and 11893 BP are reasonable. Major concerns of burrowing would indicate a youngest age, at best, still a useful marker for measuring the timing of these features, with a stratigraphic age relationship intact.

The evidence informing the pan-lunette ages in either region is conflicting. An age-relationship representative of the whole cluster must be supported by regional as well as local evidence, should the two selected features be irregular in their cluster. The Swartland cluster appears younger than Agulhas on account of its higher elevation and the finer texture but more highly weathered clay mineralogy of the Droevlei East lunette. The larger, more dissected features at Agulhas morphometrically support the seniority of that cluster. The physical and isotopic evidence from the gastropods indicate an older Agulhas cluster. As with all quantitative methods more ages would be useful, but with the support of age calculations performed in other studies, the radiocarbon chronology can be defended with confidence. The contradictory evidence corresponds to the quantified ages if the weathering in the Swartland is interpreted as a product of humidity and parent material rather than time, and altitudinal surfaces are recognized as just one of many potential factors impacting on pan-lunette formation.

In conclusion, regional and local evidence supports significantly earlier activity at Agulhas than in the Swartland. Synchronous dune-building periods have not been identified, but there are clearly differences in the factors affecting the formation of the features in either region. In the final chapter, an attempt is made to identify corresponding and reinforcing activity from the Quaternary record on either coast and in the southwestern Cape in general.

Chapter 7: Discussion and Conclusion

7.1 EVIDENCE FROM PAN-LUNETTE FEATURES IN THE SOUTHWESTERN CAPE

The evidence collected and discussed throughout this dissertation, presented more concisely below, can be interpreted to yield information regarding environments that fostered the formation of the pan-lunette features, the actual process of formation of these features, the treatment since formation, and the timing of formation.

7.1.1 DUNE ORIENTATION

The orientations of the lunettes are parallel within each cluster, indicating that the features were formed under the same wind regime. The lunettes at Agulhas are oriented, on average (mean), at 094 degrees with a standard deviation of 4.5 degrees (1.2%) (Figure 4.7, Table 4.5)). In the Swartland, the lunettes are oriented at 004 degrees with 5.4 degrees of standard deviation (1.5%) between orientations (Figure 4.8, Table 4.4).

The lunettes formed perpendicular to dry season palaeowinds. The reported lunette orientations are equivalent to propagating wind directions. Although the modern dry season winds in both clusters continue to represent the strongest winds and the least calms of the annual record, they are not from the same direction as the winds that constructed the lunettes. The Agulhas cluster was built by winds blowing from a resolved direction of 274 degrees, 33% or 119 degrees west of the resolved current dry season wind direction of 154 degrees (Table 4.5). The cluster in the Swartland was built by winds blowing from a resolved direction of 184 degrees, 40 degrees south (11%) of the resolved current dry season wind direction of 224 degrees (Table 4.4).

In the case of Agulhas, the palaeowinds predicted by the lunette orientations are most similar to the winds that currently blow during September, at the end of the modern wet season. Throughout the wet season (May-August), winds blow from the west, but with a more northerly component than the winds that produced the lunettes (WNW rather than WSW). This difference could indicate a change in seasonality of rainfall or a change in wind direction determined by sea-surface temperature anomalies.

In the Swartland, the current January winds are actually the closest fit of the monthly averages with the winds expected for dune-building purposes. A very similar SSW wind regime persists for the drier six months of the year, from October through April. The dune-forming wind was nearer to due south than the current SSW orientation. This slight shift in wind direction may have ties with sea-surface temperature anomalies caused by Benguela upwelling patterns.

7.1.2 DUNE COMPOSITION

Using the composition of the pan-lunette features, the formational history of the features can be inferred. As explained in Chapter Five, a single feature at each cluster was chosen as representative of the whole cluster for the purposes of elucidating formational history.

7.1.2a Formation of pans

Before a lunette forms, a pan must exist. In other parts of South Africa, pans tend to form on soft sediments that are prone to weathering such as shales and unconsolidated sands. The pans of the southwestern Cape present only two exceptions to this rule of thumb, in the granite-based pans of the Swartland cluster. Smith (2000) hypothesized that the Swartland cluster filled topographic lows, relicts of the historically transient Brak River that continues to flow ephemerally along the northeast trending cluster of pans (Figure 2.9). The Agulhas cluster, likewise, occurs on a flat river perforated plain. The Agulhas pans also probably formed in topographic lows along palaeo-river courses on suitable sand and shale substrates. Many of the pans are still linked, receiving water input from the Nuwejaars River (Figure 2.6). Unlike the Swartland cluster, the Agulhas pan morphologies appear to be related to underlying substrate.

7.1.2b Source of sediments

In order for a lunette to form, the pan must exhibit a saline environment, amplified by seasonal flooding and evaporation, and a hot dry season that is characterised by strong unidirectional winds (Bowler, 1973). All of these requirements are homogeneous regionally, with the exception of the salinity of the pan environment.

Approximately half the pans at both clusters have an associated lunette (Table 4.3). It is not, however, solely the brine pans, the saltiest pans of the Swartland cluster (Smith, 2000), that form lunettes, nor is there a strong correlation between underlying substrate and the formation of a lunette. Although it is undetermined if the salinity is regionally characteristic, the sediment at Voelvlei is twice as salty as at Droevlei East. Nevertheless, pans are no more common at Agulhas than in the Swartland. Pans of all sizes also exhibit lunettes. It is unclear why only half the pans have an associated lunette.

In Agulhas there is a strong positive correlation between dune size and pan height, indicating that the lunette sediment is actually derived from the pan basin (Figure 4.2). The pans without lunettes were included in this correlation revealing a trend that smaller pans, in Agulhas at least, are less likely to exhibit an associated lunette. The Swartland cluster, smaller pans throughout, does not exhibit the same correlation between pan size and dune height; in fact there is almost no correlation (Figure 4.4). Although the pans in the Swartland are generally smaller than the Agulhas pans, the lunettes produced are nearly the same elevation (Table 4.3). Overall, there is not a clear relationship recognized here to explain the occurrence or absence of a pan-side lunette.

Despite the discrepancies in pan-lunette size correlations at either site, it is expected that the sediment within the lunette dune will be the product of the substrate hosting the pan. This expectation was confirmed with mineralogical analyses. The mineralogical composition of the lunette begins to elucidate the formational process and age of the lunette by revealing relatively unaltered parent material or a weathering product of that material.

The mineralogy of the clay-size fraction of the lunette sediments at either site supports a predominant parent-material source with different extents of subsequent weathering. Voelvlei, on shale in the Agulhas cluster, is primarily composed of mica (64% mean) (Figure 5.24). In the Swartland cluster, Droevlei East, underlain by granite, exhibits a kaolinite-dominated mineralogy (56% mean), comprising from 32% to 77% kaolinite (Figure 5.25). Mica, the primary weathering product of granite, is the second most prominent mineral (28% mean). This clay mineralogy at Droevlei East indicates more extensive weathering than at Voelvlei. The non-systematic constituents such as smectite and calcite at depth indicate parent material variability or remineralization processes. There is not a regular depth relationship with these mineralogies.

The sand fraction in the sediments, likewise, is a product of the host substrate. The sand fraction composes less than 50 % of the sediment in most cases, and is a result of wetter, more beach-like environments in the pan. The history of these grains was discussed in Figure 5.12 and associated text where the sorting statistics support the argument of a beach source. The non-systematic sandiness at DV5, 1.1 m depth in Droevlei East (Figure 5.25), for example, indicates a distinctly wetter period.

