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SAND RAMPS OR CLIMBING DUNES? IDENTIFICATION AND PALAEOENVIRONMENTAL SIGNIFICANCE OF AEOLIAN DEPOSITS IN THE SOUTHERN KALAHARI AND BREEDE RIVER VALLEY, SOUTH AFRICA.

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ABSTRACT

Sand ramps or climbing dunes? Identification and palaeoenvironmental significance of aeolian deposits in the southern Kalahari and Breede River Valley, South Africa.

The study is primarily concerned with the identification of topographical dunes and their classification as either sand ramps or climbing dunes. Topographical dunes in two semi-arid regions, namely the southern Kalahari (a summer rainfall region) and the Breede River Valley (a winter rainfall region), were investigated. The study also evaluates the palaeoenvironmental significance of the topographical dunes and attempts a palaeoenvironmental reconstruction within the study regions. The two different rainfall regimes faciliated regional comparisons with respect to environmental change, most particularly during the Quaternary.

The methodology comprises a review of current literature on topographical dunes, an examination of aerial photography to identify topographical dunes in South Africa and field work to ground truth the dunes. Field sampling, laboratory work (granular composition analysis, pH, conductivity and scanning electron microscopy) as well as statistical analyses (principal component and cluster analyses) were employed to assist in the palaeoenvironmental reconstruction.

The results of the laboratory and statistical analyses do not reveal any obvious differences with respect to structure, particle size, pH, conductivity, chemical composition and the surface texture of the grains between the different topographical dunes. The dunes comprise homogeneous quartz sand that was emplaced against topographical barriers as a result of aeolian processes. They are therefore classified as climbing dunes rather than sand ramps.

Three optically stimulated luminescence dates were determined for a topographical dune from each study region. Samples from the Prynnsberg 2 dune in the southern Kalahari are dated to 100 years, and it is suggested that this is due to current reworking of the Kalahari sands from the extensive linear dune field and from the Orange River. It is proposed that the southern Kalahari topographical dunes are currently episodically active. From the Sandput dune in the Breede River Valley, three probable humid phases are identified: 762 kyr, 28.2 kyr and 9.9 kyr. These humid periods may be coupled with episodes of cooling, which supports results from previous studies. This finding has important implications for future climatic changes in the winter rainfall region of South Africa, implying that warming in the Western Cape may be associated with a decrease in precipitation. Lastly, a short historic overview of aerial photographs shows that topographical dunes are susceptible to human impacts in the form of agriculture, overgrazing, sand quarrying and through the construction of dams and weirs on rivers.

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CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

The reconstruction of Quaternary geomorphic environments is based on the concept that changes in climatic variables, such as wind régimes, temperature and precipitation, have implications for the development of landforms. On this basis, an understanding of the functioning of present day climatic variables and their influence on aeolian landforms can facilitate the use of a relict aeolian landform to infer the climatic conditions that prevailed in the past. Climate influences process, which in turn influences landforms and it is through this relationship that one can reconstruct past climatic conditions (Meadows, 1988). Palaeoenvironmental interpretations are dependent on appropriate identification of the landforms in question, as well as an indication that the landforms are indeed relict (Thomas, 1997); in other words, that they are not products of current geomorphic processes. Once the relict landforms have been identified, they should be compared to analyses of equivalent active modern analogues (Thomas, 1997). Morphological and sedimentary evidence has suggested that the world's deserts have experienced significant episodic expansions and contractions during the Quaternary in response to major tectonic and climatic changes (Thomas, 1997). To date, most of the evidence for Quaternary environmental change in arid areas has come from landforms such as sand seas (Thomas, 1997), palaeolake shorelines (Thomas, 1997; Thomas and Shaw, 1991b), and dry valleys (Nash *et al.*, 1994). Recently, however, it has been realised that other spatially-discontinuous landforms may also be of great value in reconstructing palaeoenviroments. In areas that have a history of aridity, but are not conducive to the formation of sand seas, sand transport pathways and sand ramps, as well as climbing and falling dunes (i.e. topographical dunes - Zimbelman *et al.*, 1995, Lancaster and Tchakerian, 1996; Thomas *et al.*, 1997a) may provide evidence for climatic change.

In this chapter sand ramps and climbing dunes are defined, and their potential use, as well as their limitations as palaeoenvironmental indicators are examined. Secondly, previous research on climbing dunes and sand ramps is presented. Finally, a working hypothesis and the specific aims and objectives of this study are described.

1.2 DEFINITIONS OF SAND RAMPS, CLIMBING AND FALLING DUNES

Aeolian sand deposits (excluding coastal dune systems) cover approximately 5% of the earth's land surfaces and have long attracted the attention of geographers (Thomas, 1997). Many different types of aeolian land forms exist, and these have been described in detail by previous researchers (e.g refer to Bagnold, 1941; Cook and Warren, 1993; Livingstone and Warren, 1996, Pye and Tsoar, 1990; Pye, 1993; and Thomas, 1997). It is not within the scope of this dissertation to discuss these different types of aeolian landforms, although the different types of sand dunes are briefly mentioned.

In order to fully understand the differences between aeolian landforms, how they have formed and how they interact with each other presently and in the past, it is necessary to define differences between them. A sand dune is defined merely as a hill or ridge of sand that has been piled up by the wind (Pye and Tsoar, 1990). Although numerous types of sand dunes exist, Pye and Tsoar (1990) grouped them into three categories:

- Sand dunes whose deveopment is strongly related to the presence of vegetation (e.g vegetated linear dunes, hummock dunes and parabolic dunes)
- Self accumulated dunes (e.g. transverse dunes, unvegetated linear dunes, barchans and star dunes)
- Sand dunes whose development is related to topographical barriers (e.g. climbing and falling dunes, sand ramps and echo dunes).

This dissertation is primarily concerned with climbing dunes and sand ramps, so that only these two dunes types are discussed here.

1.2.1 Sand ramps

Sand ramps are formed by the accumulation of migrating sand on the upwind side of topographic barriers where aeolian sand transport paths cross undulating terrain (Thomas, 1997). They occur in areas where sand through-flow exceeds sand accumulation until a topographic barrier obstructs the flow of sand (Thomas, 1997). These barriers have been recognised as a nucleus for sand dune development, and a key to the identification of sand ramps is that they are found on the windward side of the topographic barrier responsible for their formation. Some ramps, however, may be so large that they surmount the obstacle (Zimbelman, *et al.*, 1995). This occurs by means of saltating sand moving up the windward slope of the ramp until it spills over the barrier and begins to form a falling sand ramp on the lee side. Sand ramps generally have gradual gradients and are an amalgamation of aeolian sands, talus material, fluvial and colluvial sediments, as well as palaeosols which were formed during geomorphically stable periods (Lancaster and Tchakerian, 1996). They are potential a major source of palaeoenvironmental information and may be useful indicators of the response of aeolian processes to climatic oscillations during the Quaternary.

1.2.2 Climbing dunes

Climbing dunes, like sand ramps, are also formed by the migration of sand until it accumulates against the windward side of a topographic barrier (Tsoar, 1983). In order for climbing dunes to form there should be an abundant supply of sand coupled with a unidirectional wind and a topographical barrier which would obstruct the flow of migrating sand (Evans, 1962). As the formation and morphology of climbing dunes and sand ramps are so similar (i.e. migrating sand which comes to a halt when a topographical barrier interrupts the migration path) there is the potential for confusion of the two landforms and hence the need to define them. There are two main distinguishing factors, however, from which they can be defined. Firstly, climbing dunes are far more mobile forms than sand ramps and thus migration across the topographical barrier and the formation of falling dunes does occur in some circumstances (Thomas, 1997). Secondly, climbing dunes consist entirely of aeolian material, while sand ramps consist mainly of aeolian material interspersed with colluvial, alluvial, fluvial and palaeosol units (Thomas *et al.*, 1997a). This second difference has important implications for using climbing dunes to reconstruct palaeoenvironments as the homogeneity of the dune material does not indicate the response of aeolian processes to climatic oscillations during the Quaternary.

1.3 THE POTENTIAL USE OF TOPOGRAPHICAL DUNES AS PALAEOENVIRONMENTAL INDICATORS

The reconstruction of Quaternary climates using landforms is based on the premise that geomorphologists understand the processes responsible for the formation of specific landforms. Thus, when using sand ramps and climbing dunes to decipher oscillations in climate during the Quaternary, it is important to understand how they form. In the previous section it was stated that both sand ramps and climbing dunes form through the transportation of saltating sand grains by the wind until this wind energy is dissipated once it hits the topographical barrier. The sand is then deposited and accumulates until a sand ramp or climbing dunes is formed. Unidirectional winds are also important for their formation. The intricacies, however, of the formation of the two land forms, and how they respond to changes in aridity, wind, sediment supply and temperature is not known and not documented due to the lack of research on these landforms. It is hoped that this dissertation may shed some light on the differing processes of formation and how they interacted with climatic change in the past.

Wind and precipitation levels are the two most important factors in determining sand movement and deposition (Thomas, 1997). Relict sand dunes can therefore be used to reconstruct palaeocirculation patterns as well as to define the past and present extent of aridity in an area (Lancaster, 1981). Sand ramps and climbing dunes are especially useful in determining palaeowind directions, since the sand accumulates on the windward side of the barrier, and only sometimes creeps over to the leeward side. In addition, precipitation levels influence vegetation cover (i.e. an increase in precipitation leads to an increase in vegetation cover), and thus climbing dunes are also indicative of fluctuations in precipitation (Thomas, 1997). Where palaeosols are evident in the sand ramp sequence, and where sand accumulation decreases, increases in precipitation levels can be inferred. Temperature can also affect the aridity of an area, as it affects evapotranspiration rates which are important for soil moisture and density of vegetation cover (Thomas and Shaw, 1991a). Changes in temperature, however, are difficult to detect through the analysis of sterile dune sediments. Thus in order to determine temperature oscillations, other types of fossilised evidence such as the pollen found in the palaeosols of sand ramps should be used (Summerfield, 1991).

From a palaeoenvironmental perspective, one of the most valuable aspects of sand ramps is that the multiple accumulations of sand, interspersed with periods of soil formation, provides an indication of climatic oscillations. During dry phases, sand migrates along sand transport pathways and accumulates against topographical barriers (Tchakerian, 1997). When there is an increase in precipitation and therefore a corresponding increase in vegetation in the area (Thomas and Shaw, 1991a), sand accumulation is minimised, and soil formation takes place. At a coarse scale, therefore, sand ramps may reflect changes in precipitation. By examining the soil horizons present, the cyclicity of sand transport along these pathways can be determined (Zimbelman *et al.*, 1995). In addition, pollen may be found within the palaeosol stratigraphy, and thus pollen analysis on the sand ramps may be possible in order to further indicate the type of climate experienced in the region at the time of soil formation. Furthermore, the material within sand ramps can be dated using luminescence dating of quartz and feldspar rich sediments, or radiocarbon dating of organic sediments, thereby obtaining a well resolved chronological sequence of the sand ramp.

Evidence of Quaternary environmental change in arid areas can also be derived from the sedimentological analysis of topographical dunes. In the rocky areas of topographic barriers above these dunes there is the possibility that colluvial material may be eroded and then deposited on top of the climbing dune or sand ramp. The elucidation of a different type of environment will therefore become apparent through this sequence of deposited colluvial material.

1.4 LIMITATIONS

Despite their great potential, sand ramps and climbing dunes have limitations as palaeoenvironmental indicators. A major limitation of using topographical dunes to reconstruct climate change is that the transportation and deposition of sand may occur under a variety of arid and semi-arid conditions, and thus the degree of aridity of the landscape is often uncertain (Thomas, 1997). Furthermore, the conditions necessary for the formation of topographical dunes may form as a result of an increase in windiness, rather than merely a decrease in precipitation levels (Thomas, 1997). Research has previously highlighted one of the fundamental problems with reconstructing arid environments is that of dating (Lancaster, 1981). In dryland areas, sediments are often devoid of organic material and can therefore not be dated using radiocarbon dating (Tchakerian, 1994). With current refinements in the technique of thermoluminescence, and more recently optically stimulated and infra-red luminescence dating, detailed chronologies of dryland regions are now beginning to emerge (Shaw and Thomas, 1996).

1.5 PREVIOUS RESEARCH

In order to understand fully the implications of using topographical dunes (i.e. sand ramps and climbing dunes) for palaeoenvironmental interpretation, the factors controlling aeolian transportation along these sand transport pathways and those factors controlling deposition should be determined, thereby establishing a modern analogue. The major controls on deposition and formation of topographical dunes are wind direction and strength, available sediment supply, precipitation and, therefore, vegetation cover (Thomas, 1997). Sand ramps and climbing dunes are found in arid (50 mm of rainfall per year) to semi-arid (~150 - 350 mm of rainfall per year) climates. The slope of these ramps varies between 3° and 31°, although those sand ramps with slopes >25° are classed as falling ramps (Lancaster and Tchakerian, 1997). In the Ardakan Desert in Iran, slopes were found to be between 5° and 10° (Thomas *et al.*, 1997a). Climbing dunes, however, are found to be much steeper, with the sand lying close to its angle of repose (Thomas *et al.*, 1997a). Surfaces of sand ramps are often undulating, covered in talus material and vegetation, and can be deeply incised by rivers (Lancaster and Tchakerian, 1997). Climbing dunes, on the other hand, although often partially-vegetated, tend not to be covered by talus material due to their steep slopes. Both sand ramps and climbing dunes occur mainly on the windward side of topographical barriers, and spatial patterns are dependent on the availability of sand in the region (Lancaster and Tchakerian, 1997). Mobility of the sand is dependent on the amount of vegetation cover in the area, but is also directly related to wind velocity (Lancaster, 1987). According to Lancaster (1987), 4.5 ms^{-1} is the threshold wind velocity for sand movement in the southern Kalahari. This dissertation is not concerned with the details of the effects of the above mentioned factors on topographical dune formation. Suffice to say, further research is necessary in order to establish how these controls interact with each other to influence the formation of sand ramps and climbing dunes.

To date, very little research on topographical dunes has been undertaken, hence the need to study them (Thomas, pers. comm.). This dissertation is pioneering in its research on topographical dunes in South Africa, as no dryland topographical dunes have, as far as can be ascertained, been studied in South Africa. After this study commenced, it was realised that a sand deposit (the Klipkraal sand deposit), researched by Marker and Holmes (1993), in the Great Karoo can be classified as a topographical dune. The sand deposit was textually relatively homogeneous medium to fine grained loamy to pure sand. They concluded that the aeolian sands were emplaced as a result of aeolian activity at 20.5 ± 1.0 kyr and that a footslope fan which they identified comprises colluvial material and was reworked from the Klipkraal sand deposit (which it overlies). Marker and Holmes (1993) suggest that this deposit is a remnant of a more extensive aeolian deposit, deriving its sand from the north. It is likely that this deposit may relate to the southern Kalahari dunes and thus it is discussed in greater detail in Chapter 6.

Tchakerian (1991) was one of the first people to study sand ramps in the United states and he used geomorphic, sedimentological and scanning electron microscopy techniques to analyse the aeolian deposits. His analysis showed that the aeolian deposits accumulated in response to the availability of fine sediments and strong, persistent winds. This study was followed by a study by Rendell (*et al.*, 1996), who specifically examined the Dale Lake sand ramp and Cronese Mountains in the Mojave Desert. They used Luminescence (thermoluminesence and feldspar infra-red) dating to try and determine a chronology of landforms. Rendell *et al.* (1996) and found that there were two periods of aeolian deposition between >35 ka to 25 ka, and 15 to 10 ka. With respect to the Dale Lake sand ramp they found a long record of episodic aeolian accumulation interspersed with talus layers. Rendell and Shaffer (1996) further expanded the use of luminescence dating to date nine main sand ramps found in the Mojave Desert. Tchakerian and Lancaster (1996), on the other hand, studied the Mojave sand ramps in order to analyse their geomorphology and sediments. They found that most of the sand ramps are relict features that provide a great deal of information regarding the extent and duration of past episodes of stabilisation and aeolian activity in the Mojave Desert. The morphology of the sand ramps that they researched was described in the previous paragraph, however, they emphasise the importance of these landforms as the differing layers of talus, colluvial, palaeosols, and aeolian material can be linked to differing oscillations in climatic processes. They found that periods of geomorphic stability are represented by talus and palaeosol accumulations, while periods of geomorphic activity are represented by aeolian layers. Sand ramps could therefore provide a good record of climatic change in the past and it was anticipated that the southern Kalahari and Breede River Valley sand ramps would also have multi-depositional layers which are indicative of climatic change.

Zimbelman *et al.* (1995) also studied the Mojave sand ramps using remote sensing and field evidence in order to try to determine the sand transport paths which eventually form sand ramps. They found that sand transport along the paths was episodic, interspersed by several palaeosols, present in several dissected sand ramps.

Apart from the Mojave sand ramps, this author knows of only one other sand ramp which has been studied. Thomas *et al.* (1997a) researched a sand ramp in the Ardakan Playa in central Iran. Contrary to the Mojave sand ramps, they found that the talus and incipient palaeosol layers interspersed between the aeolian depositional layers did not represent changes of the climatic regime and geomorphological processes during development. Perhaps they were rather a result of the restricted sand supply within the area. Optical dating of the Ardakan sand ramps shows the accumulation of aeolian and talus material at the last glacial maximum until about 5 ka years ago when the climate in Iran was strongly influenced by the Siberian High Pressure.

Studies on climbing and falling dunes have been undertaken in numerous parts of the arid world. Howard (1985) and Haney and Grolier (1991) (in Lancaster and Tchakerian, 1996) have undertaken studies on climbing dunes in Peru, while Clos-Arceduc (1967) and Mainguet *et al.* (1983) (in Lancaster and Tchakerian, 1996) have studied them in the Sahara. Tsoar (1983), who studied climbing dunes in the Negev Desert, found that sand accumulates in from of topographical barriers as a result of the deceleration of the wind and subsequent deposition. He describes climbing dunes as "*featureless dunes that climb gentle slopes*" (Tsoar, 1983: p248) and uses wind tunnel models in order to gain a greater understanding of the formation of climbing dunes. He (Tsoar, 1983) found that when a topographical barrier is inclined, the size of the reverse-flow eddy decreases. In addition, when slopes are greater than 55 degrees, then the small reverse-flow eddies have no effect on the sand. The sand therefore tends to accumulate at the base of the slope, and climb up it, thus forming a climbing dune (Tsoar, 1983). Tchakerian (1991), who studied sand ramps in the Mojave, also studied climbing dunes in the United States and built on the work by Evans (1962). He (Tchakerian, 1991) found that the technique of SEM plays a significant role in determining the post-depositional modification of aeolian sediments thus allowing palaeoenvironmental reconstruction during and after deposition. Such an analysis would then form the basis for the relative dating of aeolian sediments.

Most of the studies which relate to climbing dunes focus on coastal climbing dunes, their formation and mechanics of sand transport and deposition. Marsh and Marsh (1987) investigated the role of wind erosion in the Great Lakes region where climbing dunes have been formed against high bluffs. Hellström and Lubke (1993) investigated a climbing dune on the Robberg Peninsula in South Africa and they found that a strong unidirectional wind, as well as a continual sand source was vital for an active climbing dune. They show that the encroachment of alien vegetation onto the peninsula and dune area has led to the stabilisation of the dune and has caused the climbing dune system to stop functioning. The study highlights the importance of vegetation in stabilising dunes and the importance of a continual sand source to ensure the activity of a climbing dune system.

1.6 THE SOUTHERN KALAHARI AND BREEDE RIVER VALLEY: SAND RAMPS OR CLIMBING DUNES?

This research is concerned with the identification of aeolian depositional features in South Africa, and the evaluation of these landforms as indicators of environmental change. Two study areas in South Africa which display semi-arid climatic characteristics have been selected. These topographically controlled aeolian depositional landforms were selected according to their location in the summer and winter rainfall regions of South Africa. At present, most southern African investigations into the palaeoenvironmental potential of aeolian deposits has occurred within the summer rainfall zone (Holmes, 1998), and thus the Breede River Valley topographical dunes may help to elucidate environmental changes in a winter rainfall region. In addition, the sites are invaluable as they may provide insight into the palaeoenvironmental summer rainfall versus winter rainfall "synchronous" controversy in South Africa.

This "synchronous" controversy surrounds the differing responses of the summer and winter rainfall regions to changes in general atmospheric circulation during the Quaternary in southern Africa. Although it was initially thought that cooling in South Africa was coupled with a decrease in precipitation (Adams, 1997), it has since been realised that the summer and winter rainfall regions may have responded in a dichotomous manner to periods of cooling and warming (Baxter, 1996). Baxter (1996) provides a concise summary of the discordant interpretations of the winter rainfall region at the last glacial maximum (LGM) by Deacon *et al.* (1983); Deacon and Lancaster (1988); and Partridge (1990) (in Baxter, 1996) and found that the summer and winter rainfall regions have not responded synchronously to changes in global circulation which lead to periods of cooling or warming. The present study will be compared to Baxter's (1996) research (this is described in more detail in Chapter 6), as well as to other studies which investigate this debate (e.g. Cockroft *et al.*, 1987; and Cohen and Tyson, 1995).

The southern Kalahari, the first study area, comprises four topographically controlled dunes near Upington, on the border of the Kalahari Dune Desert (Fig. 1.1). Two dunes are found at Kanoneiland and two at Prynnsberg. The second study area comprises three topographical dunes in the Breede River Valley region near Robertson in the southwestern Cape (Fig. 1.2), *viz.* Sandput, Sandberg and Moddergat.