7.1.2c Movement of sediments

Based on textural analyses, it can be established that the lunette features are, indeed, the product of aeolian processes. With the exception of samples taken at the shoreline, the sediments in Droevlei East are on average 72% fine-grained, placing the dune in a textural characterisation ranging from silt loam to clay loam (Figure 5.9). Voelvlei sediments are coarser, 53% fine-grained on average, ranging in textural characterisation from sandy loam to clay loam to clay (Figure 5.10). In recent years, the

Agulhas cluster has been subjected to higher winds than the Swartland cluster (annual averages of 4.57 m/s versus 2.64 m/s since 1990 according to SA Weather Service records). The pedogenic extension of this trend, a product of oceanic activity, to the period of dune propagation, could explain, to a reasonable extent, the coarser texture at Voelvlei.

The settling column statistics (Figure 5.14) may reveal the more complicated history of the lunette sediments, as the grains likely did experience a beach-like environment in the pan before being deflated by aeolian transport to the dune.

7.1.2d Deposition

The processes involved in the deposition and actual dune building of the pan-lunette formation may be the most difficult to separate and identify.

The textural similarities, at least, indicates that these dunes have accreted in a series of parallel beds as is diagnostic in clay dunes (Bowler, 1973). Agricultural and natural surface processes may have contributed to the similarities between the shallower samples taken from multiple sites on the same dune. The differences at depths over around 1.5 m are likely products of post-depositional weathering, where more easily weathered clay minerals have remineralized after being leached from overlying sediments.

Based on the dates obtained at various stratigraphic levels in Voelvlei lunette (section 7.1.3), it is evident that either the lunette has not been growing at a constant rate or it experienced major periods of erosion. The lunette has clearly experienced recent erosion as a product of high water: the front face of the dune now displays an eroded cliff at the pan shore. The only evidence for large-scale erosion across the top of the dune lies in its fragmented morphology. Quantifying the actual rate of dune building is not feasible.

Determining the environmental conditions based on characteristics of sediments in each sample is very difficult, in part, on account of this lack of knowledge about the depositional history. The development of a palaeosol (as will be discussed in 7.1.4) is one exception. Generally, it can be assumed that lunettes were forming when conditions were arid, but not too arid. Based on morphology, these conditions occurred when the wind was blowing from certain distinct directions. Layers rich in *T. ventricosa* indicate the occurrence and subsequent end to humid pan-full conditions when increased aridity caused mass extinctions of previously successful *T.ventricosa* populations and the ensuing desiccation of shorelines and pan-floors permitted deflation of the shells. Similarly, peaks in the organic matter content (if such were prominent) could indicate humid periods of stability. Instead, fairly stable levels of organic matter may be the product of the constant deposition of organic matter from soils existing elsewhere. This explanation would indicate a larger input of organic matter in the Swartland cluster.

The possibility of multiple periods of dune building recorded in double lunettes does exist for these sites. However, there is not adequate information at this stage to establish the implications of the morphology. More detailed sedimentology and profiling are necessary, as well as an explanation for the different morphologies at different pans (i.e. the lack of double lunettes at most features).

7.1.2e Post-depositional weathering

Once soil has formed on *in situ* sediments, complications arise in distinguishing diagenic versus pedagenic traits. Soil characteristics discussed below indicate weak pedogenic traits and no diagenesis. The characteristics of the sediments are determined by parent material and treatment during transport. The one real exception to this characterization is the redistribution of some clays through the profile. The prominence of kaolinite in Droevlei East also raises questions regarding its source as a primary or secondary weathering product; because shales weather directly to kaolinite, however, it is likely to be the direct result of that process.

The soil processes mentioned in Chapter Five have been recognized in these sediments as follows:

- *chemical weathering*

  Carbonate hydrolysis does appear to be taking place at Droevlei East where pH is high (Figure 5.18) and varies parallel to calcium carbonate levels (Figure 5.17). Additionally, based on the inverse relationship of pH and kaolinite (Figure 5.27) there, the kaolinite may be a pH-dependant weathering product. Further investigation into the likelihood that the kaolinite is a secondary weathering product of 2:1 clay minerals (Figure 5.29) is largely inconclusive, but possible based on mineralogic proportions.
- *downward leaching of soluble minerals, including weathering products*

  There is no clear depth relationship with the extent of weathering in clay-size minerals (Figure 5.25). Kaolinite, the most heavily weathered mineral present in these samples, fluctuates throughout and calcite, the least weathered mineral present, appears only at 1.45 m depth in Droevlei East, comprising 25% of the mineralogy there. Additionally, feldspar, a relatively unweathered mineral, only appears at 1.5m depth in Voelvlei. The occurrence of these two minerals does support the theory of a leached profile with remineralization of the leachate occurring at depth.
- *precipitation of soluble salts in near-surface horizons because of evaporation*

  Salt content, as measured with conductivity, is twice as high at Voelvlei (Figure 5.19) than at Droevlei East (Figure 5.15). At Voelvlei, salt content increases regularly with the associated clay content at depth (Figure 5.20). At Droevlei East, clay (Figure 5.16) and salt content are not as neatly correlated. There are a number of spikes in the regularly increasing clay content at depth that are not matched by the salt content. At 4.5 m (DL10), the basal sample, the salt content spikes dramatically, unaccompanied by clay content. This is the result of groundwater salt precipitation, as the sampled depth is actually below the level of the pan floor. There are no clear near-surface evaporative salt horizons at either dune.

- *incorporation of decomposing organic matter*
  Organic matter at Voelvlei occurs at low levels, never composing more than 10% by mass (Figure 5.21). However at Droevlei East, organic content fluctuates between 15-20% in accord with carbonate and pH, a measure of its degree of incorporation into the sediment (Figure 5.17).
- *disturbance of soils (by biological or physical processes)*
  There is evidence of human disturbance in the top half-meter from ploughing.
- *downward movement (eluviation) of clay and redeposition (illuviation)*
  The clay fraction does increase with depth in both lunettes analysed, although there is a reversal of trends at roughly 1.5 m (Figures 5.11 and 5.12). Clay proportion in sediments is a product of depth from surface rather than overall depth within the dune, indicative of post-depositional processes of eluviation and illuviation, likely resulting from more humid conditions in recent times. This coarsening pattern towards the surface could also be interpreted as evidence of increasingly strong winds in the present, but such a regular trend is more likely the result of eluviation and illuviation. There is no apparent correlation between depth and the actual mineralogical content of the clay fraction (Figures 5.24 and 5.25). The process of downward movement and redeposition of materials within the profile is supported by the above-mentioned remineralized calcite and feldspar. Because there were no truly basal samples obtained in this study, it is impossible to make a detailed comparison of parent material with overlying clay.
- *reduction of brown, yellow or ferric iron minerals to more soluble grey ferrous compounds in waterlogged conditions*
  No evidence of such activity or such conditions.

7.1.3 DUNE TIMING

Based on the radiocarbon dates discussed in Chapter Six, the lunette at Droevlei East was initiated around 8000 BP. By 300 BP the lunette was 2 m high and, by the present, 4.5 m. This chronology either represents variable rates of erosion, or, more markedly, a depositional hiatus, likely caused by more humid conditions. Based on these ages, the dune at Droevlei East may have been initiated during an arid Holocene altithermal.

It has been argued that the Swartland pans are progressively younger to the south of the cluster (Smith, 2001). Data investigated here neither supports nor negates this possibility. Pans throughout the cluster bear associated lunettes.

Over approximately the past 12 000 years, the lunette at Voelvlei has grown 1.5 m in height. Overall, the dune stands approximately 8.5 m above the pan floor, thus representing a substantially older period of initiation. The age of lunette initiation is not quantifiable with the current information. The active dune building period identified at Die Kelders between 24 000 BP and 12 000 BP could potentially coincide with the initiation of the Voelvlei lunette, although it is more likely to have been initiated previously, but developed further during that period (Tankard and Schwitzer, 1976).

Based on other ages obtained in dunes in the Agulhas cluster, there appear to be dramatic differences in age of features within the cluster; analyses from similar depths in Soutpan yield dates up to 90 000 BP. This observation brings to question the original assumption of uniform depositional environments of features in the cluster. Dune orientations of variously old dunes do remain parallel, indicating a long-term stability in wind direction and seasonality.

Generally, the ages determined here and those cited by other researchers indicate that the dunes in Agulhas are significantly older than the dunes in the Swartland. The substantially saltier conditions at Voelvlei than at Droevlei East supports this age relationship between clusters based on the assumption that all pan-lunette features are evolving through a regular hydrologic cycle that gets saltier with age (Smith, 2000; Bowler, 1986). Other evidence of age, as discussed in Chapter Six, confirms this relationship.

7.1.4 PALAEOSOLS

The correct identification and even definition of a palaeosol continues to be hotly contested (Birkeland, 1984; Retallack, 1990; Catt, 1995). The name, at least, is most useful (Catt, 1995) when reverting to early definitions of a 'palaeosol' as 'a soil formed on a landscape during the geologic past' (Ruhe, 1956, p.441).

Some of the commonly described characteristics of palaeosols include: organic matter-enriched A horizon, structure, vertical variation in coloration (oftentimes rubefaction from hematite formation) and illuvial clay, clay films, and carbonate accumulation morphologies in B or C horizons common in acidic soils (Birkeland, 1984; Retallack, 1990; Catt, 1995).

To complicate matters further, many features ascribed to pedogenesis may also form through burial-diagenesis. Palaeoenvironmental inferences from palaeosols have been made from the kind of soluble salt in profile and the depth relation of salts, the depth of clay accumulation in soils and the clay mineralogy (Birkeland, 1992). Significance of palaeosols in South Africa has been limited to an acknowledgement of their presence and a limited inference of palaeoenvironment. For interpretive purposes it must be remembered that soils are not permanently in equilibrium with the climate in which they occur and the development of a soil horizon is by no means representative of a finite point in time.

Soil development on aeolian sands has previously been interpreted as representing periods of stability resulting from reduced sediment supply and/or increased vegetation cover (Deacon and Lancaster, 1988). Hills (1940) recorded successions of buried soils in longitudinal dunes and interpreted the formational history as soils formed during humid periods, dune building during arid phases; this work comprised early anticipation of cyclical climate oscillations (Bowler, 1983). Three generations of Holocene palaeosols in the southern Cape have been identified during 8000-7000 BP, 4850-1300 BP and 500 BP (Butzer and Helgren, 1972). Butzer (1984) has specifically identified one palaeosol horizon at Swartklip (Figure 2.8) although the one age obtained is not definitive (c.22000 BP radiocarbon based on a bone from Melkbosstrand). He assumed the significance of the palaeosol to be indicative of wetter conditions, but later assumptions highlight the possibility of sea-level regression fostering dune vegetation (Deacon and Lancaster, 1988). A Holocene dune cordon a few kilometres south of Eland's Bay exhibits a well-developed palaeosol, dated around 3000 BP and interpreted as a humid episode (Miller *et al.*, 1993). There is thus a general context of palaeosols documented in the palaeoenvironmental history of the southwestern Cape.

The distinct reddish soil horizon in the Voelvlei lunette, represented by sample VL3, does exhibit a positive net colloid charge which indicates iron oxides, the cause of the rubefied colour, and a common marker of palaeosols. Besides a very distinct colour contact with surrounding layers, there is no clear structural difference within layer VL3. There is markedly more clay in VL3 than in the overlying layers, but underlying layers have roughly equivalent clay contents, indicating no clear clay accumulation. The clay mineralogy is indistinct from the other samples analysed from the same profile. There is no evidence of carbonate accumulation within the layer, but the two underlying layers are dramatically enriched in carbonate. This effect could partially be the result of shell-fragments, except the layers VL6 and VL7 which were even more enriched in shell fragments than overlying layers, have a reduced carbonate content.

The clearly rubefied nature of the horizon and potential carbonate accumulation below it provide the only obvious evidence to establish that the horizon is a palaeosol. Despite this, it is interpreted with caution as a palaeosol.

Based on the precision of calibrated ages available for this feature, it is impossible to determine which period, if any, of regional palaeosol development this soil may match up with. It is reasonable, considering other regional records of palaeosol development and the stratigraphic position, 0.9m above an age near 12000 BP, that this horizon matches up with either the humid period at 4850-1300 BP or 8000-7000 BP recorded elsewhere.

7.2 COMPLICATIONS

There are a number of complications in this study that necessarily limit the conclusions attainable.

Firstly, there is a considerable issue of scale. Because the pans at Agulhas are so much larger than the pans in the Swartland, processes may be dramatically affected by that characteristic alone. For example, Bowler (1983) established that larger dunes tend to form with a different morphology, as seen in these instances. Statistical analyses are problematic both for comparing the features at different scale and because of the limited data set. The statistics used herein must be taken with these limitations in mind.

In the light of dated samples, the assumption of single features representative for the entire cluster is simplistic. The samples at Voelvlei and Droevlei East can only represent the features from which they are taken. The environmental conditions that formed each feature must still be real conditions, it is just unclear when and how they affected the other features in the cluster. Conclusions based on one sample are always weaker than those supported by parallel sets of samples. The orientation of lunettes, standard throughout the cluster, can be used to make regional conclusions.

This point leads to the issue of interpretation, specifically regarding interpreting the record. These features represent many things besides just depositional features. Increased sedimentation coincident with the arrival of European colonialists in places such as Verlorenvlei (Meadows and Asmal, 1996) is less predictable in a substrate that might, itself, be farmed and eroded. The pan-lunette features under consideration here have also been heavily impacted by human practices of salt-making, wheat-farming, and grazing stock. It must be remembered that the modern pan-lunette features represent dynamic systems, the product of millennia of climate change and land-use practice, much of which is either not recorded in the system or the cause of a mass detraction from the system.

Another concern regards interpretations in soil science. Obtaining information on past climates from soils is only possible once the effects of time, the other soil forming factors, and post-burial changes (diagenesis) on the soil properties have been disentangled (Catt, 1995). It is for these reasons that a study with the main end of palaeoenvironment reconstruction considered so many apparently unrelated characteristics of the sediment. The relationship between soil properties and climatic factors is very complex. Equally complex, at least, is the estimation of the length of soil-forming intervals. These complexities have been demonstrated in numerous cases in section 7.1.

Potential sources of error from laboratory methods are discussed in Appendix A along with the methods themselves.

7.3 PALAEOENVIRONMENTAL CORRELATION OF PAN-LUNETTE EVIDENCE WITHIN THE DATABASE OF THE SOUTHWESTERN CAPE

"The nature of the landscape response to any climatic or hydrologic change is determined as much by the pre-existing conditions as by the directions and nature of that change" (Bowler, 1983. pp. 167). In the case of the pan-lunette features, it was the change from regionally wet to regionally dry that made the lunette building possible.

This importance placed on knowing the pre-existing conditions as well as the direction of change makes *T. ventricosa* an ideal proxy, not only for its radiocarbon utility but also for the specific nature of its living conditions. The presence of abundant *T. ventricosa* shells in a lunette can be reasonably interpreted as the result of a period of humidity followed by an arid period (Figure 7.2, 7.3). Palaeosols, also, if identified successfully, can provide an indication of the change (dry going to wet and stable conditions) for an extended period.

The times when the dune was growing at all are relatively arid periods, compared to modern conditions. The lunettes are thus the cumulative product of arid phases that were humid enough for a degree of seasonal flooding to promote clay flocculation. When envisaged in this way, the accumulation of the dunes is a product of half the record, the other half of the record potentially deconstructing the first. The dunes are not only the product of arid phases, but of arid phases characterized by winds from the appropriate direction (Figures 7.2, 7.3).