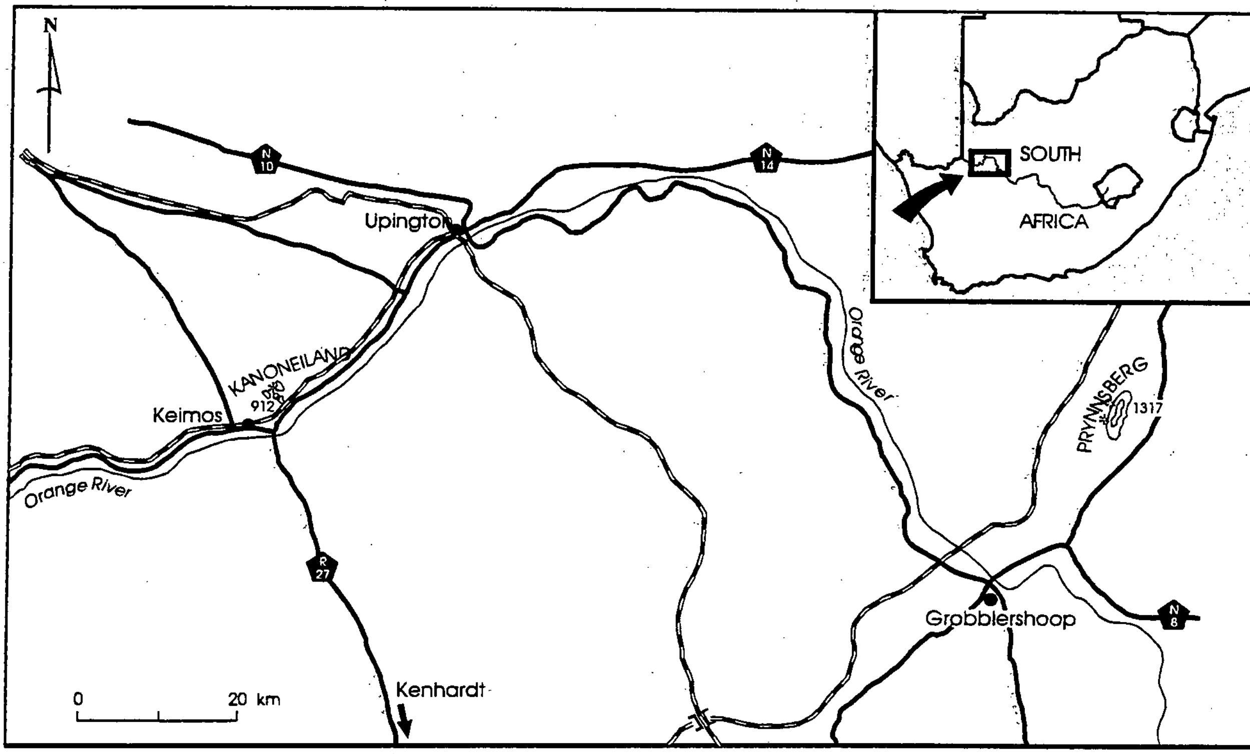


Figure 1.1 The locality of the southern Kalahari topographical dunes, Northern Cape, South Africa.

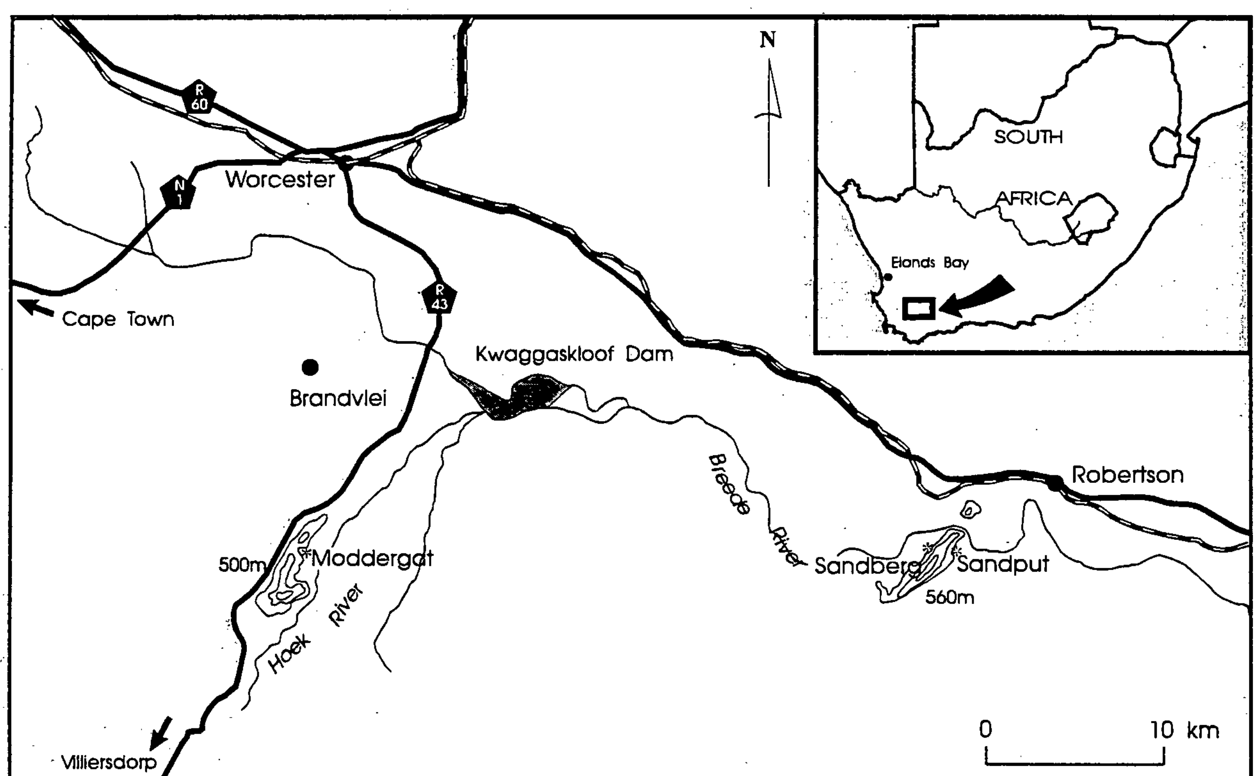


Figure 1.2 The locality of the Breede River Valley topographical dunes, Southwestern Cape, South Africa.

1.7 AIMS, OBJECTIVES AND HYPOTHESIS

The purpose of this study was to identify topographical dunes in the southern Kalahari and the Breedě River Valley, as well as to study these dunes in terms of their morphology and sedimentological characteristics. The main aim of this research was therefore to identify topographical dunes in South Africa and to classify them as either climbing dunes or sand ramps. A secondary aim was to evaluate their potential as indicators of palaeoenvironmental change. It was decided to study these dunes in South Africa as no previous studies on sand ramps or inland climbing dunes have been conducted in South Africa prior to this study. In addition, sites in two differing semi-arid regions were chosen in order to aid comparison of the dunes. The southern Kalahari topographical dunes are found within the summer rainfall semi-arid area, while the Breede River Valley topographical dunes are found within the rain shadow of the Cape Fold Mountains in the winter rainfall region in South Africa. It is also hoped that this dissertation will help to resolve the current winter versus summer rainfall synchronous debate (outlined in Section 1.6) surrounding the response of these differing regions to changes in climatic processes in southern Africa at the last glacial maximum. There are five specific objectives that have been pursued in order to achieve these aims:

1. To identify, initially with the use of aerial photographs and then by ground truthing, topographical dunes in two geographically discrete semi-arid regions of South Africa.

2. To examine the morphology and lithostratigraphy of these dunes in order to ascertain whether they are sand ramps or climbing dunes.

3. To evaluate and discuss the potential of using these landforms to reconstruct palaeoenvironments based on the results of this study.

4. Within the bounds of a rigorous chronology, to attempt a palaeoclimatic reconstruction of the topographical dunes. This reconstruction will relate to existing knowledge on palaeoclimatic changes within the Quaternary in South Africa, particularly with respect to the summer rainfall versus winter rainfall 'synchronous' controversy that was explained in Section 1.6.

5. To examine the dunes over a historic period in order to ascertain whether or not these landforms have changed as a result of human impacts on the landscapes.

It was hypothesised at the beginning of this project that the South African topographical dunes from the Breede River Valley and the southern Kalahari would be classified as sand ramps and be reliable indicators of past climatic changes. Like the Mojave ramps (Lancaster and Tchakerian, 1996), these ramps would contribute to the environmental reconstruction of dryland areas, and would contain a number of sedimentary layers rather than comprising only aeolian dune sand which could be related to oscillations in global circulation (as described in Section 1.5).

1.8 STRUCTURAL OUTLINE

This dissertation is divided into 7 chapters. In Chapter 1, an overview of topographical dunes, as well as a definition of terminology is given. The potential uses and limitations of topographical dunes as indicators of environmental change are also discussed, and a working hypothesis, aims and objectives are described. Previous research on climbing dunes and sand ramps is presented.

In Chapter 2, the regional setting of the two study sites is given, while Chapter 3 deals with the methodologies and research procedures used in the study. Chapter 4 presents descriptions of each site, as well as observations that were made in the field. In Chapter 5 the analytical results of the study are given. In Chapter 6 the results of the study are discussed with respect to the aims and objectives that were set out in Chapter 1. Chapter 7 provides a review of the impacts of humans on topographical dunes, and the topographical dunes in this study are then assessed with the use of historical aerial photographs. In the final chapter, Chapter 8, the conclusions of the study are discussed, bringing together information and arguments that are presented in the dissertation.

CHAPTER 2: REGIONAL SETTING

2.1 INTRODUCTION

Before outlining the research procedure and methodology associated with this study, it is important to describe the physical environmental characteristics of the study areas so that the reader can appreciate the type of environment that was studied. This chapter describes the present geology, macrogeomorphology climate and vegetation of the study areas. The southern Kalahari environment (Plate 2.1) is discussed, followed by the Breede River Valley region (Plate 2.2).

2.2 THE SOUTHERN KALAHARI ENVIRONMENT

2.2.1 Geology

This section describes the underlying geology of the two study sites in the southern Kalahari, namely, Prynnsberg and Kanoneiland. The geology underlying the Kalahari sands is, however, complex and unfortunately not well documented. Since the present study is concerned with the sands that overlie the bedrock, details of the geological history of the area will not be given, but can be found in Thomas and Shaw (1991b). The geology of this area is taken from Visser's (1989) explanation booklet for the 1:1 000 000 geological survey map of South Africa.

The Prynnsberg mountain (see Fig. 1.1) and surrounding bedrock form part of the Groblershoop Formation in the Olifantshoek Group. The rocks from this group build the Skeurberge, found to the west of the Langeberge and they lie concordantly on top of the neighbouring formation, the Brulsand Formation. The rocks comprise a quartz-sericite schist, with a few thin layers of greenstones and quartz intruding into the formation. East of Groblershoop (see Fig. 1.1), where a granite from the Keimos suite intrudes, the rock has been metamorphosed into an amphibolite-granite quartz-sericite schist. This metamorphosed granite is about 1268 ma and because it is intrusive, the Groblershoop Formation should be older. One of the greenstones from this formation was dated to 1780 ma, therefore implying that the Groblershoop Formation dates to the Mokolian Age. The overlying sands, which are discussed in greater detail in the next section, comprise red to flesh coloured wind blown material from the Gordonia Formation.

The Kanoneiland dune sites fall within the Vaalputs Formation (not yet approved by South African Council for Stratigraphy). This Formation is found southeast of Keimos, both to the north and south of the Orange River. The rocks comprise middle-grained grey, well-foliated quartz-feldspar adamellitic granite gneiss that contains a considerable amount of quartz. The Vaalputs Formation is considered to be of Mokolian Age and it is overlain by Quaternary red-brown windblown sands also of the Gordonia Formation.

Limited research into the basal geology of the southern Kalahari has been undertaken, though at present further research is underway. The Quaternary wind blown sands which overlie the bedrock have, however, been fairly well studied.

2.2.2 The Kalahari sands

The Kalahari sands and sediments have been documented, at some length, by Thomas and Shaw (1991b), as well as by Thomas and Martin (1987), Lancaster (1986) and Thomas (1988b and 1988c). This section provides a very brief overview of the Kalahari sands and therefore draws on the summary provided by Thomas and Shaw (1991b).

Kalahari sand is the most studied unit within the Kalahari, yet its age, origin, mode of deposition and environmental significance are not well understood. The sand varies in colour, age, thickness and composition throughout the Kalahari. In the Northern Kalahari, the sand is 200 - 300 m thick, while in the southern Kalahari, it is only 20 - 30 m thick. Perhaps the most frequently cited characteristic of the Kalahari sand is its ocherous colour, a result of iron oxide chemically precipitating onto the grains.

Despite many attempts to date the Kalahari sands, their age remains elusive to researchers, being anything from Miocene to Quaternary. One of the main difficulties of dating these sands is due to their highly mobile environment and thus a great deal of reworking of the sands occurs. Consequently, it is very difficult to date the original Kalahari sands. These sands are an accumulation derived from a local source and formed by *in situ* weathering. They are comprised mainly of quartz, but do contain a few heavy minerals.

Kalahari sand is fine to medium grained and the larger grains tend to be more well rounded and spherical than the smaller ones (Thomas and Shaw, 1991b). The sands display strong aeolian characteristics and in the southwestern Kalahari, the sands are found in direct association with dunes, therefore displaying evidence of fining as well as increased sorting in the direction of transport.

Although this evidence does not necessarily indicate a purely aeolian origin for the Kalahari sand, it does highlight the importance of aeolian processes in the environmental history of the Kalahari. Kalahari sands play a very important role in defining the landscape of the southern Kalahari, and thus the macrogeomorphic features of this region.

2.2.3 The geomorphology of the southern Kalahari

Although the geomorphology of the southern Kalahari displays a variety of characteristic landforms, it is dominated by the extensive linear dunes which form the Kalahari Dune Desert (Thomas *et al.*, 1997b). This region has attracted the attention of physical geographers from an early stage (e.g. Passarge's *Die Kalahari* written in 1904), however, its significance as an area for climatic reconstruction was first recognised by Grove (1969). He stated that it was a semi-arid region of low relief and that it "....preserves a record of the climate in the Quaternary having been at times wetter and at other times drier than now" (Grove, 1969: 192). This section provides a brief overview of the geomorphology of the southern Kalahari.

Sand Dunes

The extensive Kalahari Dune Desert is dominated by large linear dunes that form a 100 - 200 km belt in a NW-SE or NNW-SSE alignment (Lancaster, 1989). The dunes are generally 20 m - 2 km apart, with dune spacing decreasing in a southeasterly direction, and the crests of the dunes being approximately 5 - 20 m high (Thomas, 1988a). An important feature of the Kalahari Dune Desert is that all the dunes are partially vegetated, and only the crests of the dunes seem to be mobile (Lancaster, 1989). These linear dunes and their palaeoclimatic significance have been studied extensively by a number of researchers and details can be found in Grove (1969), Lancaster (1981, 1988, 1989); Thomas (1988b); Thomas and Shaw (1991b); Thomas and Martin (1987), Wiggs *et al.* (1995) and Bullard *et al.* (1997) .

Pans and Lunette Dunes

In addition to the numerous linear dunes, lunette and parabolic dunes are also found in the Kalahari Dune Desert (Shaw, 1997). The characteristics of pans and their associated lunette dunes, as well as their distribution have been described by Lancaster (1986). The lunette dunes, which occur on pan margins, have been suggested as one of the many possible sources of sand for the large linear dune field (Thomas and Shaw, 1991b).

Topographical Dunes

At present, topographical dunes in the southern Kalahari have not been identified and researched. They typically occur in areas where rocky outcrops are available to form topographical barriers along sand transport corridors. The morphology of these dunes and their formation has already been discussed in Chapter 1, and the dunes, which form the focus of this study, will be discussed in greater detail the following chapters.

Dry Valleys and Drainage

The drainage of the southern Kalahari lacks integration and it consists of a series of small pans and dry valleys (*mekgacha* or *laagte*) of the Molopo River (Shaw, 1997) which drain endoreically southwards into the Orange River and eventually into the Atlantic Ocean (Thomas and Shaw, 1991b).

These dry valleys from the Molopo River and its tributaries are known as the southern Kalahari network, and the drainage in this network is very erratic, varying between high-intensity, sporadic flooding events to seasonal rivers (Shaw *et al.*, 1992). The morphology of these mekgacha is variable, but they all tend to be found on the clay-floored channels derived from less-developed pre-Kalahari lithologies and valley sides comprise a variety of silcretes, calcretes, duricrusts derived from pre-Kalahari or altered Kalahari lithologies (Shaw *et al.*, 1992). Although these dry valleys have been well documented by Nash (1996); Shaw *et al.* (1992); Lancaster (1989); and Thomas and Shaw (1991b), they are problematic features in terms of climatic reconstructions. A constraint related to using dry valleys is that an increase in discharge does not necessarily mean that there has been an increase in rainfall in the area. Instead, because these are not closed systems, it could mean that there have been increases in precipitation in surrounding areas (Lancaster, 1989). In addition, many of these relict dry valleys could, in fact, have been formed by catastrophic high-intensity flood events rather than a seasonal increase in rainfall (Thomas, pers. comm.). Therefore, although these features form an integral part of the geomorphology of the southern Kalahari, great care should be exercised when using them to interpret palaeoenvironments.

The landscape of the southern Kalahari is therefore dominated by the extensive, semi-vegetated linear dunes which form the Kalahari Dune Desert. Pans and lunette dunes are also found in the area, and dry valleys are important features formed by the southern Kalahari's erratic drainage system. Integral to the formation of these geomophological landforms, is the role that climate plays in the environment, and therefore a brief description of the climate of the southern Kalahari will be presented.

2.2.4 Present Climate

Climate plays an important role in all regions and thus a comprehensive description of the climatic controls which govern the southern Kalahari climate is appropriate. Mean temperatures, precipitation regimes, evaporation rates, and wind patterns are also discussed in the context of this region.

The Kalahari desert lies on the Tropic of Capricorn and this latitude (23.5°S) also coincides with the descending limb on the Hadley and Ferrell Cells (Thomas and Shaw, 1991b). These two major circulation cells cause air to descend over the Kalahari, creating the 30°S high pressure belt, and thus clear, stable climatic conditions are experienced. The mean circulation of the atmosphere in the Kalahari is therefore anticyclonic throughout the year (Preston-Whyte and Tyson, 1988). The complex upper air circulation patterns which affect the Kalahari weather are described in detail in Tyson (1986). Briefly, easterly airflow is dominant during the summer, while westerlies dominate the southern Kalahari during the winter months (Tyson, 1986).

In winter (Fig. 2.1), this anticyclonic system intensifies and is displaced northwards by the development of a weak trough in the area (Tyson, 1986). This intensification of the 850 hPa anticyclone occurs in March when there is a northerly flow of moist air from the tropics towards the western parts of southern Africa, and it is often responsible for the autumn rainfall over these western parts (Preston-Whyte and Tyson, 1988). During summer (Fig. 2.2), a weak heat low is centred over the Northern Cape interior, and it is linked by a trough to a tropical low north of Botswana (Tyson, 1986). This weak heat low wanders in an east-west direction along the southern part of the Inter-tropical Convergence Zone (ITCZ), allowing moist convective air to move southwards, bringing occasional thunderstorms (Preston-Whyte and Tyson, 1988).

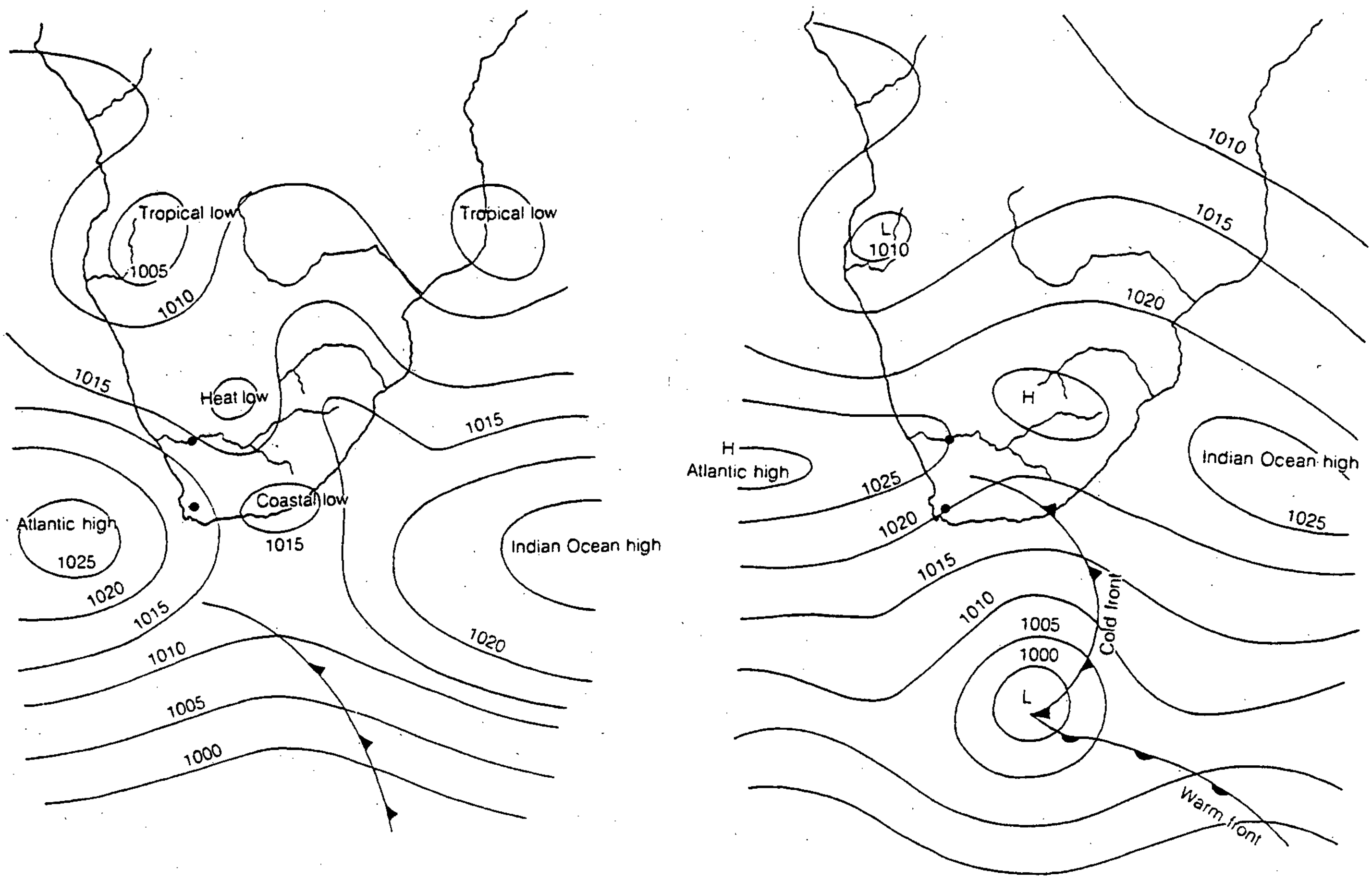


Figure 2.1 & Figure 2.2 Basic elements in the pressure pattern for mid-summer (Fig. 2.1) and mid-winter (Fig. 2.2) over southern Africa (after Hurry and van Heerden, 1981: pp. 20 - 21).