Because there are only three absolute ages determined within the dune profile and it is impossible to determine rates of accumulation, it is very difficult to correlate periods of growth at these dunes with other arid phases in the region. It becomes a combination of rationalized interpolation and estimation (see Figure 7.4). Instead of embarking too far along this path, it is more appropriate and more productive to speculate on the events occurring around the known dates.

A convenient model for comparison with this study reconstructs wind direction as well as precipitation patterns. Sea surface temperatures decreased around 8700 and 6300 years ago, as a result, in part, of increased easterly wind anomalies (Cohen, 1993). Cohen's ocean-atmospheric model (1993) indicates that these oceanic conditions are associated with increased rainfall over interior parts of South Africa, but drier conditions along the west coast. This theory opposes Walker's (1990) in terms of precipitation predictions. The anomalies are unidentified in the Voelvlei profile, but could be the initiation conditions in Droevlei East. An occurrence that is more commonly cited in regional studies, the Holocene altithermal, also occurs during this time period. The activity at Voelvlei is synchronous to dune-building events recorded at Die Kelders and in the Australian lunette record. Although many other arid events in the south coast Quaternary record correlate well with the record of Australian lunette-building, there is little indication where they might be represented in this lunette record (Figure 7.3).

The marginal degree of diagenic weathering of sediments is indicative of the extent of humid-phases between arid dune-building phases. Although the clay mineralogy does not indicate diagenesis, there is evidence of clay alluviation and illuviation, the likely product of slightly more humid climates in the past millennia. The sediments were by no means waterlogged, but there has been some degree of weathering and remineralization. Additionally, the current cliff morphology at the Voelvlei actively demonstrates increasingly humid conditions. Today, under pan-full conditions, the face of the lunette, now a cliff face, is subjected to wave energy throughout the wet winter (Figure 7.1).

Figure 7.1: Looking southeast across Voelvlei under water-full conditions towards the eroding face of the lunette. Notice the wind blowing across a full pan towards the lunette, serving an erosional rather than depositional role (SMG, October 2001).

Figure 7.2: Palaeoenvironmental interpretations of sediment characteristics at Droevlei East.

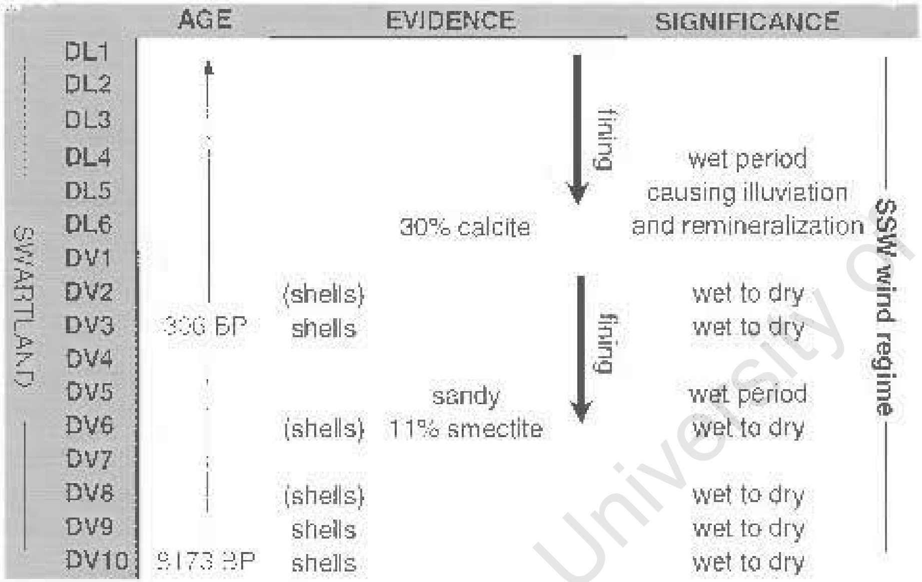


Figure 7.3: Palaeoenvironmental interpretations of sediment characteristics at Voelvlei.

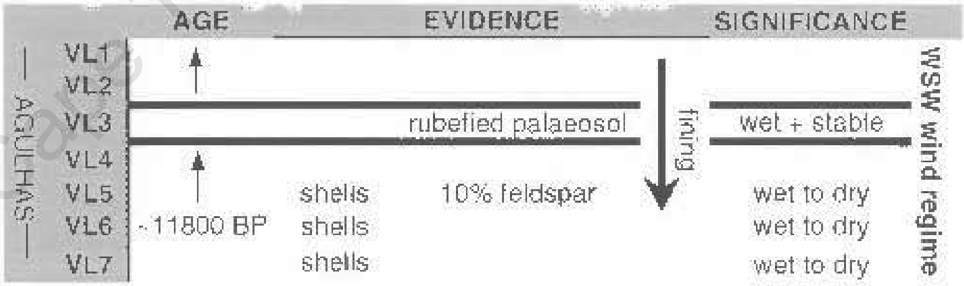
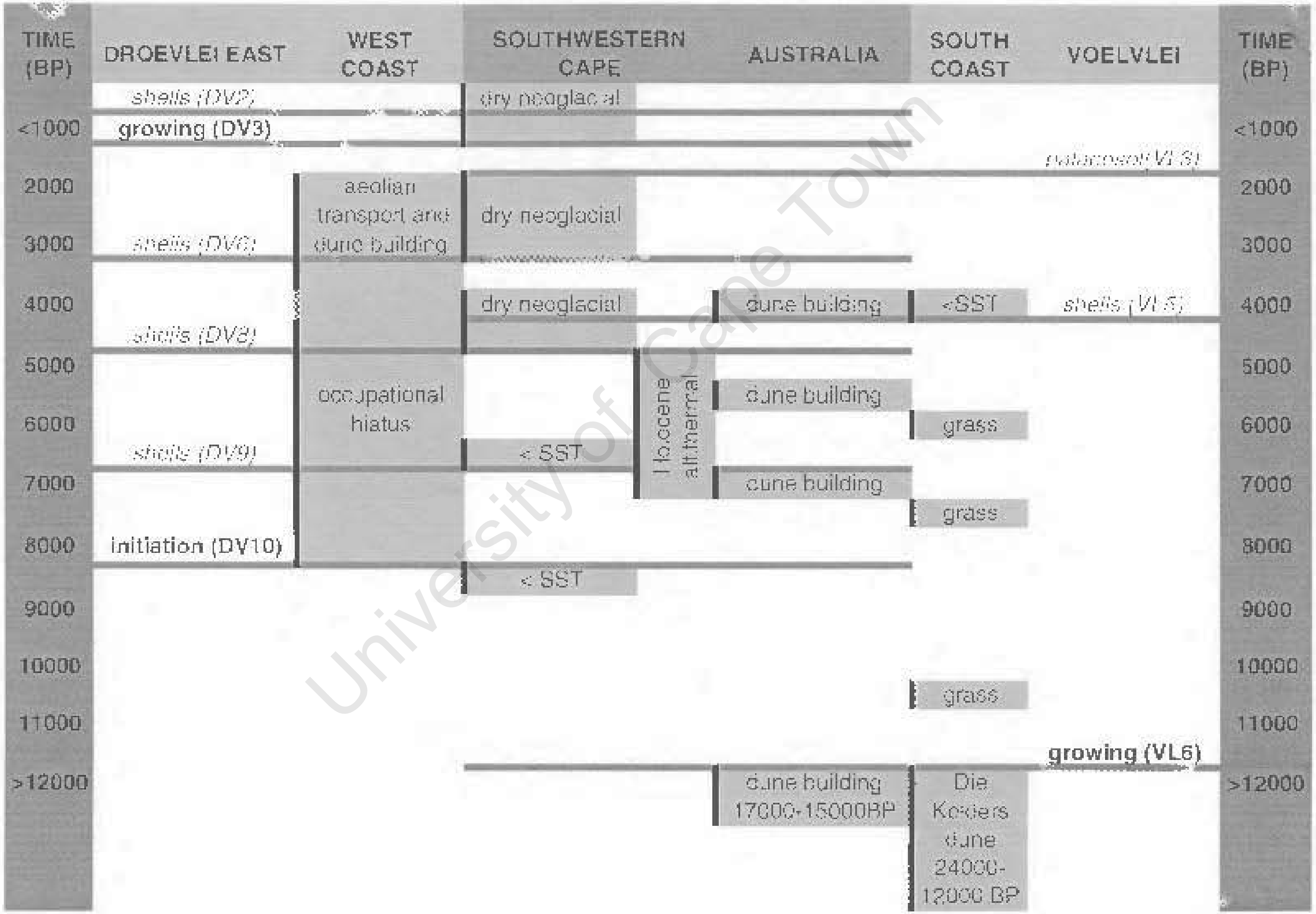