It is clear from the description of these climatic controls that rainfall in the Kalahari is sporadic and unpredictable. Another factor which contributes to the aridity of the region is the elevation of the Kalahari, as well as its continentality and interior position (Thomas and Shaw, 1991b).

Temperature

Mean annual minimum and maximum temperatures in the southern Kalahari were taken from the Computer Centre for Water Research's (CCWR) station archive data. A weather station (Fig. 2.3) situated in Upington was selected since it had the longest record (52 years) in the vicinity of the study sites and thus was seen as the most reliable data source. The mean annual maximum temperature for this region is 27.9°C, while the mean annual minimum temperature is 9.9°C. Hottest mean monthly temperatures are experienced during January at a temperature of 34.5°C maximum and 17°C minimum. The coldest mean monthly temperatures recorded a minimum of 16°C and a maximum of 20.6°C during July.

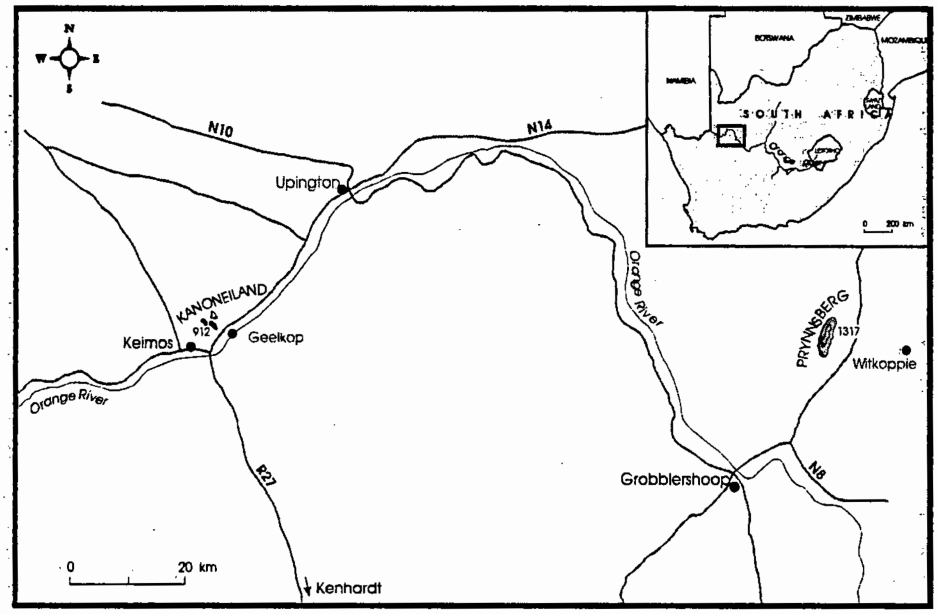


Figure 2.3 The southern Kalahari study region and the location of the weather stations.

Due to the inland nature of the southern Kalahari, the diurnal temperature range in the region is large, and this is confirmed by the data from the Upington weather station. Diurnal ranges are greatest during the dry season due to the lack of cloud cover and therefore effective night-time cooling by longwave radiation (Thomas and Shaw, 1991b).

Precipitation

Two stations (Fig. 2.3) from the CCWR data were used in order to gain a more detailed view of the precipitation regimes in the southern Kalahari. The first station is at Geelkop, and is just a few kilometers away from the Kanoneiland sites. The mean annual rainfall for Geelkop is 149.2

mm. From this record (70 years), it is clear that most of the rainfall occurs during the summer months, with the highest mean monthly precipitation in January (21.2 mm). The lowest monthly rainfall occurs in September where there is only 2.8 mm of rain for the entire month.

At the Witkoppie station (Fig. 2.3), in the vicinity of Prynnsberg, mean annual precipitation is higher than Geelkop, at 205.8 mm per annum. The highest mean monthly rainfall, 37.8 mm, occurs in April, and the lowest mean monthly precipitation, 1.3 mm, occurs in September. This station has only collected precipitation data for 12 years, and thus the data may not be reflective of long term trends. As with the data from Geelkop, it does indicate that the wet season occurs in summer and the dry season occurs during the winter months. Rainfall in the southern Kalahari is, however, sporadic, unpredictable and often very localized, and thus the rainfall data obtained may not truly reflect the conditions in reality.

Evapotranspiration and Humidity

The arid conditions of the southern Kalahari are not just due to the sporadic and unpredictable rainfall, but also to the high temperatures and low relative humidity rates (Thomas and Shaw, 1991b). When the above weather conditions are combined, then evapotranspiration rates tend to be high, leaving little available moisture for plant growth. Thomas and Shaw (1991b) have shown that evaporation rates, measured using pans, increase towards the southwestern Kalahari, where values exceed 4000 mm.

Wind

Mean annual wind speed and direction data were taken from the Weather Bureau's station at Upington. The data were collected over a 30 year period, and when presented in the form of a wind rose, some clear trends emerged. Actual wind data can be viewed in Appendix A.

The wind rose (Fig. 2.4) shows that the dominant wind directions in this region are the north and northwesterly winds. Both of these winds are very strong all year round, with the highest wind speeds occurring between August and January. September had the highest wind speed for this period at 6.9 ms^{-1}. The mean annual wind speed for the north wind is 6.1 ms^{-1}, and for the northwesterly wind is 5.2 ms^{-1}. The local and topographically induced up-valley southwesterly wind (Tyson, pers. comm.) is also important as it has a mean annual wind speed of 3.9 ms^{-1}, and is strongest during the summer months.

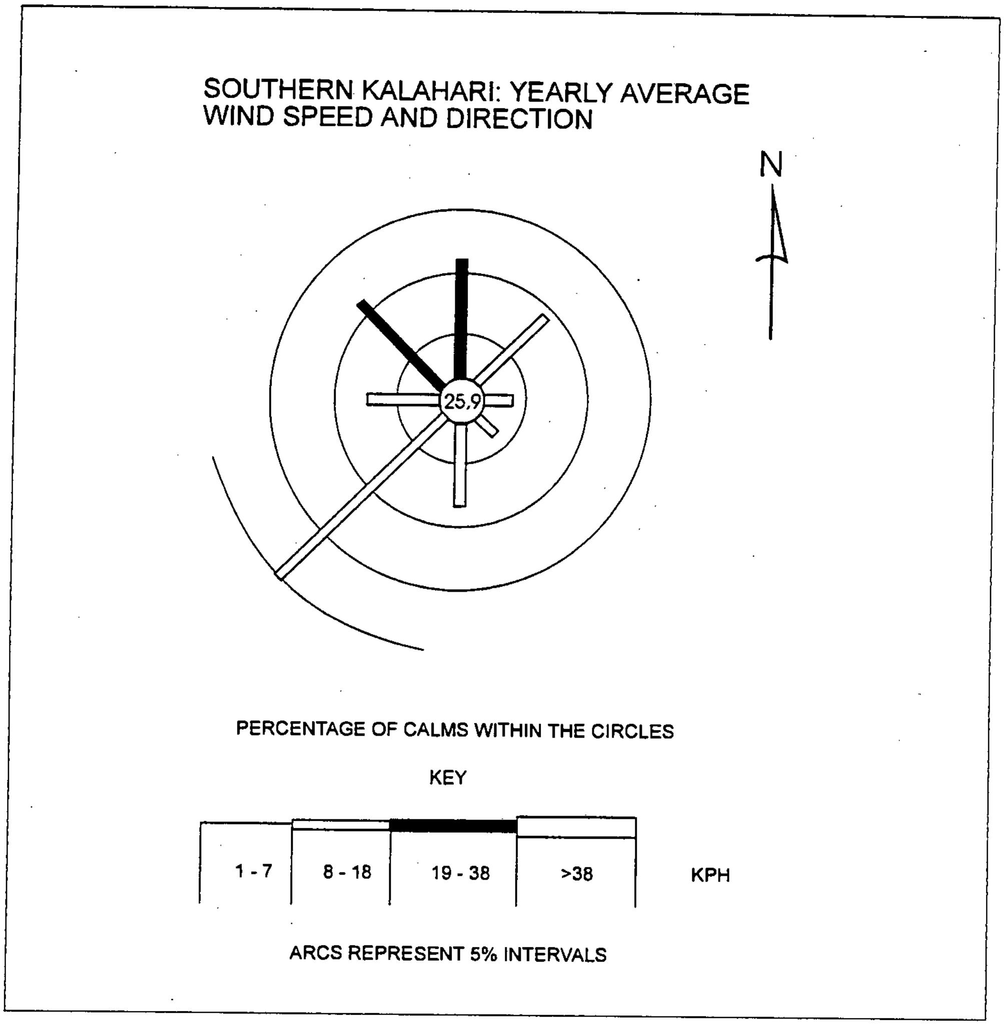


Figure 2.4 The dominant wind directions and speeds in the southern Kalahari are shown to be the southwesterly and north winds (data obtained from the South African Weather Bureau).

In summary, the southern Kalahari experiences a warm, stable and dry climate. These weather conditions have important implications for the types of vegetation that can grow in the southern Kalahari, as well as the types of agriculture that the land can support. The natural vegetation of this area, which is discussed in the following section, comprises plants specially adapted to surviving in arid areas where evapotranspiration rates are so high.

2.2.5 Vegetation

Despite the climatic conditions of the southern Kalahari or Kalahari Dune Desert, the vegetation found here is diverse and well adapted to the harsh climate. The vegetation communities are, however, less well developed than in other parts of the Kalahari due to the reduced moisture availability in this area (Thomas, 1988a).

The main veld type in this area is known as the Western Form of the Kalahari Thornveld Proper (Acocks, 1988). The Western Form consists of open arid shrub savanna as well as open savanna species such as *Acacia erioloba* (camelthorn) and some desert grasses (Acocks, 1988). The arid shrub savanna is found in conjunction with the southern Kalahari dunefield, sparsely covering it (<35%) with clumped grasses such as *Schmidtia kalahariensis* (Thomas and Shaw, 1991b). The open savanna tree species consist mainly of *Acacia* species such as *Acacia erioloba, Acacia haematoxylon, Boscia albitrunca* and *Acacia mellifera* (Acocks, 1988).

Due to the aridity of the area, agricultural potential of the land is low (Thomas and Shaw, 1991b), and the sparseness of the grass clumps and looseness of the Kalahari sand make the Kalahari Dune Desert very vulnerable to overgrazing and desertification (Acocks, 1988). Most of the land, with the exception of the land next to the Orange River, is not cultivated, but is rather used as grazing for cattle, sheep and goats. Cultivated land, under vineyards, is found adjacent to the Orange River, as the river provides a valuable source of irrigation water for crops.

The southern Kalahari thus experiences arid to semi-arid conditions with sporadic rainfall occurring in summer. The landscape is dominated by the extensive relict linear dune field and is vegetated mainly by open arid shrub savanna. The Breede River Valley is also a semi-arid area, but the climatic controls which determine this aridity, as well as the nature of the landscape and the vegetation differ greatly from the southern Kalahari.

Plate 2.1 A typical view of the southern Kalahari landscape. Note the partly vegetated linear dune in the background, with the Kokerbooms and arid shrubs growing on the uniquely ocherous Kalahari sands.

Plate 2.2 A view from the flank of a topographical dune in the Breede River Valley looking across at the vineyards, with mountains of the Cape Fold Belt in the background.

2.3 THE BREEDE RIVER VALLEY ENVIRONMENT

2.3.1 Geology

The geology of the Worcester-Robertson Valley is dominated by two groups within the Cape Supergroup. The country rock which underlies the Sandberg hills comprises Bidouw shales from the Bokkeveld Group, while at Moddergat, shales from the Witteberg Group are prominent. Both these groups are of Devonian Age (De Villiers, 1955). The geological description of this valley is taken from the geological survey explanation book on Worcester by Gresse and Theron (1992).

The country rock of the Sandberg hills comprises Waboomberg Formation shales and sandstones from the Bokkeveld Group. "It consists of dark-grey siltstone with immature sandstone and thin shale intercalations in the lower half, overlain by dark-grey carbonate bearing shale and mudstone. Thin siltstone beds are present near the top of the formation" (Gresse and Theron, 1992:25). The more silty units within this formation display evidence of bioturbation, oscillation ripple marks and small-scale cross-laminated scour-and-fill structures. In addition, the upper shale and mudstone portion displays marked evidence of being fossiliferous.

Although also part of the Cape Supergroup, the Witteberg Group differs from the Bokkeveld Group in that the sandstones have a higher sericite content, greater maturity and are therefore of a lighter colour. The Witpoort Formation, the most prominent unit in this group, is found on the Moddergat hills and is in places approximately 65 m thick. It is divided into three groups, the basal Rooirand Member, the Perdepoort Member and the top Skitterykloof Member.

The Rooirand Member is reddish-brown in colour and comprises medium to thick-bedded, fine to medium grained quartzitic sandstone. It lies conformably on the Swartruggens Formation and locally consists of thinner-bedded siltstone and sandstone. The second member, Perdepoort, is more mature than Rooirand and it is a prominent white-weathered sandstone marker horizon. It comprises medium to fine grained, well sorted quartzitic sandstones, and individual beds vary in thickness from about 0.5 to 2 m. Tabular cross-bedding is often prominent. The top member, the Skitterykloof Member, is discontinuous and has not been identified south of Worcester, and to the north it is only a few metres thick. It comprises coarse-grained pebbly sandstones, interspersed with thin conglomerate layers.

The geology of the area is overlain by alluvium, calcrete and sand (often aeolian) which are of Quaternary Age (De Villiers, 1955). No work on the sands of the Breede River Valley had been conducted prior to this study.

2.3.2 The Geomorphology of the Breede River Valley

As far as could be ascertained, no published work on the geomorphology of the Breede River Valley exists and thus the description of the macrogeomorphology of the area is presented primarily on the basis of observations made in the field.

The dominant topographical feature of the Robertson-Worcester area is the Cape Syntaxis, i.e. the prominent mountain ranges of the Cape Fold Belt (Gresse and Theron, 1992). These ranges are separated by wide intermontane valleys that have been cultivated with vineyards and orchards (Gresse and Theron, 1992). The valleys lie about 1000 m below the peaks of the Cape Fold Belt (Gresse and Theron, 1992) and there is an abrupt break of slope between the hillslope and the valley, thus allowing features such as alluvial fans and topographical dunes to form. The main ranges in the area are the Langeberg, Hex River, Witzenberg, Skurweberg, Du Toits, Drakenstein, Riviersonderend, and Kleinriviers mountains (Gresse and Theron, 1992). The Tulbach-Worcester-Robertson Valley is underlain mainly by Bokkeveld shale and Malmsbury phyllite (Gresse and Theron, 1992), and this bedrock is in turn overlain by rounded boulders and clasts supported by finer-grained alluvium. This infill is up to about 15 m thick as observed from road cuttings between Worcester and Robertson. This alluvium clast infill is then topped by a thin veneer of stony soil, suitable for agriculture.

The mountains which form the Cape Syntaxis, form a prominent watershed in the area between the rivers which flow west (Berg), north (Olifants and Doring), east (Breede and Riviersonderend), and south (Bot, Klein and Nuwejaars) (Gresse and Theron, 1992). The eastward flowing Breede River forms a braided channel, although it has been canalized in some areas for agriculture. One such area is to the west of the Sandberg topographical dune. The sands from the Breede River are well sorted quartzitic grains, and are the probable sand source for the surrounding topographical dunes.

Due to the lack of geomorphological research data from the area, a more comprehensive description of the landscape cannot be given here. Perhaps future research in this region should focus on recording the present day geomorphological features, thus enabling relict geomorphological features to be compared to a modern analogue.

2.3.3 Present Climate

The Robertson district falls in the winter rainfall region of South Africa and it thus experiences hot, dry summers and cold, wet winters (Tyson, 1986). This simple scenario is, however, complicated by the position of Robertson which is situated in the rain shadow of the Cape Fold Belt Mountains. During summer (Fig. 2.2), the South Atlantic High Pressure System dominates the southwestern Cape weather, causing hot, dry and stable conditions, often coupled with very strong southeasterly winds (Preston-Whyte and Tyson, 1988). During winter (Fig. 2.1), however, this South Atlantic High Pressure System moves 6° northwards, allowing mid-latitude cyclones (westerly waves) to move over the area bringing cold wet weather coupled with strong northwesterly winds (Preston-Whyte and Tyson, 1988). In the Robertson area, however, the Cape Fold Belt causes a rain shadow, and thus in the valleys to the east of this belt, precipitation is decreased greatly and is associated with local aridity (Tyson, 1986). Rainfall in this region is therefore more sporadic and unpredictable than areas to the west of the Cape Fold Belt.

Temperature

Mean annual minimum and maximum temperatures for the Robertson region in the Breede River Valley were taken from the CCWR's station archive data. Data were extracted for a weather station in Robertson (Fig. 2.6), as it had the longest record of temperatures in the area. The annual mean maximum temperature in this area is 24.6°C and the mean minimum is 10.5°C. The highest temperatures occur in January, with a mean monthly maximum of 31.1°C and minimum of 15.1°C. July is the coldest month with a mean monthly maximum of 18°C and minimum of 5.4°C. There is a large diurnal temperature range throughout the year, but it is slightly larger in summer. This is also due to the clear skies at night, allowing long wave radiation to escape and cooling to occur.

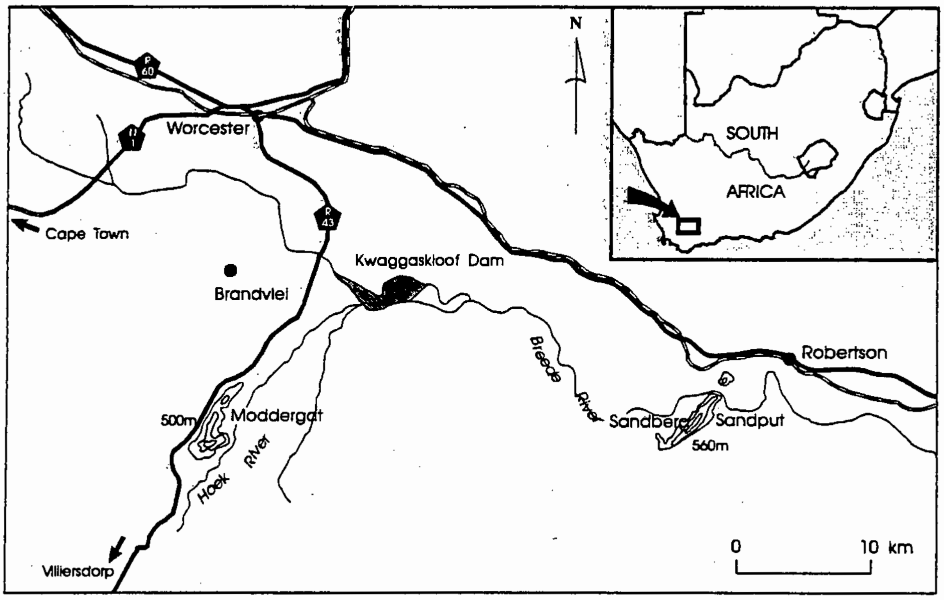


Figure 2.5 The Breede River Valley and the location of the weather stations.

Precipitation

Precipitation data, also taken from the CCWR, were extracted from the Brandvlei Dam weather station (Fig. 2.5) due to its long record of data (70 years). Mean annual precipitation for the area is 306.5 mm, with the highest rainfall occurring during the winter month of August (39.6 mm) and the lowest during summer in December (11.2 mm). Rainfall is often sporadic and unpredictable, and this is mainly due to the position of the region on the eastern border of the Cape Fold Belt mountain range.

Although evaoporation rates in this area are high, water loss by evaoporation is less in the winter rainfall areas due to a cooler climate when the rain falls. Humidity data for this area, however, area not available.

Wind

Wind data for the Breede River Valley were taken from the Weather Bureau's weather station at Robertson (Fig. 2.5). The data (Appendix A), in the form of a wind rose (Fig. 2.6), show that the strongest mean wind direction and speed during the year is the northwesterly wind at 6.3 ms^{-1}, then the westerly wind at 5.3 ms^{-1}, and finally the southeasterly wind at 4.3 ms^{-1}. Winds are the strongest during the winter months when the westerly wind is dominant.

Although not as strong, the southeasterly wind dominates during the summer. As the Breede River Valley is a winter rainfall region, soil moisture will be at its maximum during winter, and thus summer winds are more important with respect to the transportation of sand. The northwesterly wind dominates throughout the year and is likely to be the main sand transporting wind in the region at present.