Figure 7.4: Potential correlations between sediment records in the pan-lunette clusters and palaeoenvironmental activity in the region and hemisphere: the product of rationalized interpolation and estimation. These records were drawn from the sources discussed in detail in Section 1.2.



7.4 CONCLUSIONS

7.4.1 CURRENT WORK

This thesis studied pan-lunette clusters in the Agulhas Plain and the Swartland on both a regional scale and a local scale in an attempt to elucidate their formational history and the palaeoenvironment that has fostered that formation. In Chapter One, four objectives for this work were introduced and have been resolved as follows.

The first objective was to determine the spatial distribution and morphology of pan-lunette features in the Swartland and Agulhas Plain. This goal was tackled as described in Chapter Four by composing maps, completing surveyed profiles of a series of dunes, and comparing morphological characteristics statistically. This work provided the basis for the subsequent research.

Secondly, an objective was to investigate the formational history of pans in the southwestern Cape. This objective was approached by building on the morphological work with sediment analyses in Chapter Five. The process, while not entirely settled, is discussed in section 7.1.2. The theoretical process of formation that was researched in the literature and discussed in Chapter Three was confirmed by the fieldwork and laboratory analyses at these sites. There is a further process of erosion observed at these sites, and not previously referred to in the literature

The next stated objective was to elucidate climatic conditions, specifically, that would impact the development of the features. Resolving this issue required background research reported in Chapters Two and Three to inform field observation and sediment analyses. The most successful component in this regard was the reconstruction of palaeowinds.

Finally, the research was used to establish environmental changes, both anthropogenic and climatic, documented by the formation of the pans and dunes. The lack of concise dating complicates the fourth objective. As discussed in the previous section, proxies that retain information about a change in conditions, not just a state, are the most useful for inferring palaeoenvironment. A multi-proxy study referring to a multi-proxy database of previous work, as used here, provides the basis for the most robust reconstruction possible.

7.4.2 FUTURE WORK

There is a considerable amount of work that could flesh out the initial framework established here. The two largest uncertainties lie in the chronology and the question of homogeneity between features.

By obtaining more quantified ages it should be possible to expound upon conclusions with more vigorous correlations to other events in the Quaternary record. The argument would be strongest by diversification of methods, using both luminescence and radiocarbon techniques. Most relevant to this study would be a revised chronology for the individual profiles analysed and discussed here. In order to understand the clusters on a regional scale and more successfully interpret the climate signal, more dates must be obtained on other regional records of aeolian activity.

The assumption of an individual representative feature has been counter-indicated by all sediment analyses. By excavating other features and interrogating the sediment there, it will be possible to confirm the formational process described here for a regional scale and enforce palaeoenvironmental conclusions. Analyses of a similar nature on other features in the clusters could only strengthen arguments initiated here.

Settling the question of the alleged double lunettes will assist to clarify both previous points. Without more detailed analyses on a number of these duplicate features it is impossible to make conclusions. A double lunette is potentially a record of distinct environmentally different dune-building periods.

Finally, further pursuit of the correlations between the records preserved in these landscape features and ocean-atmospheric models that register and predict the relationship between winds in these coastal regions and sea surface temperatures driven by major currents could establish climate trends of global importance. Based on the latitudinal position and oceanic nature of the southwestern Cape, the pan-lunette clusters on either coast in the Swartland and Agulhas Plain are tied into global scale palaeoenvironmental activity. This study establishes a foundation and indicates the presence of a diverse record of the palaeoenvironmental activity of the Holocene in the pan-lunette features of the southwestern Cape.

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Appendix A: Lab Procedures

COLOUR

The colour of soils was quantified using the Munsell Soil Colour Charts (Munsell Colour, 1994). In the Munsell system, the colours are described in terms of three dimensions that combine to describe all colours: Hue, Value, and Chroma. Hue describes the colour's relation to Red, Yellow, Green, and Purple. Value describes the lightness of a colour and Chroma, the strength. Using the Munsell system, Sample DL6 (10YR 7/2, Figure 5.1) with hue 10 Yellow-Red is closer to Red than Sample DL5 which exhibits (2.5Y 6/3) 2.5 Yellow. DL6 is 70% along the scale from black to light, lighter than the 6/ value of DL5. The Chroma value of /2 indicates a small, near neutral strength of colour. The Munsell system also provides an abbreviated verbal description. In the case of Sample DL6, "light grey".

GRAIN SIZE ANALYSIS PROCEDURE

1. preparation with dispersal agent

- Dry sample in oven @ 30°C.
- Sift each sample through a 2000μm sieve. Do not break peds much, though can use a mortar and pestle loosely on them before hand.
- Weigh out 50g accurately into a graduated cylinder.
- Add 100mL Calgon: (Akroyd 1957, Catt 1988, Lewis and McConchie 1994, Smith 2001)
    - 35.7g sodium hexametaphosphate,
    - 7.1g sodium carbonate
    - distilled water to 1L
    - makes a 3.85% solution
- Add 400 mL distilled water (50mL Calgon in 200mL distilled water can be used to fit in 250mL flask).
- Place on shaker overnight.

2. hydrometer readings

- Rinse sample into 1L graduated cylinder. Fill to 1L.
- Agitate with plunger. Measure 1,2,4,6,8 hour readings with hydrometer from top of miniscus.
- Refill cylinder to 1L if evaporation occurs.

3. wet sieving

- Rinse through 63μm sieve until water rinses out clear.
- If won't rinse through, let settle for 5 minutes until the sand falls out and then pour-off top and rinse again.
- Pour off some organics.
- Dry in oven @ 70°C.
- Weigh dry samples after 1 night in oven.

4. settling column

- Weigh out accurately 2.50 g (2.40 to 2.80, record) of rinsed, sieved sample (coarse fraction). Place in small glass vial.
- Using the settling column (John Rogers, Marine Geoscience, UCT) record the time of settling, and size fraction of the sample.

5. calculations

- Hydrometer calculations are based on Stokes' Law of settling:

$$\textbf{Particle size} = F \sqrt{\left(\frac{\textbf{effective depth}}{\textbf{Time}}\right)}$$

from Akroyd, 1957

where

F= a factor dependent upon temperature and specific gravity of soil particles (assumed quartz)
Effective depth= a distance determined from the calibration of the hydrometer and measuring cylinder used. Measured in cm
Time= measured experimentally and recorded in minutes
Particle size is determined in mm

- Sources of error:
  - Assumes round, quartz particles
  - Flocculation of clay particles indicates coarser grained population
  - Human error in reading hydrometer
  - Potentially damaged sieves
  - Representative sample?
    - 50g samples
    - Subsampling by 'thief scooping' (~5% standard deviation) (Gale and Hoare, 1991).