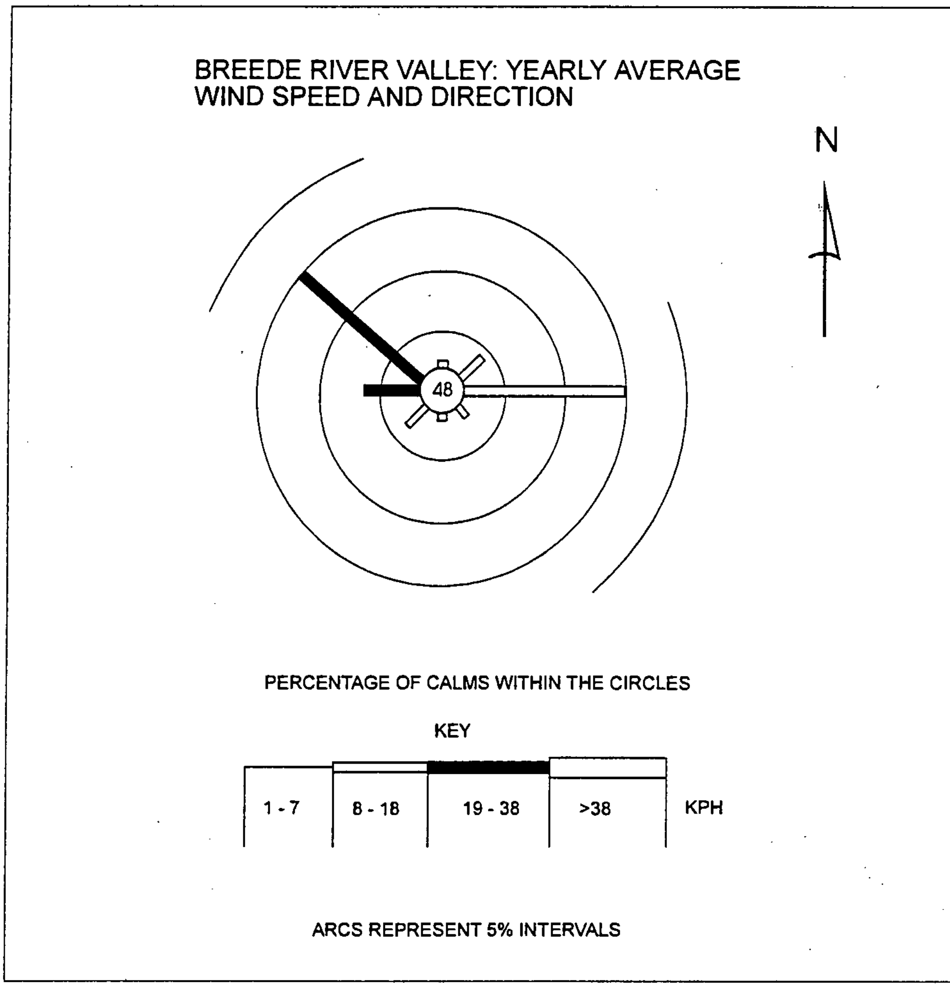


Figure 2.6 The dominant wind directions and speeds in the Breede River Valley are shown to be the northwesterly and easterly winds (data obtained from the South African Weather Bureau).

The Breede River Valley region is a semi-arid area that experiences hot, dry summers and cold, moist winters. This type of climate is therefore conducive to specific vegetation communities.

2.3.4 Vegetation

According to Acocks' vegetation map (1988), the Breede River Valley forms the interface between the Fynbos and Karoo biomes. Acocks' (1988) provides a comprehensive description of the vegetation in this area, and thus this section will draw on his work.

The type of Fynbos vegetation which is found in this area is known as Arid Fynbos. It only requires 250 mm of rain per annum, and it often tends to flourish in areas where the land and vegetation have been mismanaged. Its overall composition is very similar to that of the Karroid False Fynbos, where Restionaceae dominate, and typical Fynbos families such as Proteaceae, Ericaceae and Rutaceae are poorly represented or even absent.

Karroid Broken Veld is the Karoo vegetation type that is found in the Breede River Valley. Three main types of Karoo are found in this group: the Great Karoo; the Little Karoo (including the Roberston Karoo); and the Grassy Mountain Scrub. The area that this research is concerned with is the Little Karoo (Acocks, 1988). The Little Karoo includes dwarf trees and shrubs with various amounts of succulents and grasses. It does, however, have a greater number of shrubs and succulents than the Great Karoo. The vegetation includes sparse Karoo veld with stunted shrubs (especially in rocky places) and some thornveld as well as *Tamarix usneoides* along the rivers. A great deal of *Mesembryanthemum* also occur in this area, not all of which have been identified. Typical shrubs include *Euclea undulata* and *Euphorbia mauritanica*. On the ridges in this area, *Elytropappus rhinocerotis* is present and around the margins of the Little Karoo it forms an important transition to Renosterveld or Arid Fynbos.

In the Robertson Karoo, the Karoo bush tends to get quite thick and it develops in clumps of *Euphorbia mauritanica.* Because of this bush's relatively thick growth near the ground, it impedes wind blown sand causing mounds to build up. This is also a result of a relative absence of grasses in the area, thus exposing the sand to transporting agents such as wind.

In the wide intermontane valleys of the Cape Fold Mountains, most of the aforementioned natural vegetation has been removed and replaced by vineyards and orchards. The area is also susceptible to alien vegetation (e.g. *Acacia cyclops; Acacia longifolia; Hakea*), which are spreading rapidly through the area, leaving very little pristine vegetation.

2.4 PALAEOENVIRONMENTAL STUDIES

Shaw and Thomas (1996) provide a concise summary of the palaeoenvironmental history of the southern Kalahari, mentioning that caves, palaeolakes, pans and valleys, and aeolian landforms have all provided evidence for environmental change. In the southern Kalahari, three dune building phases were identified by Stokes *et al.* (1997b) during the Late Pleistocene, *viz.* 28 - 23 ka, 17 - 10 ka and around 5.5 ka. These periods are characterized by cooler and drier conditions than present, therefore evoking aeolian activity (Thomas and Shaw, 1996). The above dune building phases were interspersed by periods of greater moisture availability (Stokes *et al.*, 1997b). A caveat which should be mentioned with respect to the chronology of the southern Kalahari, is that previously, the record of aeolian activity has been evaluated in the context of humid chronologies. More recently, however, new evidence from the dating of quartz and feldspar dune sediments using optically stimulated luminescence (OSL) dating by Stokes *et al.* (1997a and 1997b) and Thomas *et al.* (1997b) has given researchers better insights into dune emplacement in the southern Kalahari. A more comprehensive record of the Quaternary environment in the southern Kalahari is thus beginning to emerge (Thomas, pers. comm.)

No previous studies on the palaeoenvironment of the Breede River Valley have been undertaken, but the region can be compared to other sites in the southwestern Cape that have been researched. The site which this study will be compared to in Chapter 6 is Verlorenvlei, a seasonal lagoon found on the semi-arid southwest coast of the Cape near Elands Bay (see Fig. 1.2) (Meadows, 1998). Baxter (1996) found that during the last glacial maximum (LGM) at Elands Bay there appears to have been increased rainfall and reduced temperatures. By the terminal Pleistocene, temperatures had increased and an decrease in moisture is indicated by the fossil pollen assemblage. During the Holocene, Baxter (1996) found that environmental changes during this period were not as pronounced as during the Late Pleistocene.

It is clear from these two regions that precipitation and temperature patterns are not consistent between the winter (southwestern Cape) and summer rainfall regions (southern Kalahari) of South Africa. This issue will be debated further in Chapter 6 in the context of the results from this study.

2.5 SUMMARY

In this chapter, the physical environment from the two study sites, the southern Kalahari and the Breede River Valley, have been described. Both sites are semi-arid regions where evaporation rates exceed rainfall. They therefore both have vegetation communities which are especially adapted to dry conditions. The geology of the two areas does, however, differ, and therefore different types of geomorphic landforms are found in the Breede River Valley and the southern Kalahari. Previous palaeoenvironmental studies indicate that the southern Kalahari environment experience cool dry conditions at the LGM, whilst the southwestern Cape experienced cool moist conditions. This dichotomous response of the summer and winter rainfall regions has been the subject of much debate with researchers over the last decade (Tyson, 1986; Cockroft *et al.*, 1987; Partridge, 1997, Baxter, 1996; and Holmes, 1998) and it is an aim of this research to contribute information in order to clarify this controversy. In the following chapter, a description of the research methodology used to help achieve this aim is presented.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 INTRODUCTION

In the previous chapter, the physical environment of the southern Kalahari and Breede River Valley regions was reviewed. This chapter discusses the research methods that were employed in these environments. A description of the research procedure (which includes the method and problems of using aerial photographs to identify topographical dunes), and the research methodology will be given. In the research methodology, the field, laboratory and statistical analyses for this dissertation are discussed.

3.2 INITIAL IDENTIFICATION OF TOPOGRAPHICAL DUNES

3.2.1 Aerial Photography

The use of aerial photography in the identification of landforms is advantageous due to the direct nature of the interpretation (i.e. the actual landform can be seen), and it also requires less deduction compared with other techniques (Verstappen, 1977). It can thus yield quick and accurate representations of landforms. This method of identifying features does, however, have its difficulties, as one can only see the surface layer of the earth, and there is usually distortion of landforms in the photographs (Verstappen, 1977). A very brief overview of the method of using aerial photographs to identify topographical dunes will be discussed, and the pitfalls of using this method will be highlighted.

In order to determine initially the location of topographical dunes in the southern Kalahari and the Breede River Valley, an analysis of current aerial photography and topographical maps was undertaken. The maps were first used to try to identify areas in which the likely topographical conditions for the possible formation of topographical dunes prevailed. Once this had been completed, a more detailed analysis using aerial photography was conducted so as to locate these dunes.

When using aerial photographs to identify possible sites where topographical dunes might be found there are certain features which aid the process. Firstly, a topographic barrier against which sand can accumulate should be present in the photograph. Secondly, the windward side of the barrier should be sloping very gently in comparison to other topographic barriers in the area. Thirdly, this gently sloping area which rests against the topographic barrier should appear lighter in colour as it is an aeolian deposit rather than bedrock. Fourthly, vegetation may be present on these slopes, especially if they are relict features and are therefore no longer active. Fifthly, falling dunes, which would form on the leeward side of the topographic barrier, could also be present. Before examining the aerial photographs, it is also useful to establish prevailing wind directions. Another important consideration when identifying topographical dunes is the possible sand source for accumulation. Because topographical dunes usually form relatively close to their aeolian source, source areas (e.g. in the southern Kalahari, the Orange River and linear and transverse dunes) may also be visible on the aerial photographs.

According to Thomas (pers. comm.), identifying topographical dunes from aerial photographs can be problematic. One of the main problems associated with using aerial photographs to identify relict topographical dunes is that the researcher cannot tell from examining an aerial photograph whether or not the dune has achieved relict status (as defined by Thomas and Shaw, 1991a). The presence of vegetation on the dune surface is probably the most widely used indicator of relict dune status, but is not necessarily an indication of inactivity. In arid areas there is no distinct level of dune activity and inactivity, but rather different levels of activity which relate to levels of windiness and vegetation cover, i.e. a corresponding decrease in sand movement with an increase in vegetation cover (Thomas, 1997). There is also the logistical problem of identifying, for example, ten topographical dunes on the photographs, and then from further investigation in the field it becomes evident that none of the identified dunes are in fact relict. Here, however, the use of satellite images would lessen the problem as studies have shown (Blount *et al.*, 1990, Paisley *et al.*, 1991, Lancaster *et al.*, 1992, Laity, 1987 and 1992, Zimbelman and Williams in preparation; in Zimbelman *et al.*, 1995) that active sand can be distinguished from sand stabilised by vegetation through subtle yet consistent differences in the reflectance properties between the LANDSAT Thematic Mapper spectral bands. It is also very difficult to determine the difference between a reasonably well vegetated topographical dune and a talus slope with a gentle gradient comprised of the bedrock and debris of the topographical barrier (again, through the differential reflectance properties of aeolian sands, satellite images may help to reduce this problem). The distortion of landscapes in the photographs, as well as the possible modification of a topographical dune due to soil erosion and cultivation also tends to make the identification process more difficult (Holmes, pers. comm.). The angle of the sun at the time at which the aerial photograph was taken could also influence the interpretation of features, as some landforms may be obscured by shadows. It is far easier, to identify topographical dunes, however, when aerial photograph pairs are viewed stereoscopically in three dimensions.

3.2.2 Ground Truthing

In each study area a reconnaissance field trip was undertaken in order to ground truth those topographical dunes identified using aerial photographs. Once appropriate dunes had been selected using the above method, a sampling field trip was undertaken, where appropriate sites were chosen according to a number of criteria. The most important factor, especially in the southern Kalahari, was that of accessibility. Many of the topographical dunes identified on aerial photographs proved to be totally inaccessible, even to a four wheel drive vehicle. Another factor was that work commenced only on those farms where permission to work was given by the farmer. Where possible, the subjective choice of the best example was used. In addition, sites on both sides of the topographical barrier, according to the prevailing wind, were included and sampled.

Once this procedure of identification and ground truthing was complete, and permission from farmers to work on their land had been obtained, field work was able to commence. In the following section, methods that were used in the field are reviewed, and a description of the laboratory and statistical methods used to analyse the field samples is presented.

3.3 FIELD METHODS

Research in the field was based on the principles outlined by Gardiner and Dackombe (1983). Slope profile measurements were taken, and pits and exposed faces were investigated.

3.3.1 Slope Profile Measurements

Slope profile measurements were taken in order to determine the gradient of the topographical dunes. In the southern Kalahari, measurements were taken using an abney level, a tape measure and a ranging rod, as described by Young (1972). This method was also used in the Breede River Valley, but measurements were checked using 1:10 000 orthophotographs. No orthophotographs are available for the southern Kalahari study sites. One slope profile measurement per dune was taken along the centre ridge of the topographical dunes.

3.3.2 Exposed Face and Pit Sampling

Both the southern Kalahari dunes and the Breede River Valley dunes were examined for exposed faces so that profiles could be studied. The only exposed face that was found was one in a topographical dune (the Sandput) in the Breede River Valley. On all the other dunes, pits were dug in order to try to expose a profile. One pit was dug at each of the Prynnsberg dunes, and two pits were dug at the Moddergat topographical dune. At Prynnsberg, the pits were dug approximately half way up the dunes, while at Moddergat a pit was dug near the base of the dune (due to a road cutting exposure) as well as half way up the dune. At Kanoneiland (southern Kalahari) and Sandberg (Breede River Valley), the slopes of the dunes were too steep for pits and therefore only surface samples were taken. Even at Prynnsberg, the maximum depth of the pits that were dug was limited to 2 m, as the pits kept collapsing. In addition to the steep slopes, pits collapsed due to the sandy substrate and lack of dune structure. The exposed face and pit profiles were then photographed and their depth was determined using a tape measure, and the colour of the sand was defined according to the Munsell Colour System (1994). Grab surface samples were taken at regular intervals on all the topographical dunes. After cleaning the exposed face and pits, samples were taken at regular intervals down the profiles. Where no stratigraphic units were visible, samples were taken every 30 cm. Samples for optically-stimulated luminescence dating were also taken in the pits on the Prynnsberg sand ramps at the top, middle and base of the pits. The face of the pits were cleaned and then 20 cm PVC pipes were hammered into the face of the pits. The ends of the pipes were then sealed off to prevent sunlight from contaminating the samples. The pipes were wrapped in black plastic and packed away in a dark room ready for laboratory analysis at the University of Sheffield, United Kingdom. Three samples for dating were also taken from the Sandput exposed face from the top, middle and bottom of the face, using the same method as described above.

3.4 LABORATORY METHODS

On the 38 sediment samples from the southern Kalahari and the 17 from the Breede River Valley that were collected in the field, the following laboratory analyses were undertaken:

(a) Granular Composition Analysis

(b) Conductivity and pH Measurements

(c) Scanning Electron Microscopy Analysis

(d) Optically Stimulated Luminscence Dating

3.4.1 Granular Composition Analysis

Approximately 100 g of each sample was sieved through a 2 mm sieve in order to separate the coarse fraction (> -1 ϕ) from the finer fraction ($\leq$ -1 ϕ) (McManus, 1988).

The finer fraction was then dried at 45°C for 24 hours. Exactly 50g of each sample was measured and treated with 20 g of Calgon solution (sodium hexametaphosphate) and 100 g of distilled water. The samples were then dispersed by agitating them in a Protea SC:201 mechanical agitator for 24 hours. The silt and clay fractions were then determined using the hydrometer method, as described by Akroyd (1957). The sand fraction was then separated from the silt and clay fraction by means of decantation, sieving and washing through a 23 μm sieve. The washed sand was then dried for 24 hours at 45°C in a drying oven.

A small sub-sample, weighing 3 g, of each of the dried washed sand samples was accurately weighed and then placed through the settling column. This laboratory procedure was utilised in order to determine the percentages of coarse, medium and fine sand. Through the use of this apparatus, as described by Leeder (1989), the following Folk and Ward (1957) statistical parameters were generated:

- Mean - the mean size of the sediment
- Median - the middle most grain size in the distribution
- Sorting - a measure of how well the sample is sorted
- Skewness - a measure of the symmetry of the distribution of the sample
- Kurtosis - a measure of the peakedness or flatness of the distribution curve

These moment statistics were first described by Folk and Ward (1957), who developed equations on log-normal distributions to represent the above parameters for grain size distribution within a sample.

3.4.2 pH and Conductivity

pH, a measure of the hydrogen ion concentration, and therefore the acidity of a sample, was determined for all the sand samples using a M90 pH microprocessor meter. pH was measured in order to ascertain, *inter alia*, the degree of leaching which occurs within a sand profile. The pH meter was first calibrated using two buffer solutions (i.e. pH of 7 at 25°C and pH of 4 at 25°C), and then measurements for each sample were taken by submerging the pH electrode probe into a supernatant of 5 g of sand and 12.5 m*l* of distilled water.

Conductivity values are a relatively good and reliable indication of the ionisable salts within an arid environment, and it is also useful in determining whether processes have occurred which are atypical on the dryland region. The greater the concentration of ionisable salts, the more conductive the sediment and the higher the conductivity reading. Conductivity was measured using the M90 conductivity meter. The conductivity meter was calibrated by holding the probe in free air and then setting the meter to 0.00 μS. The probe was then placed in a supernatant of 5 g of sand and 12.5 m*l* of distilled water, and conductivity levels were recorded.

3.4.3 Scanning Electron Microscopy (SEM)

Sand grains from a selection of the washed sand samples were viewed under a Cambridge S200 Scanning Electron Microscope. Grains were carefully prepared by coating metal stubs with a carbon graphite and glue mixture. A few grains of sand were then carefully poured on to the stubs. Once dry, the stubs were re-coated with gold palladium and placed in a vacuumed container for 24 hours. The micrographs were compared to Krinsley and Doornkamp's Atlas of Quartz Sand Surface Textures (1973).

In addition, chemical analysis was utilised in order to determine the chemical composition of the samples. The sand grains were prepared using the same laboratory procedure as for the above described SEM analysis. The stubs were examined under a Leica S440 Microscope and the chemical composition of the grains was analysed using the chemical analysis computer program, KEREX.

3.4.4 Optically Stimulated Luminescence Dating

Optically stimulated luminescence (OSL) is a method of dating quartz and feldspar sediments found in depositional environments, such as the regions in this study. A detailed overview of the rationale behind this method of age determination, the laboratory procedure and its application in the southern African context can be found in Holmes (1998). The reader should refer to Lowe and Walker, 1984; Botha, 1992; Wintle, 1995; Bateman and Bragg, 1996 and Stokes, *et al.* 1997b for primary studies using the OSL dating technique in southern Africa.

3.5 MULTIVARIATE STATISTICAL ANALYSES

3.5.1 Introduction

A number of different multivariate statistical analyses were conducted in order to classify the data from the 38 southern Kalahari and 17 Breede River Valley samples. In addition, analyses were conducted to ascertain how different variables within a dune environment (e.g. particle size, slope angle, vegetation cover, etc.) relate to each other. These techniques were also used to identify statistically significant differences between the sites in the same general locality, as well as to compare the data between the two locations. The statistical analyses were undertaken using the computer package STATISTICA, and two main techniques were employed, namely, principal component analysis and cluster analysis. This section provides a brief overview of the two techniques, as well as describing how they were used in this research.

3.5.2 Principal Component Analysis

Principal Component Analysis (PCA) is one of the most widely used methods of multivariate analysis in the earth sciences (Davis, 1986), and it is used in order to succinctly describe relationships between a complex set of observed measurements (Till, 1974). There are four main reasons why PCA is an important type of multivariate analysis. Firstly, it allows the researcher to detect groups of inter-connected variables within the data. Secondly, it reduces the number of variables that are studied. Thirdly, it enables the researcher to rewrite the data set into an alternative form (Johnston, 1978). Finally, it allows for the classification of variables, thus identifying structure in relationships between variables (Statistica, 1995). PCA was first developed by psychologists to analyse a number of results from aptitude tests, but since then it has become a rigorous statistical tool for the resolution of variables within a scientific data set (Joreskog, 1977). It was hoped that by using this technique, relationships between the sedimentological data from the South African topographical dunes would emerge and background noise within the data set would be eliminated. It was also hoped that, though the PCA, these relationships could then be related to back to causal environmental factors.

Before beginning a PCA, data must be standardized so that variables which are expressed in different units can be compared with each other (Davis, 1986). The components or eigenvectors are the new factors which have been created, and the component loadings are the inter-correlated variables and components. (Davis, 1986). An eigenvalue is the total variance accounted for in a component (Davis, 1986). PCA is an inductive technique that allows background noise in the data set to be reduced while not losing any resolution within the data set (Till, 1974). The researcher can even rotate the component loadings in order to further highlight the important variables, further minimising noise (Till 1974).

A PCA was conducted on the sedimentological data from this research in order to discover more about how different variables in a dune environment relate to each other (i.e. slope angle, vegetation cover, chemical composition of the grains and scanning electron microscope results were not included in the PCA). The data were standardized using the STATISTICA Factor Analysis standardization by column program, and then the PCA was conducted on all samples for all variables using the STATISTICA PCA program. PCA's were also conducted on all variables using only the Breede River Valley samples, and all variables using only the southern Kalahari topographical dune samples. The component loadings were then rotated using STATISTICA's varimax rotation as this rotation strategy maximises variance rotation of original variables while minimising variance of new variables (Statistica, 1995). Because there was very little difference between the rotated and unrotated component loadings, the unrotated loadings were used for the cluster analysis.

3.5.3 Cluster Analysis

The conceptual basis of cluster analysis lies in the computation of 'distances' between observations and then tries to find groupings of phenomena in parameter space (Hewitson, pers. comm.). There is no one correct classification of the data, and thus different numerical strategies will often produce different results (Williams and Lance, 1977). Cluster analysis is therefore the placing of data into homogeneous groups such that a relationship between the groups is revealed (Davis, 1986). In this sense, cluster and discriminant analysis are similar (Till, 1974), and it is for this reason that it was not considered necessary to carry out a discriminant analysis. Two types of clustering were conducted, namely, single linkage, and Ward's method.

In a single linkage cluster, the nearest (and therefore most similar) objects are joined to build a group until all objects have been grouped to form clusters (Till, 1974). The distance between objects can be measured in a variety of ways, but the most common, and the one used in this research, is Euclidean distance (Statistica, 1984). This single linkage method was used as it strings "like" objects together and therefore identifies outliers within the data set (Hewitson, pers. comm.).

Ward's clustering finds regions in space that are poorly populated by observations and it groups them together, therefore identifying groups within the data set (Hewitson, pers. comm.). It is distinct from the single linkage method in its use of analysis of variance to determine clusters. Although it is regarded as an efficient method of clustering, it does tend to create clusters of a small size (STATISTICA, 1995).

As the PCA method reduces noise within a data set, therefore providing a reflection of the important variables (Hewitson, pers. comm.), cluster analysis was performed on the PCA results of the three different scenarios already described. Both cluster methods were used in order to highlight not only the outliers of the data set (single linkage), but also the main groups within the data (Ward).

3.6 SUMMARY

This chapter has reviewed the research procedures and methods that have been used in this dissertation. The identification of topographical dunes using aerial photographs was discussed, as well as the field work and laboratory analysis that took place once the topographical dunes had been identified. A comprehensive description of the statistical methods that were used by the researcher has also been presented. The following chapter discusses the observations that were made during the field work, and thus a description of each topographical dune in the southern Kalahari and Breede River Valley is given.

CHAPTER 4: SITE DESCRIPTIONS

4.1 INTRODUCTION

This chapter presents descriptions of the topographical dunes, based on fieldwork observations. The southern Kalahari topographical dunes are first presented, followed by a description of the Breede River Valley topographical dunes. Table 4.1 shows the grid reference, aspect (i.e. on which side of the topographical barrier the dune rests), slope, and metres above sea level (m.a.s.l.) for each site, and these should be viewed in conjunction with the site sketches and photographs so as to gain a clearer understanding of each topographical dune site.

Site	Grid Reference	Aspect	Mean Slope	m.s.a.l.
Kanoneiland 1 & 2	28°39'11"S 20°10'30"E	SW Face	10.2° (K1) 18.1° (K2)	~ 820 - 880
Prynnsberg 1	28°40'58"S 22°08'26"E	NW Face	4.6°	~ 1040 - 1120
Prynnsberg 2	28°41'04"S 22°08'27"E	SW Face	12.1°	~ 1040 - 1140
Sandput	33°50'51"S 19°48'29"E	SE Face	8.6°	~ 220 - 400
Sandberg	33°50'43"S 19°47'52"E	NW Face	23.5°	~ 320 - 560
Moddergat	33°49'51"S 19°24'57"E	SE Face	16.7°	~ 210 - 320

Table 4.1 The location and mean slope statistics for each topographical dune from the southern Kalahari and Breede River Valley.

4.2 THE SOUTHERN KALAHARI

4.2.1 Kanoneiland 1 and 2

These two very steep topographical dunes (Plates 4.1 and 4.2) are approximately 750 m from each other on a communal farm, about 7 km from Keimos in a northeast direction (see Fig. 1.1). Both topographical dunes are 8.25 km north of the present course of the Orange River, and are surrounded by numerous linear dunes (Fig. 4.1). The topographical dunes are relatively well vegetated near their bases (approximately 40% ground cover), but there is a decrease in vegetation cover with an increase in gradient. The vegetation comprises Karroid open shrubland about 0.5 to 1 m in height, dominated by various Acacias, Euphorbia and Crassula species. Kokerbooms (*Aloe dichotoma*) are also present around the topographical dune. The base of the dunes are hard and stony (mainly quartz fragments), becoming very sandy further up the dune. The surrounding land is utilized for grazing for cattle, goats and sheep. A few indigenous buck (duiker and springbok) species also inhabit the area, but none were observed. The land does appear to be overgrazed in certain areas. The reddish-brown windblown sand of the Gordonia Formation (Quaternary age) rests on mesocratic well-foliated adamellitic granite gneiss of the Vaalputs Granite Formation of Mokolian Age (Late Proterozoic) (Steyn, 1988).

No exposed faces are visible on either of the topographical dunes, and pits were not excavated due to the steepness of the dunes. Surface samples were taken, and these samples consisted of well sorted, apedal dune sand with a Munsell Colour of 5YR 5/8 (Yellowish Red).

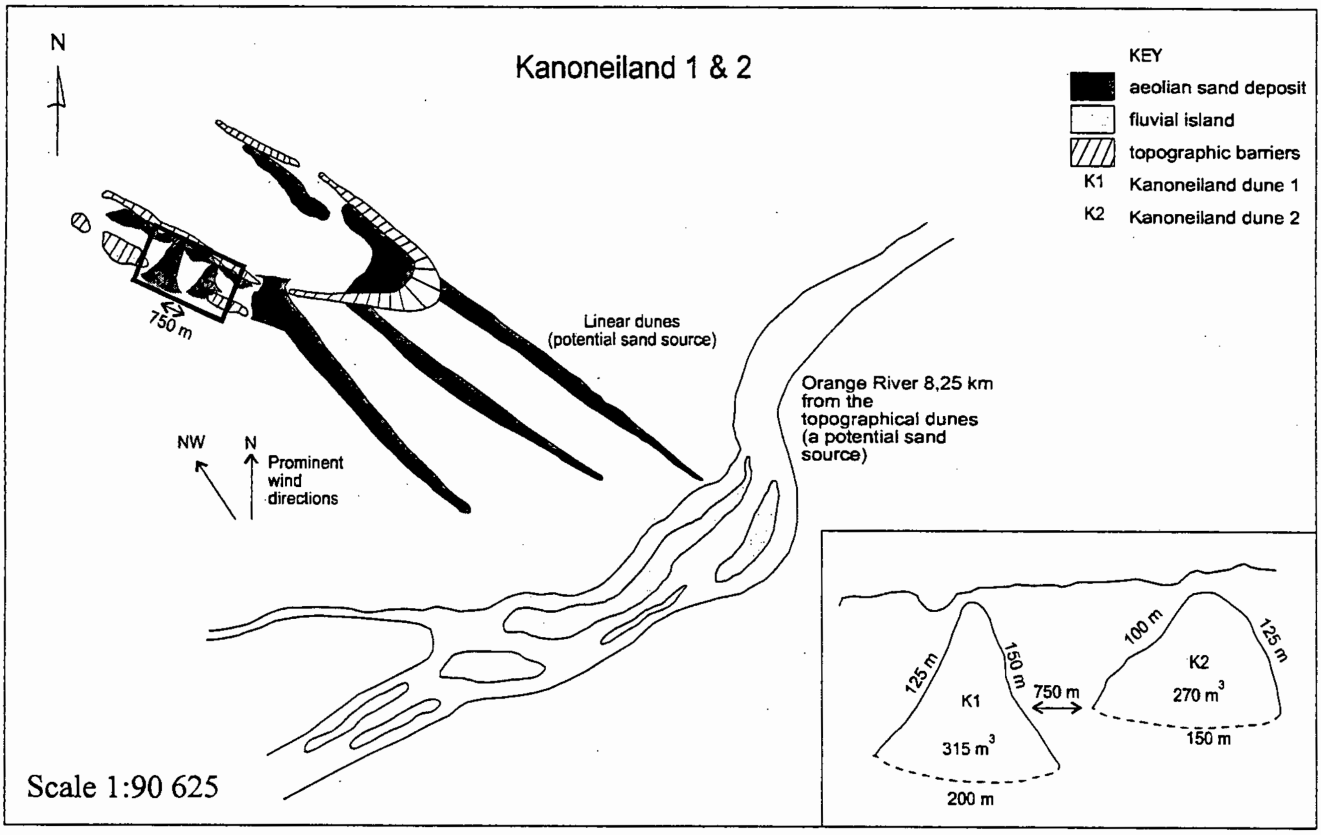


Figure 4.1 A plan view of the Kanoneiland 1 & 2 topographical dunes with an insert showing the size and volume of sand of each dune.

e **4.1** *A view of the Kanoneiland* 1 topographical dune. The savanna trees are approximately 0.5 m high for scale.

e **4.2** The Kanoneiland 2 topographical dune while taking slope profile measurements.

e **4.3** The top of the Prynnsberg 1 topographical dune. Note how it descends sharply before adjoining the topographical barrier.

4.2.2 Prynnsberg 1

The topographical dune is found on Prynnsberg Farm, situated 30.75 km northeast of Groblershoop (Figs. 4.2 and 4.3). The dune is about 38 km northeast of the present course of the Orange River, and it is also surrounded by numerous linear dunes. A feature of this dune is the way it peaks before reaching the rocky hill (Plate 4.3), and then descends sharply before ramping onto the rocky outcrop. The dune is exceptionally well vegetated (approximately 80% ground cover) with grasses and open shrubland on average 0.5 to 1 m high. Acacia and Crassula species are prominent. The land is used for grazing for goats and sheep, but indigenous buck (duiker and springbok) are present. The land appears to be well managed and there are no signs of overgrazing. The country rock comprises quartz-sericite, schist and quartzite from the Groblershoop Formation. This formation is part of the Olifantshoek Group, also of Mokolian age (Moen, 1975).

There are no noticeable stratigraphic units in the pit which was excavated on this dune (Fig. 4.4), and therefore samples were taken every 30 cm down the pit. The sand is well sorted and apedal, with a Munsell Colour of 5YR 5/8 (Yellowish Red), without any mottling. Roots are present near the top of the pit, and a few roots are also evident throughout the profile. Samples for laboratory analysis were taken at 30 cm intervals. These are discussed in more detail in Chapters 5 and 6.

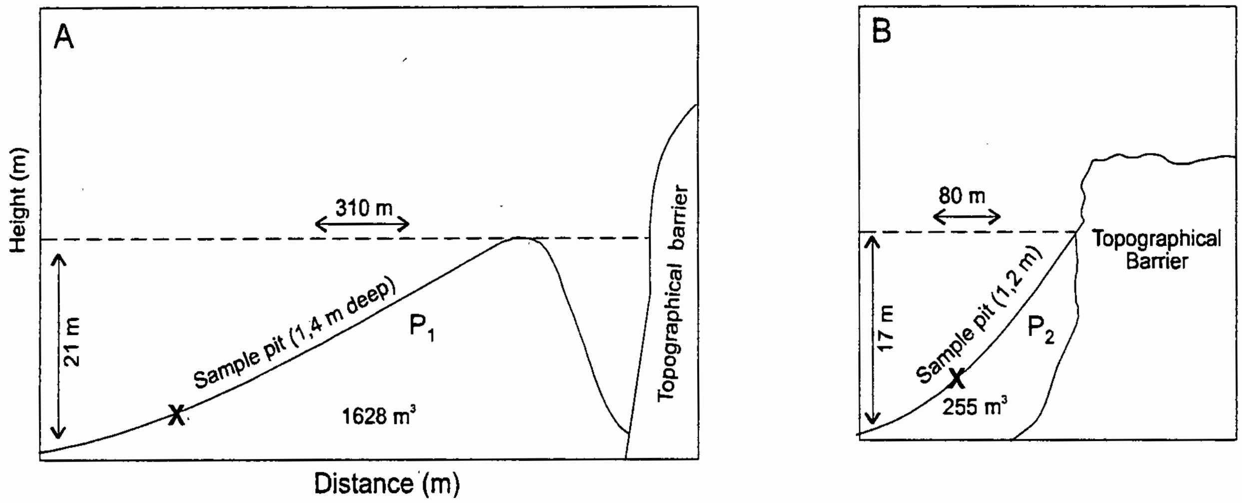


Figure 4.2 Cross-sections of the Prynnsberg 1 (A) and 2 (B) topographical dunes.

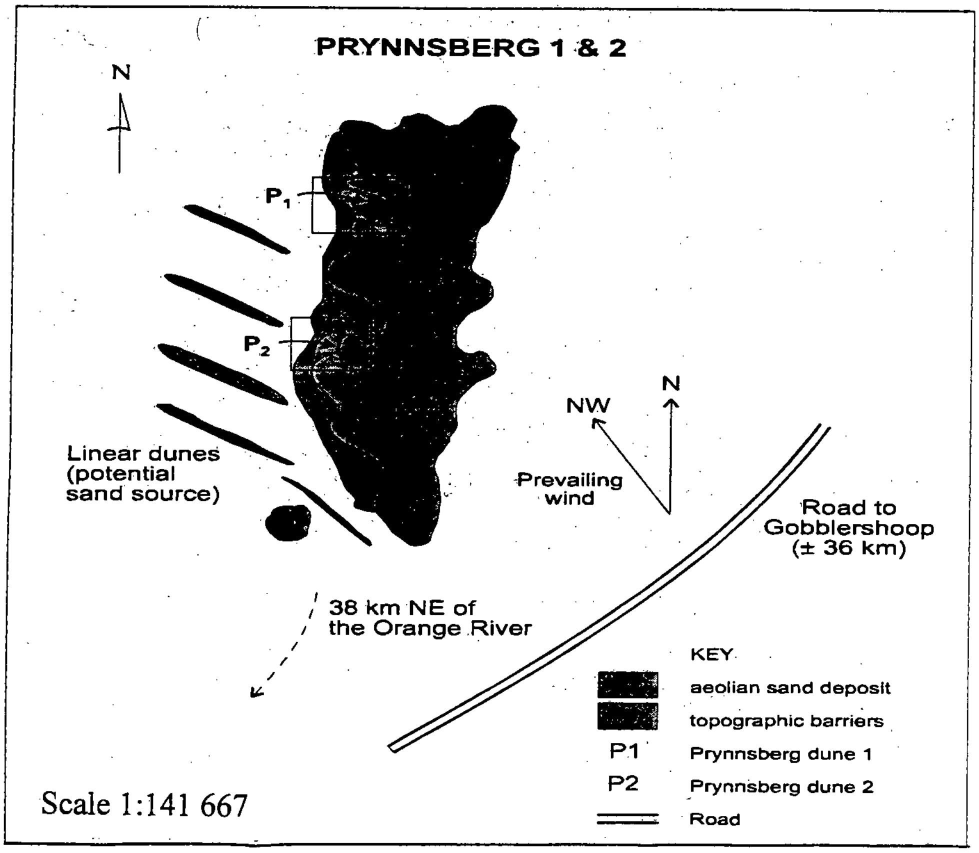


Figure 4.3 A plan view of the Prynnsberg 1 and 2 topographical dunes which are banked against the Prynnsberg Mountain, northwest of Groblershoop.

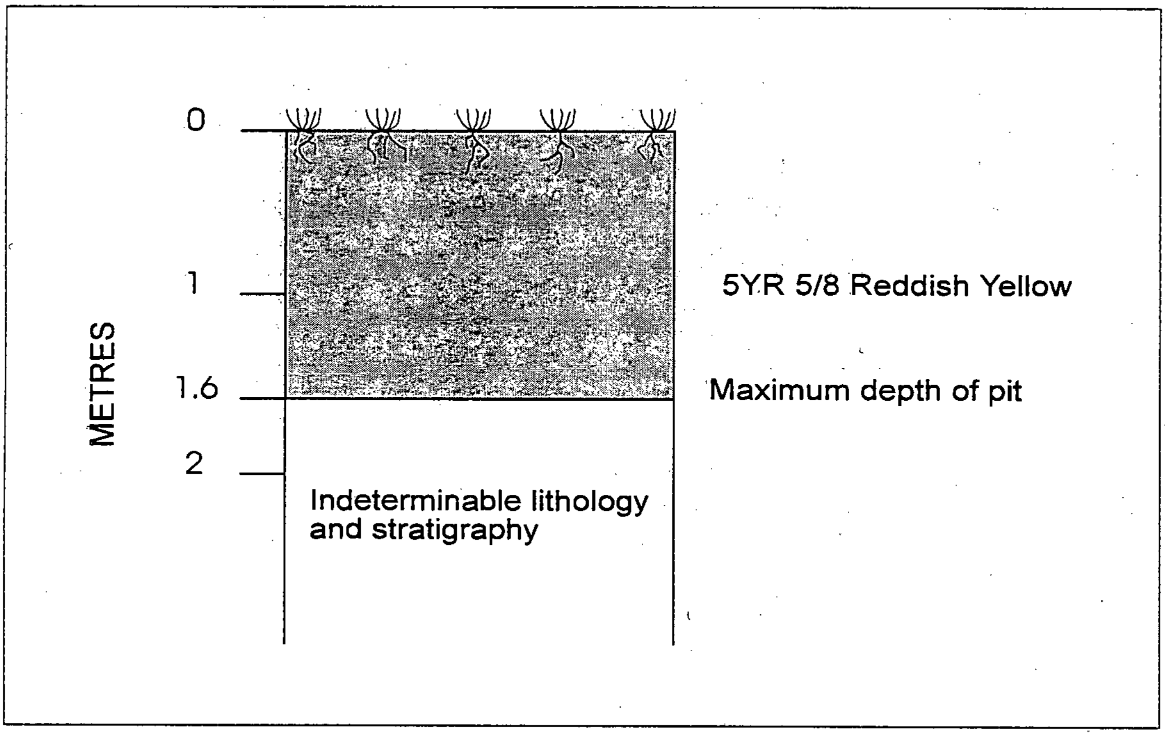


Figure 4.4 Prynnsberg 1 topographical dune pit profile.

4.2.3 Prynnsberg 2

This dune is also on Prynnsberg Farm, about 30 m from Prynnsberg 1, and is situated approximately 30 km northeast of Groblershoop (see Fig. 1.1). Prynnsberg 2 is approximately 38 km northeast of the present course of the Orange River and is surrounded by linear dunes (Figs. 4.2 and 4.3). It is a short and rather steep topographical dune (Fig. 4.2) that is well vegetated at the base, and there is a decrease in vegetation with an increase in gradient (Plate 4.4). The physical characteristics of the surrounding environment are identical to that of Prynnsberg 1 as they are only 30 m apart.

There are no noticeable stratigraphic units in the pit (Fig. 4.5) and the sands do not display any structure. The sand is well sorted with a Munsell Colour of 5YR 5/8 (Yellowish Red). A few roots are present at the top of the pit. Samples for OSL dating were systematically taken near the top, middle and base of the pit, and samples for laboratory analysis were taken at 30 cm intervals. These are discussed in more detail in Chapters 5, 6 and 7.

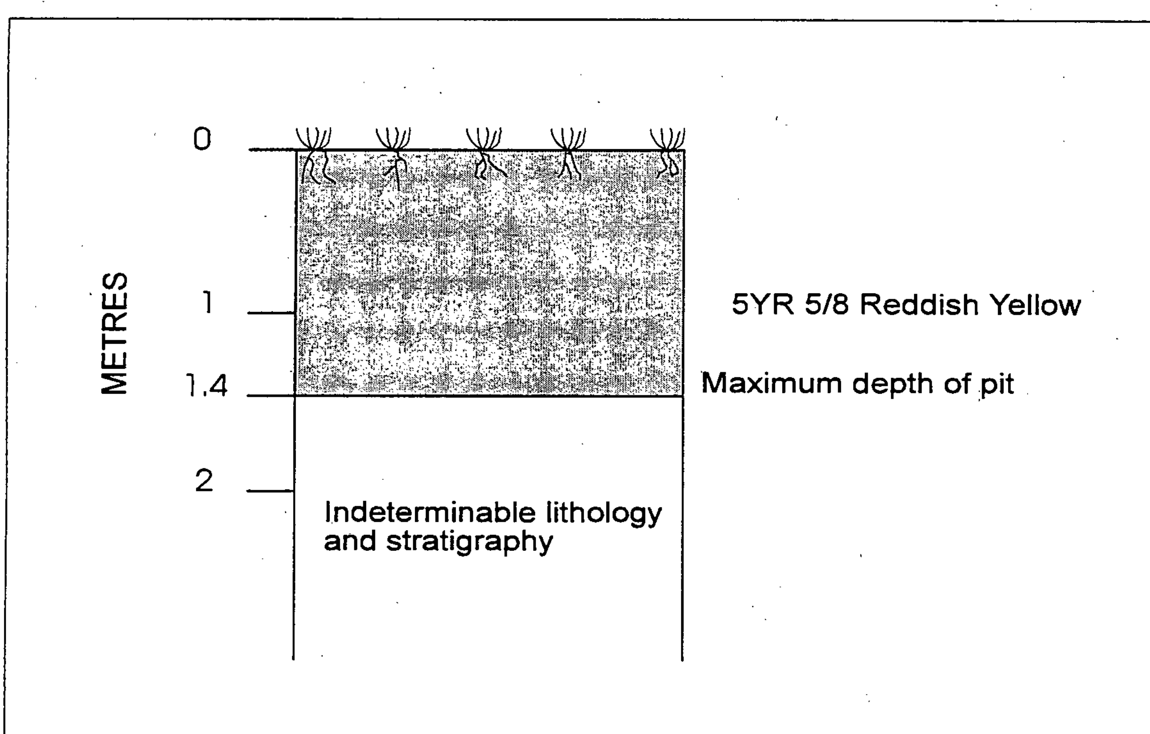


Figure 4.5 The Prynnsberg 2 topographical dune pit profile.

ate 4.4 A view of the Prynnsberg 2 topographical dune.