- Settling column calculations are also based on Stokes' Law, on the basis of an ideal settling velocity.

$$\textbf{Settling velocity}=([(d_s-d_f)g]/18\mu)d^2$$

From Lewis and McConchie, 1994

where

ds=density of solid (assumed to be quartz=2.65 g/cm^2)
df=density of fluid, temperature dependent
g= acceleration of gravity (980cm/sec^2)
μ= viscosity of fluid, temperature dependent
d=diameter in cm of an assumed sphere

- Sources of error
  - Assumes round, quartz particles
  - Problem of representative samples: small sizes + split accuracies
  - Flocculation of clay particles indicates coarser grained population
  - Representative sample?
    - 2.5g samples
    - Subsampling by 'coning and quartering' (~7% standard deviation, up to 3 order of magnitude greater than theoretical random variation (Gale and Hoare, 1991).

ORGANIC COMPONENT

The organic component was determined by loss on ignition.

- 2.00g dried (30°C oven) and sieved (2000μm seive) sample was weighed into a porcelain crucible.
- The sample was combusted overnight (at least 12 hrs) at roughly 550°C (increased heat has been shown to cause clays to lose water).
- Percent organics determined by mass lost during combustion.

Sources of error
  - Oven error- irregular temperatures
  - Irregular combustion lengths
  - Dehydration of clay minerals. Ideal times and heats are disputed (375°C for 16hrs, 430°C for 24hrs) (Gale and Hoare, 1991)

CARBONATE COMPONENT

The carbonate component was determined by hydrolysis. The rinsing with distilled water is necessary to prevent recrystallization of once-dissolved carbonates.

- 10g dried (30°C oven) and sieved (2000μm seive) sample was weighed into a flask
- Add 150mL 10% HCl
- Swirl flask and wash down sides with HCl. Continue adding HCl until reaction stops (no more CO_2 produced).
- Let sit for ~1 hr.
- Fill flask to neck with distilled water.
- Let settle until clay has fallen out of suspension (overnight).
- Pour off water and refill with distilled water.
- Let settle and pour off.
- Dry in oven at 30°C.
- Weigh
- Deflocculate with Calgon (as above)
- Seive through 63μm mesh.
- Dry in 30°C oven.
- Weigh coarse fraction.

Sources of error

- Incomplete hydrolysis
- Incomplete rinsing and recrystallization of carbonates
- Partial dissolution of magnesium and calcium silicate.

pH(H_2O) AND pH(KCl)

- Place 10g of dried, sieved soil (30°C oven, 2000μm seive) in centrifuge tube.
- Add 25mL distilled water (or KCl).
- Stir rapidly with a glass stirring rod for 5 seconds.
- Stir again after 50 minutes and let stand for 10 minutes
- Calibrated the pH meter using commercial standards at a noted temperature.
- Determine the pH after at least 30 seconds in the supernatant- try to wait for the reading to stabilize.
- EC is measured at the same time as pH(H_2O) with an EC meter.

Sources of error

- Premature readings- probe not yet stabilized

RADIOCARBON ANALYSES

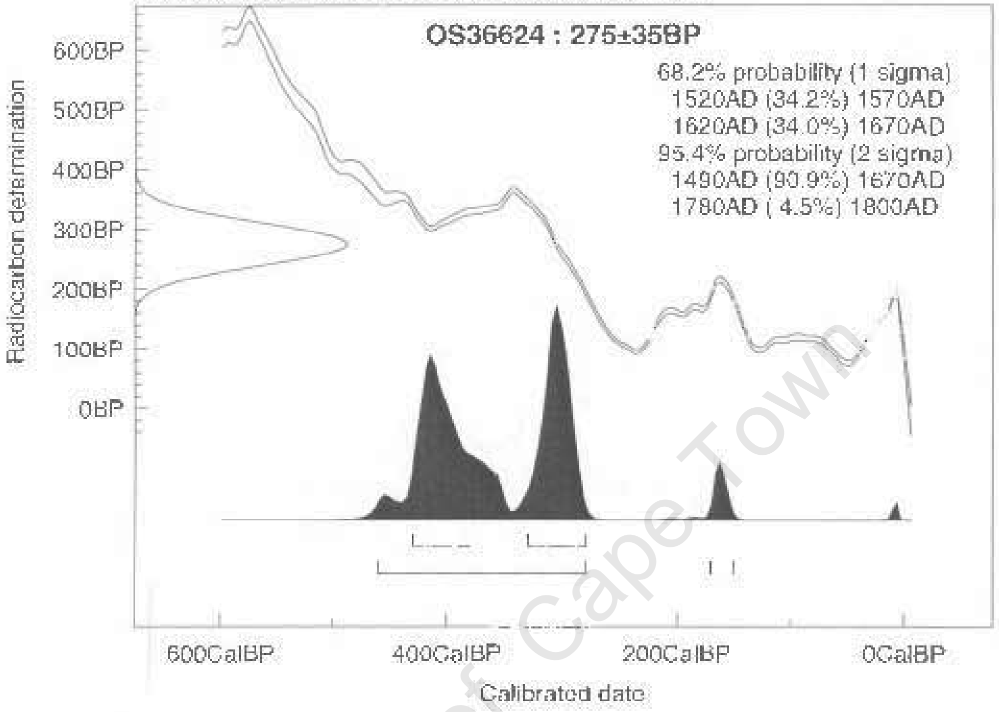
The radiocarbon analyses were performed at the National Ocean Sciences Accelerating Mass Spectrometer (NOSAMS) at the Woods Hole Oceanographic Institution (WHOI). Sample preparation was performed by the author, by sonnication in milli-Q water and oven-drying before weighing and hydrolysis.

X-RAY DIFFRACTION ANALYSES

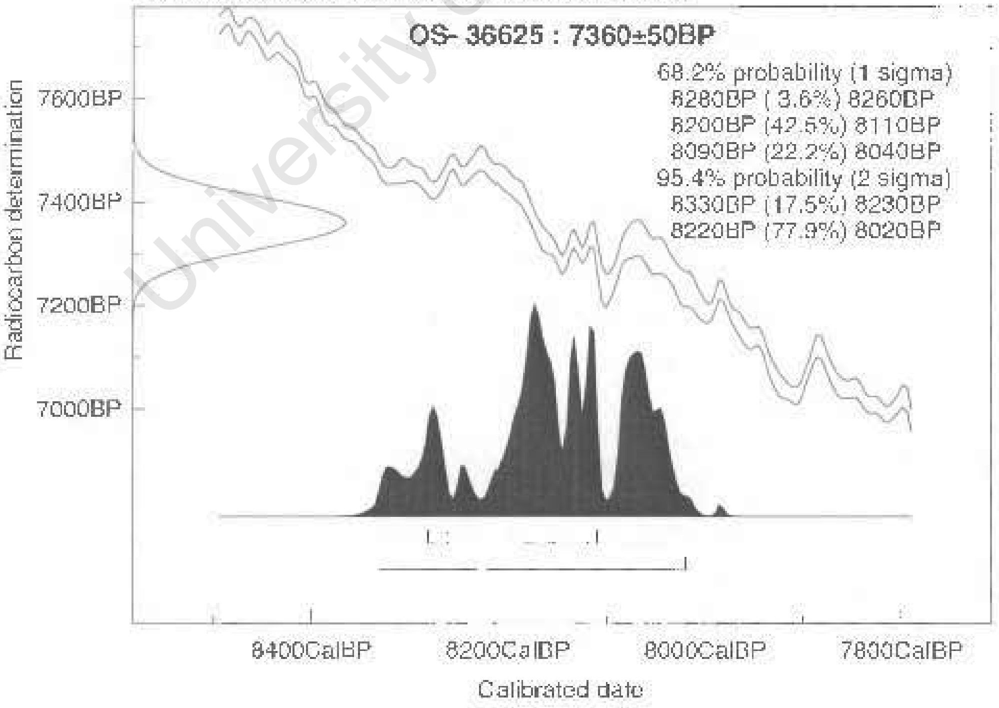
The XRD analyses were performed at the Institute for Soil, Climate and Water (ISCW) by Willem Kirsten on the < 2 micron fraction.