Plate 4.5 A view of the Sandput topographical dune. Note the deflation hollows evoked by sand quarrying. The study site on this dune is at the bottom of the left hand side deflation hollow.

Plate 4.6 The exposed face which was found as a result of the sand quarrying activities which are currently taking place on the Sandput dune.

te 4.4 A view of the Prynnsberg 2 topographical dune.

late 4.5 A view of the Sandput topographical dune. Note the deflation hollows evoked by sand quarrying. The study site on this dune is at the bottom of the left hand side deflation hollow.

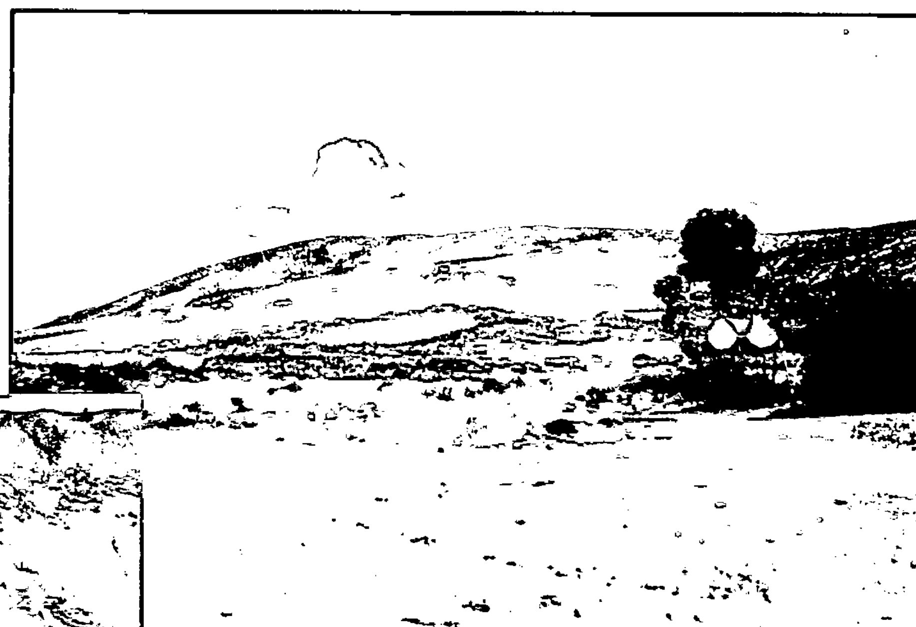


Plate 4.6 The exposed face which was found as a result of the sand quarrying activities which are currently taking place on the Sandput dune.

4.3 BREEDE RIVER VALLEY

4.3.1 The Sandput

The Sandput is a sand quarry approximately 7.75 km southwest of Robertson (see Fig. 1.2). The topographical dune is about 1.75 km southeast of the present course of the Breede River (Figs. 4.6 and 4.7). The dune is covered in part (about 40% ground cover) by a mixture of Karroid shrubs and grasses, and fynbos restios (Plate 4.5). No agriculture is taking place on or around the dune, but the base of the dune is extremely disturbed due to the current sand quarrying activities. The topographical dune rests on Bidouw shales, siltstones and sandstones from the Waboomberg Formation. This formation is part of the Bokkeveld Group of the Cape Supergroup, which is of Devonian Age (Late Palaeozoic) (Visser, 1984).

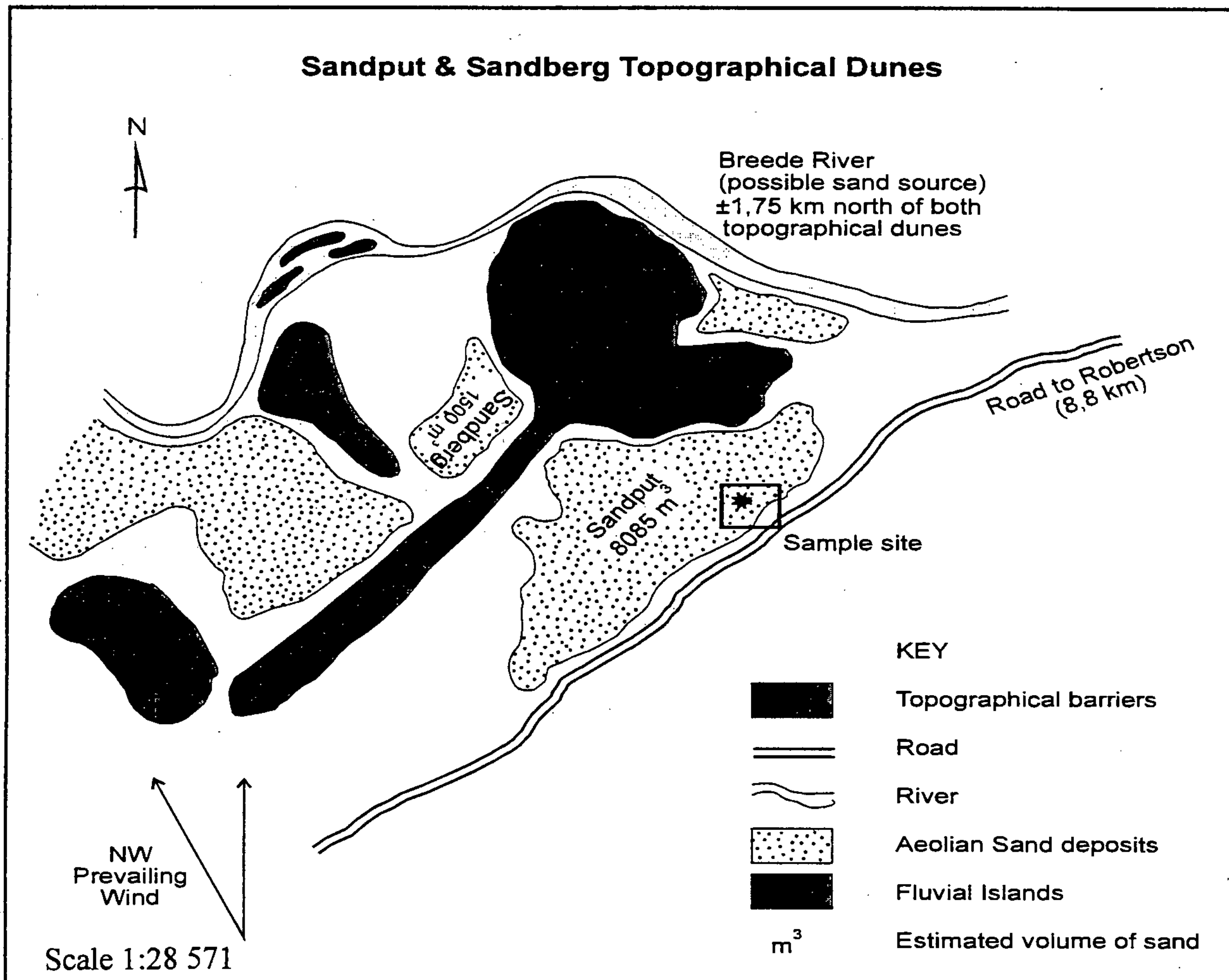


Figure 4.6 The Sandput and Sandberg topographical dunes in the context of their surrounding environment.

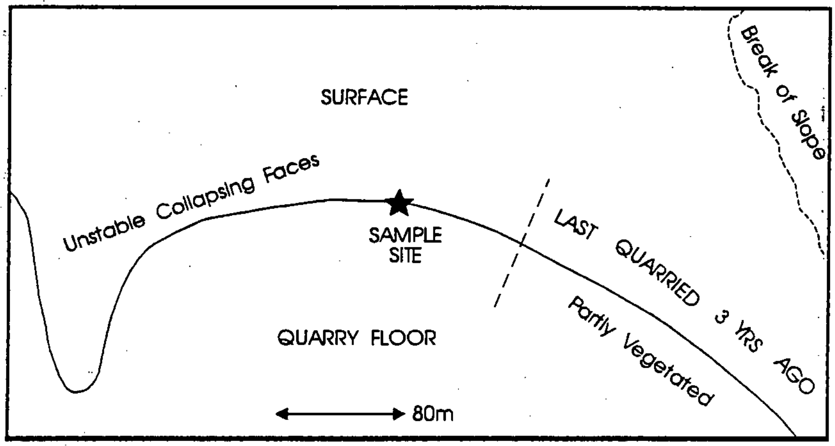


Figure 4.7 A plan view of the Sandput exposed face in relation to the rest of the topographical dune.

Throughout the profile (Fig. 4.8; Table 4.2; Plate 4.6) there are well sorted medium sized sand grains. With the exception of the columnar structure near the top of the profile, the sands are apedal. The white stone line at the base of the profile comprises a 10 cm layer with weathered quartz and sandstone pebbles protruding *in situ*. These vary between 2 mm to 15 mm in long axis length. There is a smooth transition from one layer to the next, and layers have been identified by changes in colour due to the lack of structure.

Depth (m)	Munsell Colour	Texture	Structure
0 - 0.5	10YR 5/3 Brown	Sandy (surface layer with organics)	Apedal
0.5 - 1.1	10YR 7/6 Yellow	Sandy	Apedal
1.1 - 2.2	10YR 7/6 Yellow	Sandy (sample for dating taken)	Columnar structuring
2.2 - 6.1	10YR 7/6 Yellow	Sandy	Apedal (pitted surface from the abrasive action of windblown sand)
6.1 - 6.3	10YR 5/2 Greyish Brown	Sandy	Apedal
6.3 - 6.9	10YR 6/6 Brownish Yellow	Sandy	Apedal
6.9 - 7.0	10YR 5/2 Greyish Brown	Sandy	Apedal
7.0 - 7.2	10YR 6/6 Brownish Yellow	Sandy	Apedal
7.2 - 7.6	10YR 5/2 Greyish Brown	Sandy (sample for dating taken)	Apedal
7.6 - 7.8	10YR 6/6 Brownish Yellow	Sandy	Apedal
7.8 - 8.6	10YR 8/1 White	Sandy	White stone layer

Table 4.2 The depth and description for each stratigraphic layer from the Sandput exposed face profile.

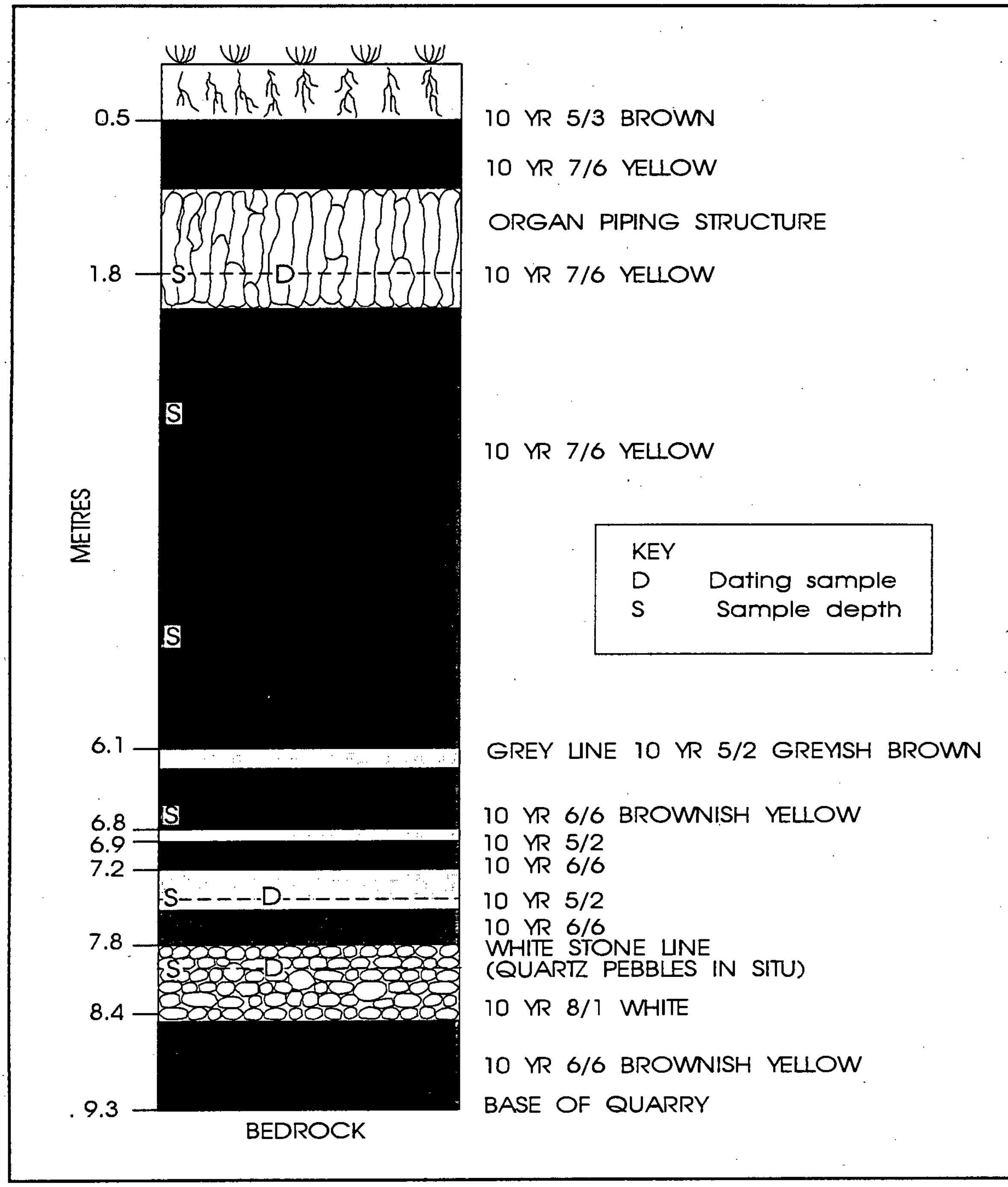


Figure 4.8 The Sandput topographical dune exposed face.

4.3.2 Sandberg

This very steep topographical dune (see Fig. 1.2) is on the opposite side of the Sandberg Ridge to the Sandput, on the farm Goedereede. The Sandberg topographical dune is approximately 8.8 km southwest of Robertson (Plate 4.7, Fig. 4.6), and is about 1.75 km south of the present course of the Breede River. This site displays around 45% vegetation comprising undisturbed mountain fynbos. At the base of the slope is the Breede River, which has been canalized in this area, and on the other side of the river are vineyards. A veneer of poorly sorted, angular to subangular gravels (long axis length from 2 mm to 5 cm) lie on the surface of the topographical dune. These clasts vary greatly in roundness and sphericity. The geology of the surrounding area is similar to the Sandput as this topographical dune is on the opposite side of the Sandberg Ridge.

No exposed faces are visible on the dune and no pits were dug due to the steepness of the topographical dune. Surface samples were, however, taken at regular intervals up the dune. The dune is sandy and apedal, with a Munsell Colour of between 10YR 6/4 (light yellowish brown) to 10YR 7/6 (yellow).

4.3 Moddergat

This topographical dune is situated on the wine farm Moddergat (see Fig. 1.2). It is approximately 25 km southwest of Worcester. The Moddergat dune (Figs. 4.9 and 4.10) is about 500 m northwest of the present course of the Hoek River (a tributary of the Breede River). The dune is vegetated, in part (around 40% ground cover), by Karroid shrubs and restionaceaes. The most distinctive feature of this dune is the numerous deflation hollows that are visible on the dune (Plate 4.8). These hollows are very sparsely vegetated and are covered in angular to subangular gravels which vary greatly in shape, size (long axis length from 2 mm to 5 cm), roundness and sphericity. There is no agriculture on the dune, but on the other side of the road, which parallels the base of the dune, vineyards are present. The country rock comprises shales and weathered quartzite from the Witpoort Formation, Witteberg Group. This group is also part of the Cape Supergroup. The rock is overlain by aeolian sands of Quaternary origin (De Villiers, 1955).

No exposed faces were visible on the topographical dune and thus two pits were dug, one at the bottom of the dune (Moddergat Base; Fig. 4.11) and one approximate one-third up the dune (Moddergat Middle; Fig. 4.12).

ate 4.7 A view of the very steep Sandberg topographical dune which is on the opposite side of the Sandberg Mountain to the Sandput dune.

ate 4.8 The Moddergat topographical dune is well vegetated, but has numerous deflation hollows.

ate 4.9 The Moddergat 2 (middle) pit which displays a marked and abrupt change in sand colour.

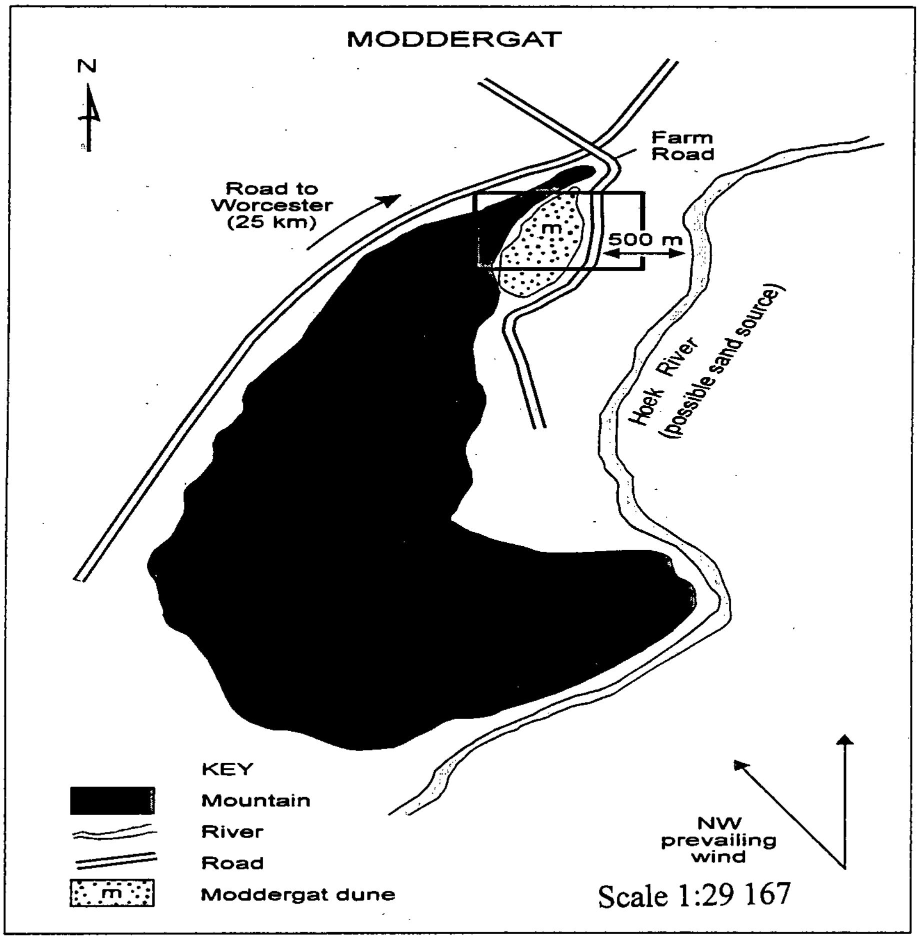


Figure 4.9 A plan view of the Moddergat topographical dune and its surrounding environment.

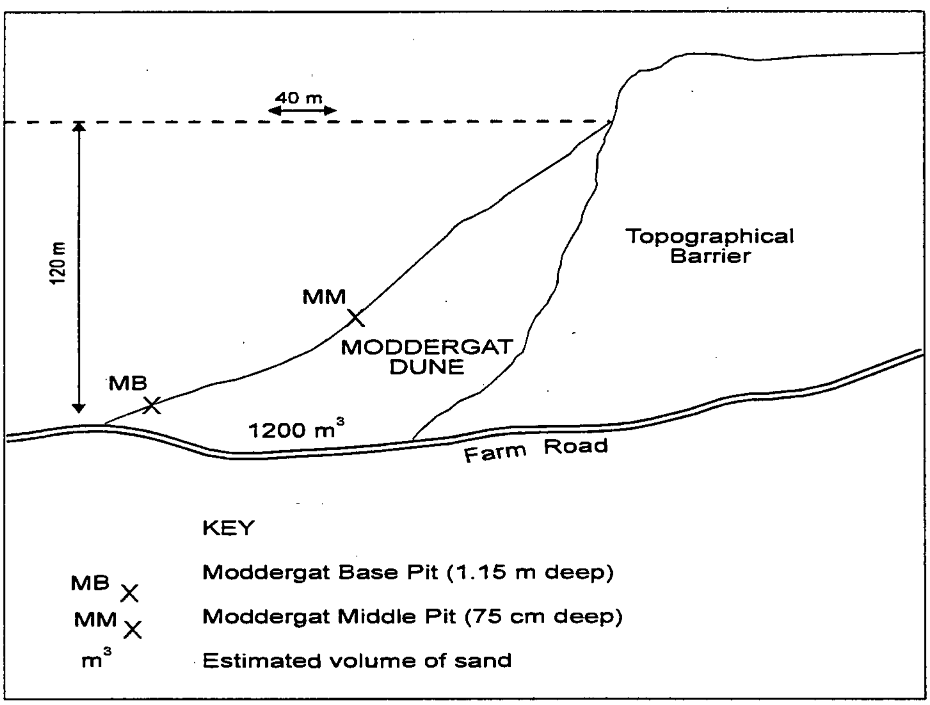


Figure 4.10 The estimated volume of sand and dimensions of the Moddergat topographical dune.

Moddergat Base

Upon examination of the pit, no distinct stratigraphic units were visible, and thus samples were taken at regular intervals down the pit (Fig. 4.11). No vegetation is present in this area and no organic layer is visible. The sands are apedal with a Munsell colour of 10YR 6/4 Yellowish Brown, no mottling is evident. The basal contact of the sand with the underlying geology is indeterminable due to the construction of a road near the base of the dune.

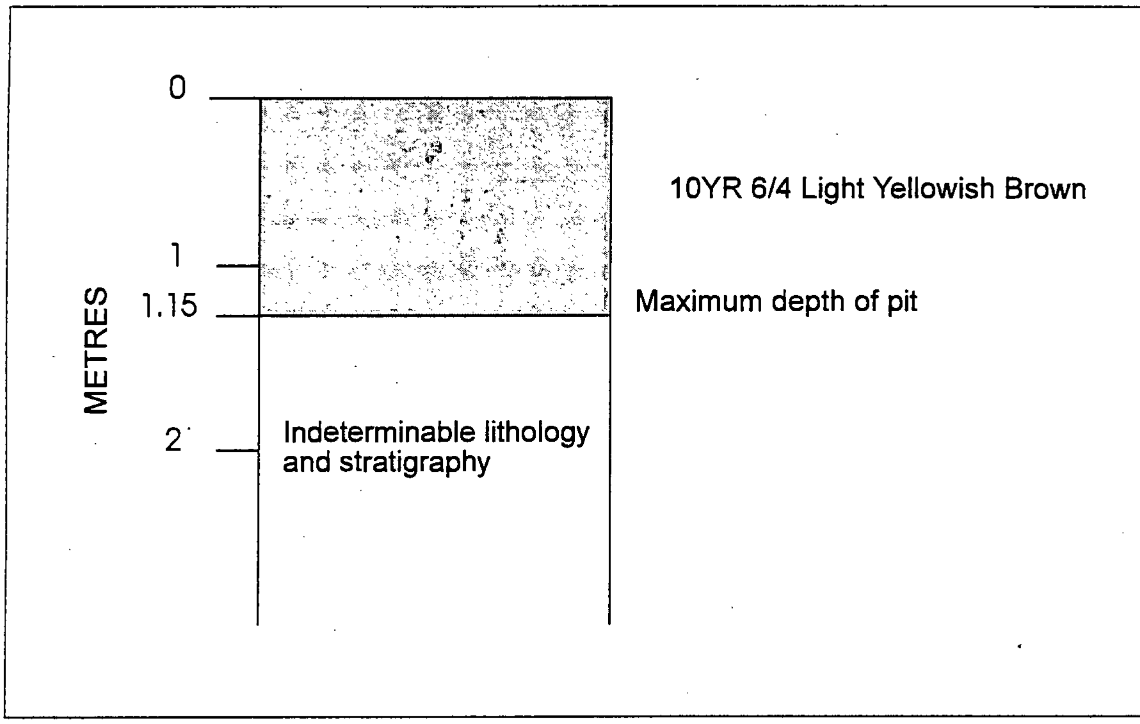


Figure 4.11 The Moddergat Base topographical dune pit profile.

Moddergat Middle

The Moddergat Middle pit (Table 4.3) comprises sandy apedal material which has a very sharp Munsell colour transition from yellowish brown to brown. No organic material was present within the profile, and due to the steepness of the dune, only a 75 cm pit could be dug.

Depth (cm)	Munsell Colour	Texture	Structure
0 - 10	10YR 6/4 light Yellowish Brown	Sandy (some plant roots present)	Apedal
10 - 75	10YR 5/3 Brown	Sandy	Apedal

Table 4.3 The depth and description for each stratigraphic layer from the Moddergat Middle pit.

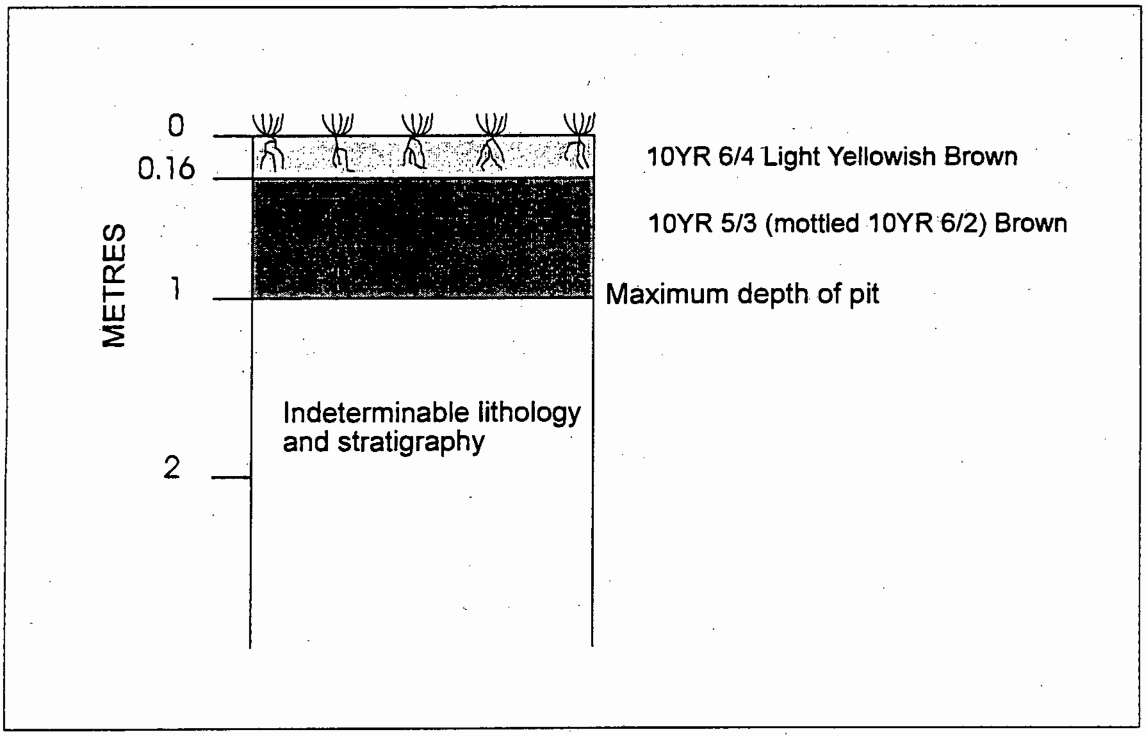


Figure 4.12 The Moddergat Middle topographical dune pit profile.

4.4 SUMMARY

Both the Breede River Valley and the southern Kalahari sites displayed similar gross morphologies. All the dunes comprised apedal, unconsolidated and well sorted sands. All stratigraphic units were defined on the basis of colour. The Kalahari topographical dunes appear to be very uniform, as no changes in colour were detected. The topographical dune that demonstrates the greatest potential for a detailed palaeoenvironmental reconstruction is the Sandput, as it is the only dune where an exposed face of 10 m was found, thus allowing a profile to be examined. The Sandput also showed numerous colour changes, and one layer even displayed columnar structuring (Fig. 4.10).

In the field, it was observed that the possible sand sources for these dunes are the Breede River and its tributaries in the Breede River Valley area, and the Orange River, as well as the large linear dune field in the southern Kalahari region. It is evident from the location of the topographical dunes and their proximity to the respective sand sources that there are dominant winds in the region which must have caused these types of dunes to form. In the Kalahari, two main winds were observed, i.e. the northwesterly wind and the southwesterly wind. In the

Breede River Valley, the dominant sand moving wind is the southeaster. These winds and their relevance to the study will be discussed in more detail in Chapter 6.

In this chapter the details of each topographical dune site have been outlined and discussed on the basis of observations made in the field. In the following chapter, the analytical results of the field, laboratory and statistical components of this research will be presented.

CHAPTER 5: ANALYTICAL RESULTS

5.1 INTRODUCTION

In this chapter, the results of the study are presented. The slope profiles for each topographical dune are presented first, followed by the results of the granular composition analysis. The results of the chemical laboratory procedure, namely pH, conductivity and chemical composition analysis, are also given. Scanning electron micrographs of the sand grains from each site are shown and the results of the optically stimulated luminescence dating procedure are presented. Finally, the results of the statistical analyses performed on the raw data are described.

5.2 SLOPE PROFILES

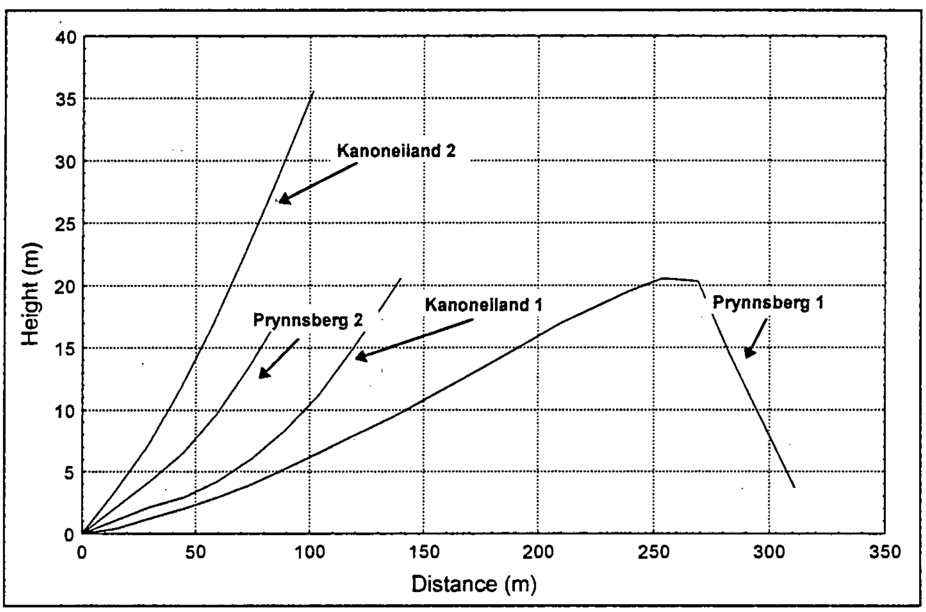


Figure 5.1 Slope profiles of the four southern Kalahari topographical dunes.

Figures 5.1 and 5.2 show the gradient of the topographical dunes in each region. The gradients of topographical dunes Kanoneiland 1 and 2 in the southern Kalahari (Fig. 5.1), and the Sandberg in the Breede River Valley (Fig. 5.2) are steep in comparison with the other topographical dunes, and thus pits which were dug kept collapsing. It is evident from Figure

5.1 that Prynnsberg 1 has a gentle windward slope culminatng in a crest and a leeward slope before reaching the topographical barrier. Slope profile data is presented in Appendix C.

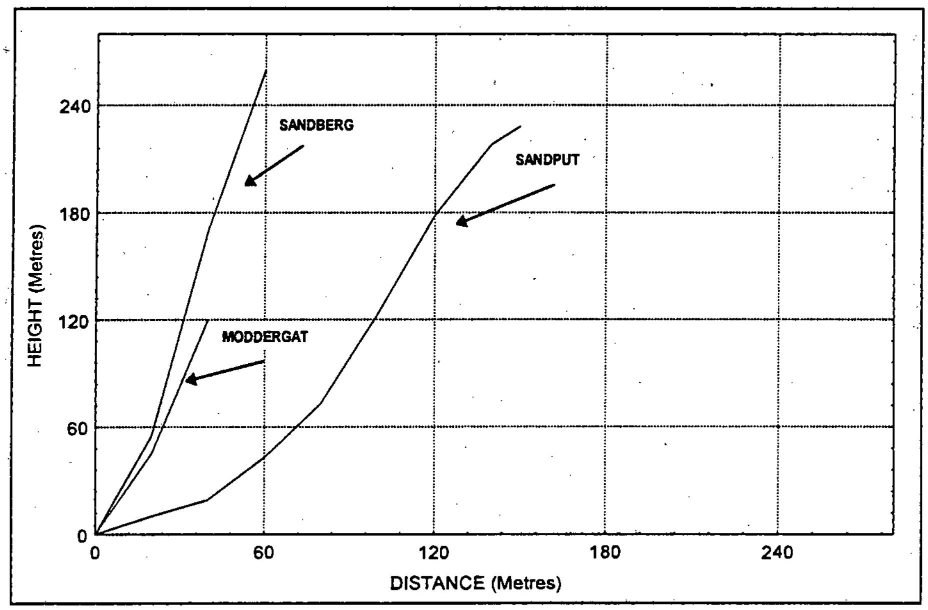


Figure 5.2 Slope profiles of the three Breede River Valley topographical dunes.

5.3 PARTICLE SIZE ANALYSIS

5.3.1 Texture and Munsell Colour

Tables 5.1 and 5.2 present the results of the texture analysis. All the samples from the Breede River Valley constitute pure sand (i.e. samples comprise between 95% - 100% sand), while the samples from the southern Kalahari are a mixture of pure sand and sand (i.e. samples comprise 85% - 100% sand). It can be seen in Table 5.1 that the sand in the southern Kalahari is exceptionally uniform in colour, i.e. 5YR 5/8 (yellowish red). The colour of the Breede River topographical dunes (Table 5.2) is slightly more varied, ranging from 10YR 8/1 (white) to 10YR 5/2 (greyish brown).

SAMPLE	MUNSELL COLOUR	SAMPLE TEXTURE
PRP1	5 YR 5/8	Pure Sand
PRP2	5 YR 5/8	Pure Sand
PRP3	5 YR 5/8	Pure Sand
PRP4	5 YR 5/8	Sand
PRP5	5 YR 5/8	Sand
PYP1	5 YR 5/8	Pure Sand
PYP2	5 YR 5/8	Pure Sand
PYP3	5 YR 5/8	Pure Sand
PYP4	5 YR 5/8	Pure Sand
PRS1	5 YR 5/8	Sand
PRS2	5 YR 5/8	Sand
PRS3	5 YR 5/8	Sand
PRS4	5 YR 5/8	Sand
PRS5	5 YR 5/8	Sand
PRS6	5 YR 5/8	Pure Sand
PYS1	5 YR 5/8	Pure Sand
PYS2	5 YR 5/8	Pure Sand
PYS3	5 YR 5/8	Pure Sand
PYS4	5 YR 5/8	Pure Sand
PYS5	5 YR 5/8	Pure Sand
PYS6	5 YR 5/8	Pure Sand
PYS7	5 YR 5/8	Pure Sand
KA1	5 YR 5/8	Sand
KA2	5 YR 5/8	Sand
KA3	5 YR 5/8	Sand
KA4	5 YR 5/8	Pure Sand
KA5	5 YR 5/8	Pure Sand
KA6	5 YR 5/8	Pure Sand
KA7	5 YR 5/8	Pure Sand
KA8	5 YR 5/8	Pure Sand
KN1	5 YR 5/8	Sand
KN2	5 YR 5/8	Sand
KN3	5 YR 5/8	Pure Sand
KN4	5 YR 5/8	Pure Sand
KN5	5 YR 5/8	Pure Sand
KN6	5 YR 5/8	Pure Sand
KN7	5 YR 5/8	Pure Sand

Table 5.1 Munsell colour and texture of the southern Kalahari topographical dunes (refer to Appendix B for the key to site names).

SAMPLE	MUNSELL COLOUR	SAMPLE TEXTURE
S1	10YR 6/4	Pure Sand
S2	10YR 7/4	Pure Sand
S3	10YR 7/6	Pure Sand
S4	10YR 7/4	Pure Sand
MB1	10YR 6/4	Pure Sand
MB2	10YR 6/4	Pure Sand
MB3	10YR 6/4	Pure Sand
MM1	10YR 6/4	Pure Sand
MM2	10YR 5/3	Pure Sand
MM3	10YR 5/3	Pure Sand
SP1	10YR 5/3	Pure Sand
SP2	10YR 7/6	Pure Sand
SP3	10YR 7/6	Pure Sand
SP4	10YR 6/6	Pure Sand
SP5	10YR 5/2	Pure Sand
SP6	10YR 7/3	Pure Sand
SP7	10YR 8/1	Pure Sand

Table 5.2 Munsell colour and texture of the Breede River Valley topographical dunes (refer to Appendix B for key to site names).

5.3.2 Ternary Diagrams

Figures 5.3 - 5.5 show the percentages of coarse, medium and fine sand within each sample. In the southern Kalahari topographical dunes (Fig. 5.3 - 5.4), the samples vary between fine and medium sand. All samples at Prynnsberg, with the exception of two, comprise fine sand, while at Kanoneiland, with the exception of two, the samples comprise medium sand. The Breede River topographical dunes (Fig. 5.5) comprise medium and coarse sand. The Sandput comprises solely medium sand, while Moddergat and Sandberg comprise a mixture of coarse and medium sand. It should be noted that in general, the Breede River Valley dunes consist of coarser sand than the southern Kalahari dunes.

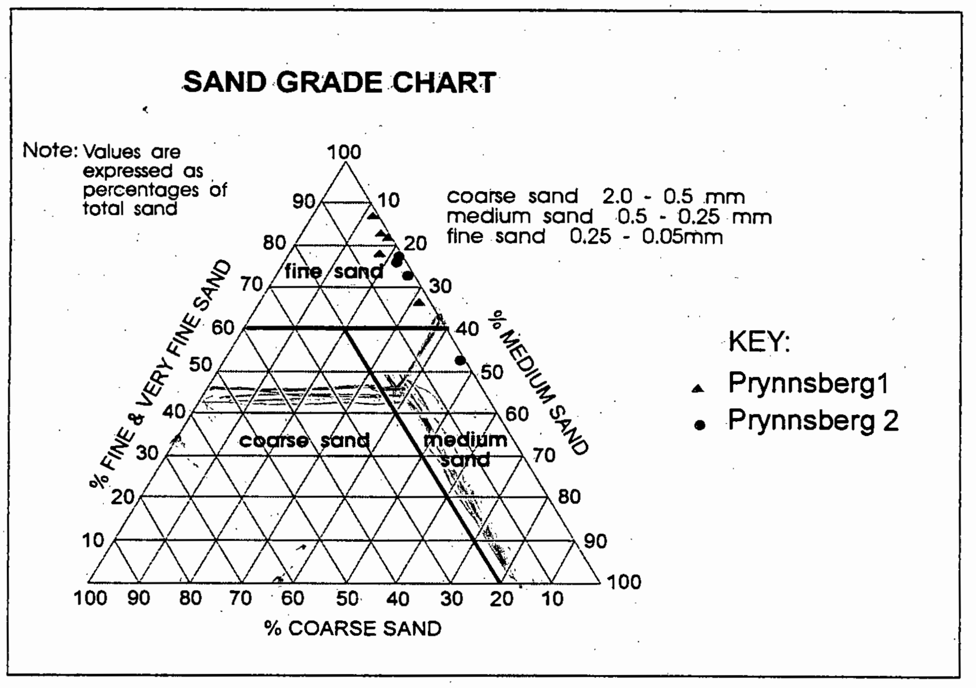


Figure 5.3 Classification of the sand fraction for the Prynnsberg 1 and 2 dune pits.

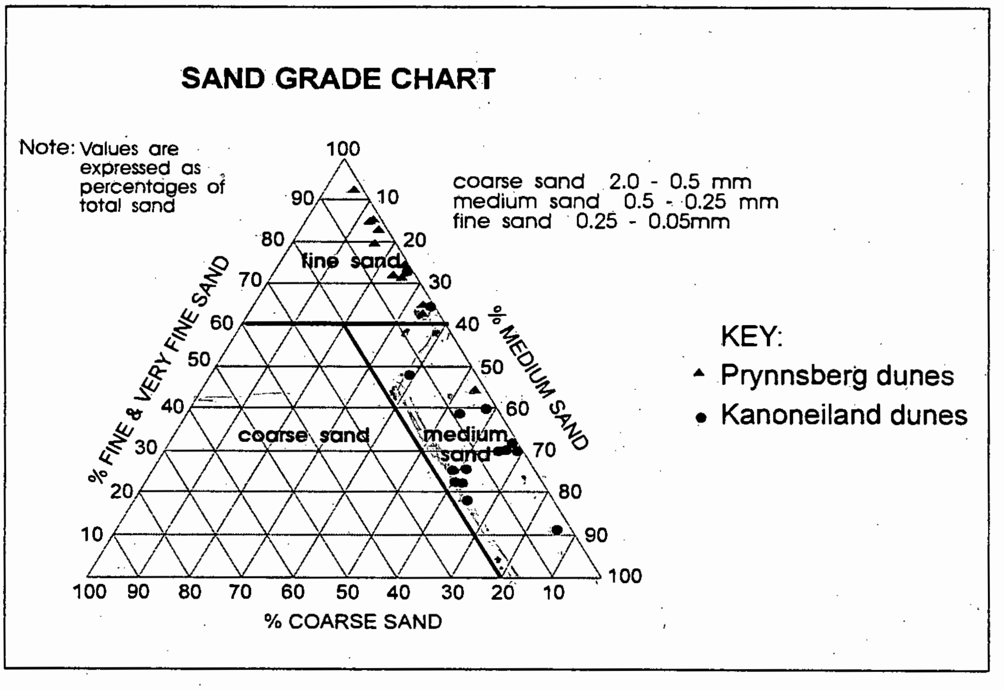


Figure 5.4 Classification of the sand fraction for the Prynnsberg and Kanoneiland topographical dunes.