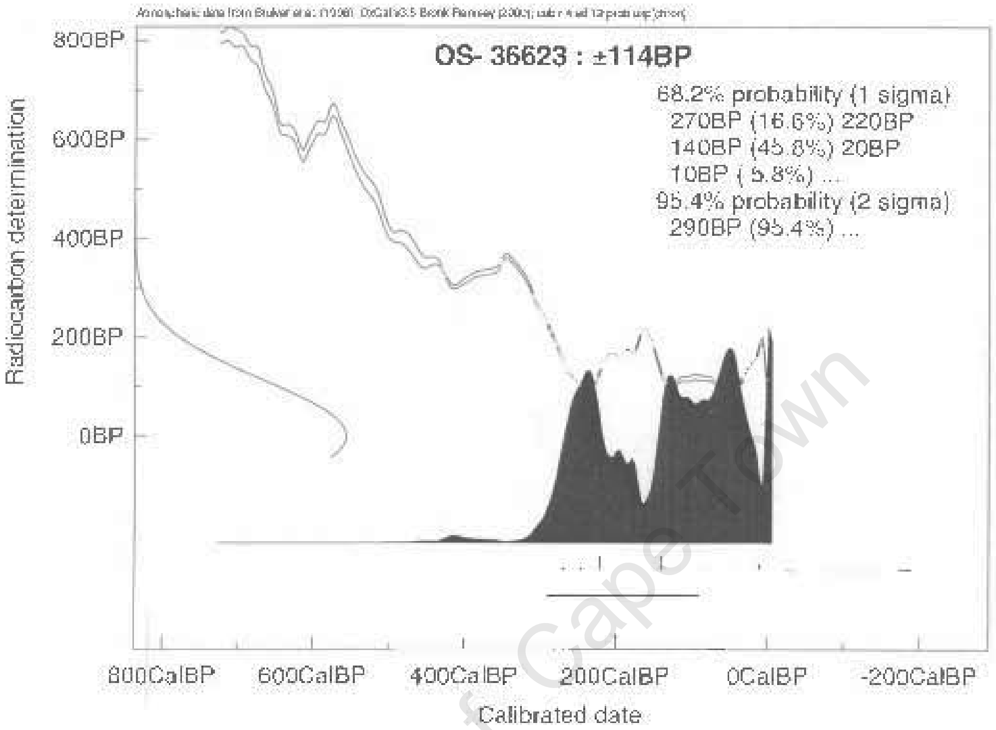
Appendix B: Radiocarbon calibration

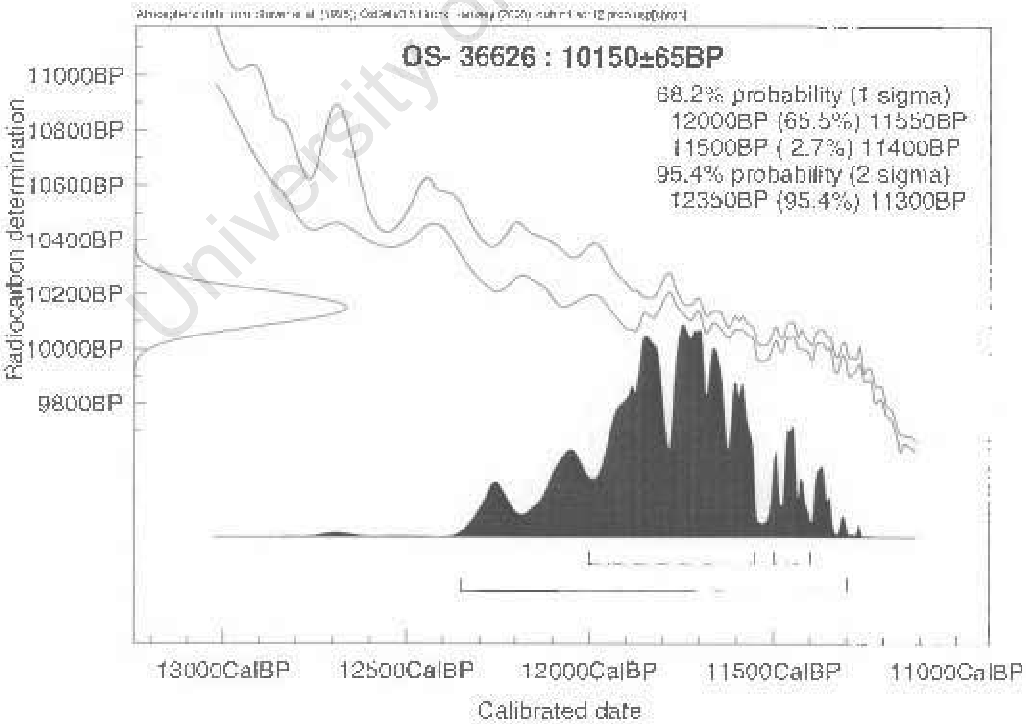
Atmospheric data from Stuiver et al. (1998); OxCal v3.5 Bronk Ramsey (2000); cub r:4 sd:12 prob usp[chron]



Atmospheric data from Stuiver et al. (1998); OxCal v3.5 Bronk Ramsey (2000); cub r:4 sd:12 prob usp[chron]




Atmospheric data from Stuiver et al. (1998); OxCal v3.5 Bronk Ramsey (2000); cub r:4 sd:12 prob usp[chron]
OS- 36623 : ±114BP
68.2% probability (1 sigma)
270BP (16.6%) 220BP
140BP (45.8%) 20BP
10BP (5.8%) ...
95.4% probability (2 sigma)
290BP (95.4%) ...
800BP
600BP
400BP
200BP
0BP
Radiocarbon determination
800CalBP
600CalBP
400CalBP
200CalBP
0CalBP
-200CalBP
Calibrated date


Atmospheric data from Stuiver et al. (1998); OxCal v3.5 Bronk Ramsey (2000); cub r:4 sd:12 prob usp[chron]
OS- 36626 : 10150±65BP
68.2% probability (1 sigma)
12000BP (65.5%) 11550BP
11500BP (2.7%) 11400BP
95.4% probability (2 sigma)
12350BP (95.4%) 11300BP
11000BP
10800BP
10600BP
10400BP
10200BP
10000BP
9800BP
Radiocarbon determination
13000CalBP
12500CalBP
12000CalBP
11500CalBP
11000CalBP
Calibrated date

Appendix C: Data

Contents:

- Textural data
- Chemical data
- XRD data
- Lunette orientation

Textural data for Droevlei East lunette based on the Udden-Wentworth grain scale.

	Sand/Fines		Fines as % of total		Sand fraction only				Statistical analysis of sand fraction		
Sample	**% Sand**	**% Fines**	**% Silt**	**% Clay**	**% coarse**	**% med**	**% fine**	**Sand Grade & description**	**Mean**	**Sorting**	**Skew**
DV shoreline	91.31	8.69	5.08	3.61	15.32	67.46	16.68	sand	1.53	0.53	-0.11
DL1	38.32	61.68	46.52	15.16	19.01	31.23	49.32	loam	1.87	0.94	-0.12
DL2	42.57	57.43	42.39	15.04	16.03	27.89	55.89	loam	2.05	0.98	-0.14
DL3	41.15	58.85	39.75	19.10	15.17	26.25	58.15	loam	2.07	0.98	-0.15
DL4	18.86	81.14	54.17	26.97	14.46	27.64	57.41	silty loam	2.06	0.95	-0.13
DL5	13.33	86.67	52.57	34.10	8.90	29.49	61.18	silty clay loam	2.20	0.86	-0.06
DL6	11.24	88.76	50.78	37.99	16.34	31.05	52.20	silty clay loam	1.95	0.96	-0.10
DV1	17.43	82.57	72.94	9.63	8.77	20.53	70.07	silty loam	2.38	0.92	-0.19
DV2	12.87	87.13	77.50	9.63	8.39	18.59	72.79	silty loam	2.48	0.93	-0.18
DV3	20.37	79.63	68.01	11.62	9.72	20.70	69.39	silty loam	2.34	0.93	-0.20
DV4	34.84	65.16	37.58	27.58	12.07	25.16	62.44	clay loam	2.17	0.93	-0.16
DV5	46.85	53.15	31.53	21.62	10.92	29.74	59.00	loam	2.17	0.86	-0.14
DV6	32.51	67.49	25.92	41.57	6.08	27.57	65.99	clay	2.23	0.76	-0.06
DV7	29.47	70.53	34.94	35.59	13.88	37.71	47.93	clay loam	1.77	0.73	-0.02
DV8	28.89	71.11	43.49	27.62	12.27	38.76	48.71	clay loam	1.92	0.79	-0.10
DV9	21.31	78.69	45.08	33.61	13.76	37.57	48.55	clay loam	1.88	0.79	-0.11
DV10	33.72	66.28	36.66	29.62	14.11	56.15	29.20	clay loam	1.66	0.63	0.03

Textural data for Voelvlei lunette based on the Udden-Wentworth grain scale.

	Sand/Fines		Fines as % of total		Sand fraction only				Statistical analysis of sand fraction		
Sample	**%Sand**	**%Fines**	**% Silt**	**% Clay**	**% coarse**	**% med**	**% fine**	**Sand Grade & description**	**Mean**	**Sorting**	**Skew**
VL1	62.87	37.13	21.40	15.73	0.85	4.30	94.37	sandy loam	3.10	0.56	-0.23
VL2	74.46	25.54	13.78	11.76	1.73	9.13	88.83	sandy loam	3.01	0.68	-0.37
VL3	37.06	62.94	13.18	49.76	0.38	6.82	92.65	clay	3.01	0.60	-0.22
VL4	35.80	64.20	20.44	43.76	0.86	6.25	92.28	clay	2.95	0.60	-0.09
VL5	26.78	73.22	21.46	51.76	0.82	6.92	91.36	clay	2.89	0.62	-0.11
VL6	28.12	71.88	18.12	53.76	0.71	4.37	93.14	clay	3.04	0.59	-0.18
VL7	42.10	57.90	28.14	29.76	0.63	3.77	94.66	clay loam	3.16	0.52	-0.27
VS1	74.24	25.76	14.00	11.76	0.65	8.92	88.99	sandy loam	2.86	0.63	-0.19
VS2	42.78	57.22	23.46	33.76	0.77	2.18	95.25	clay loam	3.20	0.51	-0.24

Chemical data for Droevlei East

sample	depth (m)	pH (water)	pH (KCl)	colloid charge	Conduct (uS/m)	% organic	% carbonate	munsell color	Gastropods
DV shoreline	0.0	9.25	8.25	-1.00	436	2.44	1.48	mottled	
DL1	0.2	8.37	7.51	-0.86	368	13.79	6.80	2.5Y 5/2	
DL2	0.3	8.74	7.59	-1.15	377	16.27	17.53	2.5Y 5/3	
DL3	0.6	9.68	8.07	-1.61	544	16.92	20.30	2.5Y 6/2	
DL4	0.9	9.14	8.45	-0.69	1156	16.02	18.71	2.5Y 7/3	
DL5	1.2	9.91	8.30	-1.61	2680	15.17	16.83	2.5Y 6/3	
DL6	1.5	9.20	8.46	-0.74	2500	18.81	24.78	10YR 7/2	
DV1	2.2	8.39	7.96	-0.43	519	17.41	10.06	10YR 5/2	
DV2	2.3	8.87	7.88	-0.99	316	16.50	12.45	10YR 6/2	shells
DV3	2.5	8.98	7.89	-1.09	367	13.30	12.67	2.5Y 6/2	shells +
DV4	2.8	9.49	8.00	-1.49	630	18.05	19.74	2.5Y 6/2	
DV5	3.1	9.50	7.94	-1.56	973	17.73	15.85	2.5Y 6/2	
DV6	3.4	9.53	8.25	-1.28	1161	19.23	18.20	2.5Y 6/2	shells
DV7	3.7	9.27	8.25	-1.02	951	16.59	16.15	2.5Y 6/2	
DV8	4.0	9.58	8.19	-1.39	933	19.51	18.04	2.5Y 6/2	shells
DV9	4.3	9.52	8.24	-1.28	1009	16.75	19.90	2.5Y 6/3	shells +
DV10	4.5	8.97	8.25	-0.72	3460	14.22	16.15	2.5Y 6/2	shells +

Chemical data for Voelvlei

sample	depth (m)	pH (water)	pH (KCl)	colloid charge	Conduct (uS/m)	% organic	% carbonate	munsell color	Gastropods
VL1	0.06	7.65	6.78	-0.87	231	4.95	16.73	10YR 5/3	
VL2	0.24	7.63	7.59	-0.04	143	1.50	22.88	10YR 7/3	
VL3	0.63	7.56	7.69	0.13	4930	9.50	23.3	10YR 4/4	
VL4	1.05	7.83	7.96	0.13	5140	10.95	53.34	2.5Y 6/3	
VL5	1.26	8.15	7.74	-0.41	6740	10.45	59.74	2.5Y 7/2	shells
VL6	1.53	8.33	7.70	-0.63	7480	8.96	47.7	2.5Y 6/2	shells
VL7	1.88	8.64	7.70	-0.94	1584	4.48	35.86	2.5Y 6/2	shells+
VS1	0.2	6.74	4.84	-1.90	184	2.49	18.99	2.5Y 6/2	
VS2	0.6	7.87	6.47	-1.40	806	4.50	20.64	2.5Y 5/2	

XRD results:

REPORT NUMBER: CHEM200203 1597

Interstratified = smectite/mica interstratification
Only the <2micron fractions were used to do the analyses.

	% Kaolinite	% Mica	% Interstratified	% Quartz	% Feldspar	% Calcite	% Smectite
VL3	20	66	7	7	0	0	0
VL4	22	74	0	4	0	0	0
VL6	16	51	9	13	11	0	0
DL4	32	53	15	0	0	0	0
DL5	56	31	13	0	0	0	0
DL6	40	21	12	0	0	27	0
DV4	77	23	0	0	0	0	0
DV5	62	21	9	8	0	0	0
DV6	65	14	0	0	0	0	21
DV7	51	36	13	0	0	0	0
DV8	68	24	8	0	0	0	0

Swartland
lunette orientation

pan	angle connecting horns	lunette orientation
Slangkop	280	010
Droevlei	270	000
Droevlei E	273	003
Swartwater	271	001
Burgerspan S	277	007
Burgerspan N	281	011
Rooipan S	278	008
Rooipan N	264	354

Agulhas lunette
orientation

pan	angle connecting horns	lunette orientation
Langepan	004	094
Voelvlei east	009	099
Soutpan	007	097
Voelvlei	001	091
Soetendalsvlei	355	085
Renosterpan	005	095