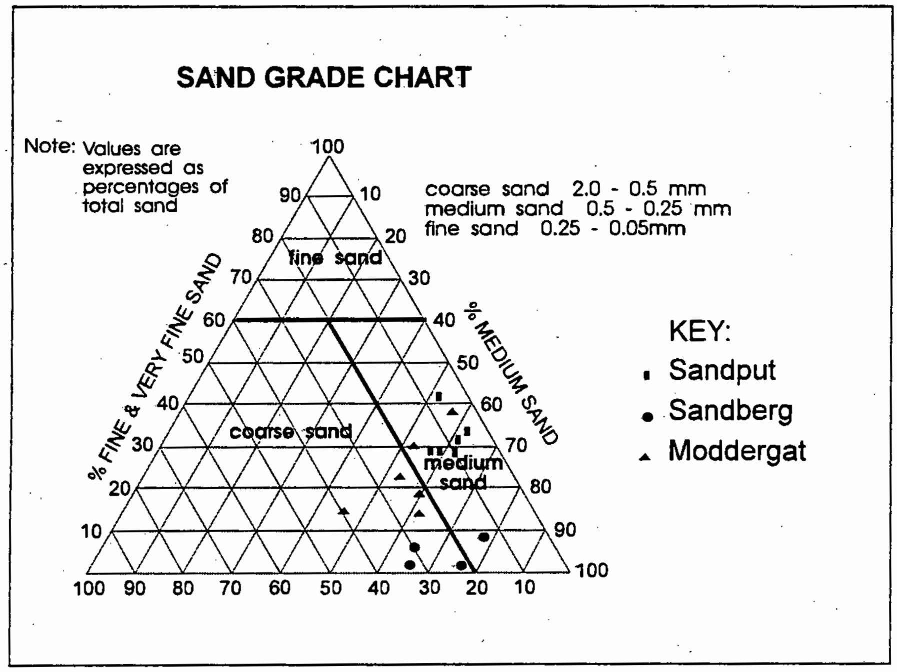


Figure 5.5 Classification of the sand fraction for the Breede River Valley topographical dunes.

5.3.3 Settling Column Results

Tables 5.3 and 5.4 indicate the sorting, skewness and kurtosis values for each sample, as well as the mean and median grain sizes for individual samples. The results (Tables 5.3 and 5.4) show that the samples vary from very well sorted to moderately well sorted. Most of the distributions are symmetrical, with a few samples showing positive skewness (samples PRS6, PYS6, PYS7, KA8, KN3, KN4, KN5, KN6, KN7, and MB3) and only one showing negative skewness (sample SP1). The majority of the topographical dune sample distributions are mesokurtic, a few are leptokurtic (samples PRP5, PYS1, PYS4, KA3, KN3, KN4, SP3, SP3, SP4, SP6 and SP7) and only one sample is platykurtic (sample MB3).

SAMPLE	MEAN	MEDIAN	SORTING	SKEWNESS	KURTOSIS
PRP1	2.21	2.2	0.52 Moderately well Sorted	0.02 Symmetrical	1.06 Mesokurtic
PRP2	2.26	2.27	0.54 Moderately well sorted	-0.01 Symmetrical	1.04 Mesokurtic
PRP3	2.46	2.48	0.52 Moderately well Sorted	-0.06 Symmetrical	1.17 Leptokurtic
PRP4	2.44	2.43	0.55 Moderately well sorted	0 Symmetrical	1.13 Leptokurtic
PRP5	2.43	2.44	0.58 Moderately well sorted	-0.08 Symmetrical	1.24 Leptokurtic
PYP1	2.32	2.3	0.45 Well sorted	0.06 Symmetrical	1.09 Mesokurtic
PYP2	2.28	2.27	0.48 Well sorted	0.06 Symmetrical	1.07 Mesokurtic
PYP3	2.03	2.01	0.46 Well sorted	0.08 Symmetrical	1 Mesokurtic
PYP4	2.31	2.31	0.44 Well sorted	-0.01 Symmetrical	1.05 Mesokurtic
PRS1	2.35	2.36	0.6 Moderately well sorted	0 Symmetrical	1.04 Mesokurtic
PRS2	2.25	2.24	0.61 Moderately well sorted	0.05 Symmetrical	1.05 Mesokurtic
PRS3	2.21	2.21	0.56 Moderately well sorted	0.02 Symmetrical	1.06 Mesokurtic
PRS4	2.26	2.24	0.6 Moderately well sorted	0.08 Symmetrical	1.05 Mesokurtic
PRS5	2.37	2.34	0.59 Moderately well sorted	0.07 Symmetrical	1.05 Mesokurtic
PRS6	2.56	2.52	0.4 Well sorted	0.16 Positively skewed	1.09 Mesokurtic
PYS1	2.47	2.47	0.48 Well sorted	0.02 Symmetrical	1.13 Leptokurtic
PYS2	2.31	2.3	0.48 Well sorted	0.05 Symmetrical	1.04 Mesokurtic
PYS3	2.39	2.4	0.43 Well sorted	0.01 Symmetrical	1.05 Mesokurtic
PYS4	2.34	2.34	0.42 Well sorted	0.03 Symmetrical	1.2 Leptokurtic
PYS5	2.26	2.24	0.39 Well sorted	0.09 Symmetrical	1.05 Mesokurtic
PYS6	2.31	2.29	0.33 Very well sorted	0.12 Positively skewed	1.1 Mesokurtic
PYS7	2.76	2.75	0.3 Very well sorted	0.1 Positively Skewed	1.04 Mesokurtic
KA1	1.89	1.97	0.76 Moderately sorted	-0.1 Symmetrical	1.05 Mesokurtic
KA2	1.55	1.6	0.56 Moderately well sorted	-0.09 Symmetrical	0.94 Mesokurtic
KA3	1.82	1.84	0.59 Moderately well sorted	-0.04 Symmetrical	1.24 Leptokurtic
KA4	1.61	1.62	0.57 Moderately well sorted	-0.01 Symmetrical	0.93 Mesokurtic
KA5	1.48	1.46	0.53 Moderately well sorted	0.08 Symmetrical	0.92 Mesokurtic
KA6	1.77	1.75	0.49 Well sorted	0.08 Symmetrical	0.98 Mesokurtic
KA6	1.78	1.76	0.45 Well sorted	0.1 Symmetrical	1.01 Mesokurtic
KA8	1.82	1.78	0.41 Well sorted	0.15 Postively skewed	1.02 Mesokurtic
KN1	1.56	1.59	0.63 Moderately well sorted	-0.03 Symmetrical	1.1 Mesokurtic
KN2	1.66	1.69	0.54 Moderately well sorted	-0.05 Symmetrical	1.05 Mesokurtic
KN3	1.54	1.51	0.36 Well sorted	0.23 Positively skewed	1.16 Leptokurtic
KN4	1.94	1.9	0.38 Well sorted	0.2 Positively skewed	1.13 Leptokurtic
KN5	1.89	1.88	0.27 Very well sorted	0.12 Positively skewed	1.09 Mesokurtic
KN6	2.17	2.16	0.29 Very well sorted	0.11 Positively skewed	1.08 Mesokurtic
KN7	2.14	2.12	0.33 Very well sorted	0.12 Positively skewed	1.11 Mesokurtic

Table 5.3 Graphic statistics (Folk and Ward, 1953) for the sand fraction of the samples from southern Kalahari (refer to Appendix B for key to site names).

SAMPLE	MEAN	MEDIAN	SORTING	SKEWNESS	KURTOSIS
S1	1.22	1.21	0.39 Well Sorted	0.09 Symmetrical	1.08 Mesokurtic
S2	1.43	1.41	0.39 Well Sorted	0.11 Symmetrical	1.08 Mesokurtic
S3	1.19	1.19	0.30 Very Well Sorted	0.06 Symmetrical	1.06 Mesokurtic
S4	1.12	1.11	0.27 Very Well Sorted	0.07 Symmetrical	1.03 Mesokurtic
MB1	1.64	1.67	0.64 Moderately Well Sorted	-0.03 Symmetrical	0.94 Mesokurtic
MB2	1.47	1.46	0.58 Moderately Well Sorted	0.06 Symmetrical	0.98 Mesokurtic
MB3	1.25	1.19	0.68 Moderately Well Sorted	0.12 Positively Skewed	0.87 Platykurtic
MM1	1.89	1.91	0.53 Moderately Well Sorted	-0.04 Symmetrical	1.04 Mesokurtic
MM2	1.44	1.43	0.53 Moderately Well Sorted	0.06 Symmetrical	0.96 Mesokurtic
MM3	1.58	1.57	0.60 Moderately Well Sorted	0.07 Symmetrical	0.96 Mesokurtic
SP1	1.62	1.67	0.61 Moderately Well Sorted	-0.1 Negatively skewed	1.08 Mesokurtic
SP2	1.69	1.71	0.59 Moderately Well Sorted	-0.04 Symmetrical	1.17 Leptokurtic
SP3	1.71	1.73	0.54 Moderately Well Sorted	-0.07 Symmetrical	1.13 Leptokurtic
SP4	1.78	1.79	0.48 Well Sorted	-0.01 Symmetrical	1.12 Leptokurtic
SP5	1.74	1.75	0.50 Well Sorted	-0.02 Symmetrical	1.08 Mesokurtic
SP6	1.75	1.78	0.51 Moderately Well Sorted	-0.09 Symmetrical	1.12 Leptokurtic
SP7	1.87	1.88	0.58 Moderately Well Sorted	-0.02 Symmetrical	1.19 Leptokurtic

Table 5.4 Graphic statistics (Folk and Ward, 1953) for the sand fraction of the samples from the Breede River Valley (refer to Appendix B for key to site names).

5.4 pH AND CONDUCTIVITY RESULTS

Figures 5.6 - 5.14 show the pH and conductivity for each sample. No major trends are apparent for the pH or conductivity values. All the topographical dunes, with the exception of the Kanoneiland dunes are slightly acidic, ranging from 4.8 (Moddergat) to 6.9. The Breede River Valley topographical dunes are more acidic than the southern Kalahari dunes which tend towards 7 pH. The Kanoneiland dunes are basic to neutral, with values ranging between 7.85 to 7.05.

As with the pH values, there are no significant trends in the conductivity readings. The southern Kalahari conductivity values are relatively low, ranging from 6.18 µS/cm to 132.1 µS/cm. The average conductivity value for these dunes is 27.2 µS/cm. The Breede River Valley samples are lower than those for the southern Kalahari, ranging from 5.58 µS/cm to 13.43 µS/cm.. The only anomaly in this data set is the value of 214 µS/cm which was obtained for SP1 of the Sandput topographical dune. Excluding the conductivity value for SP1, the average value obtained for the Breede River Valley dunes is 8.77 μS/cm.

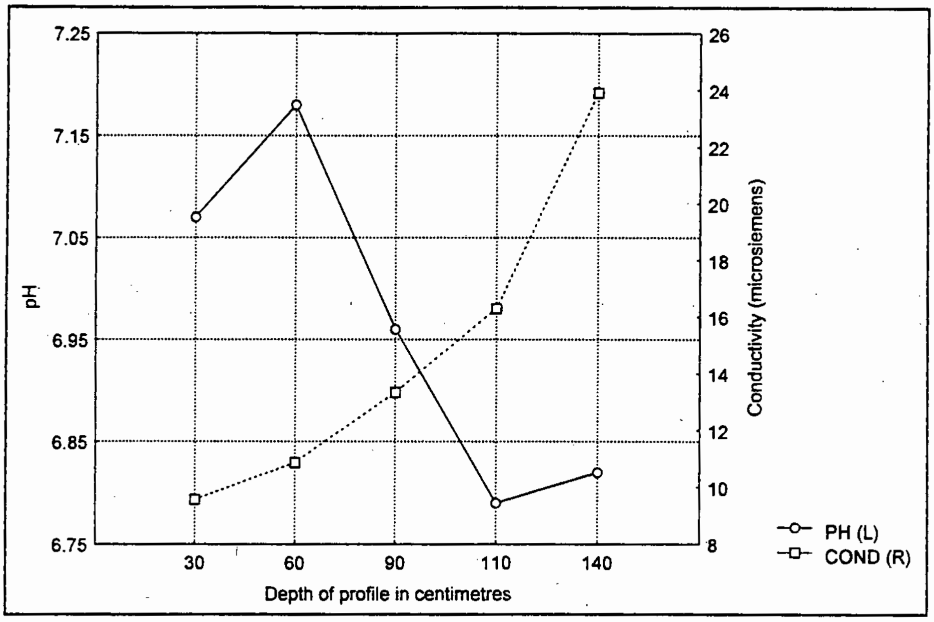


Figure 5.6 pH and conductivity readings for the Prynnsberg 1 pit.

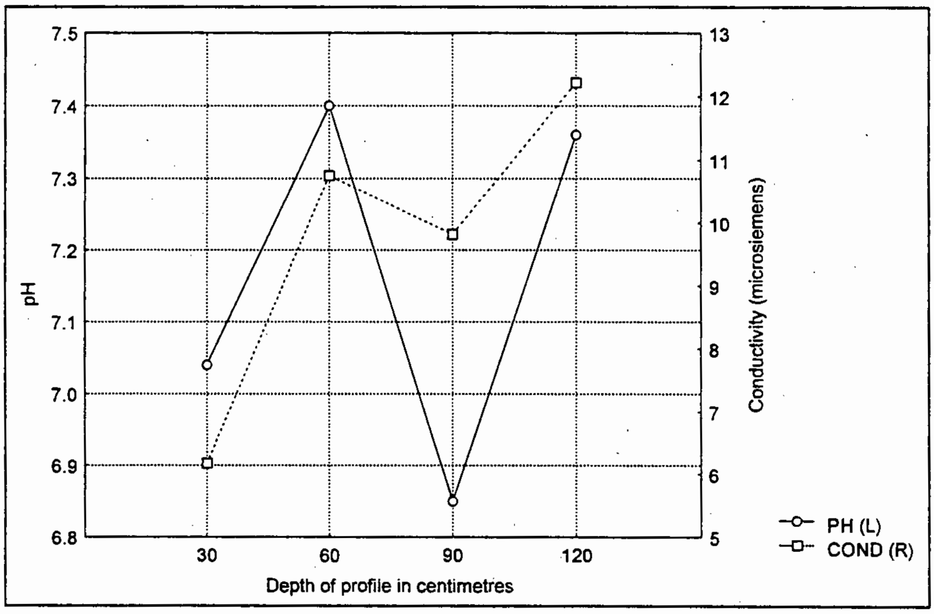


Figure 5.7 pH and conductivity readings for the Prynnsberg 2 pit.

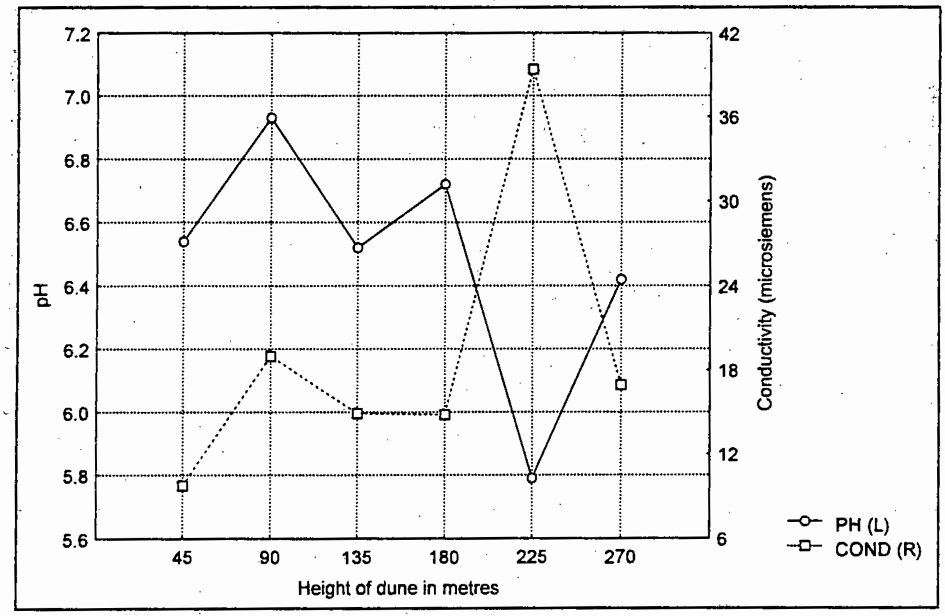


Figure 5.8 pH and conductivity readings for the Prynnsberg 1 topographical dune.

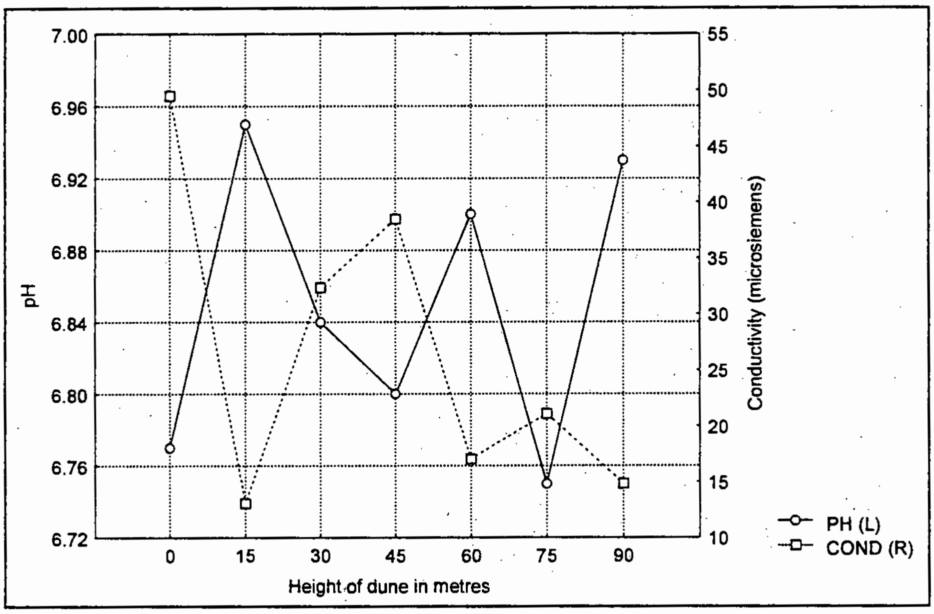


Figure 5.9 pH and conductivity readings for the Prynnsberg 2 topographical dune.

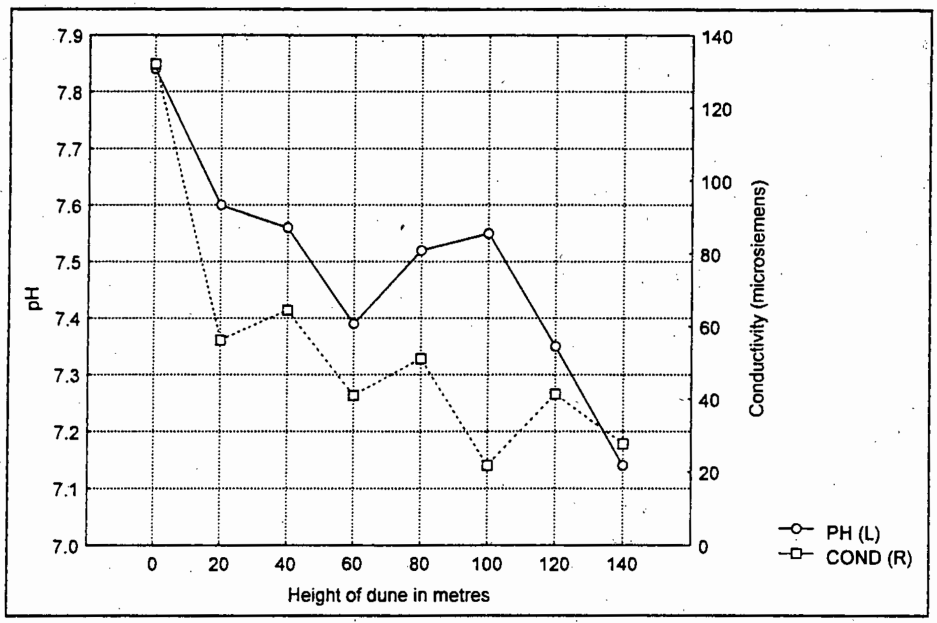


Figure 5.10 pH and conductivity readings for the Kanoneiland 1 topographical dune.

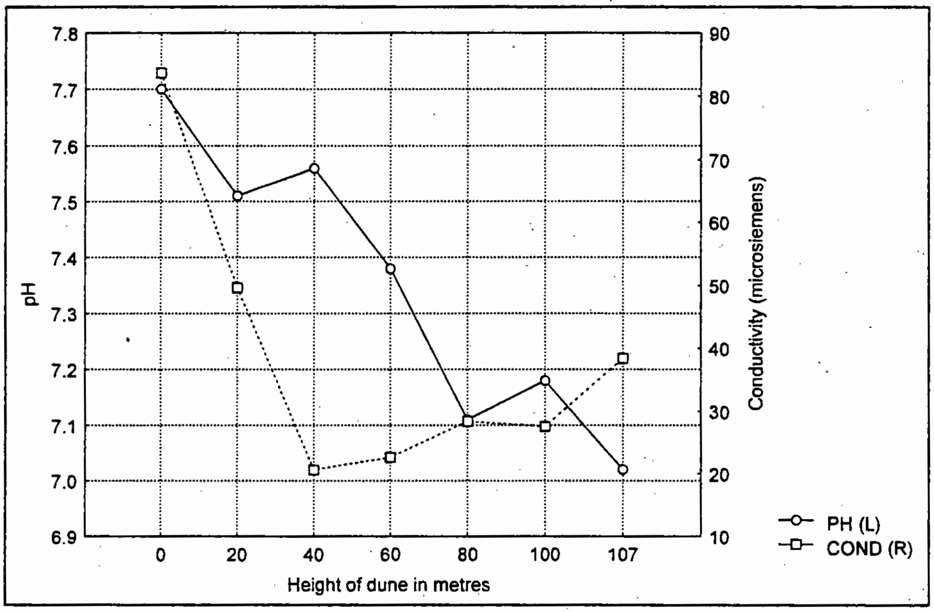


Figure 5.11 pH and conductivity readings for the Kanoneiland 2 topographical dune.

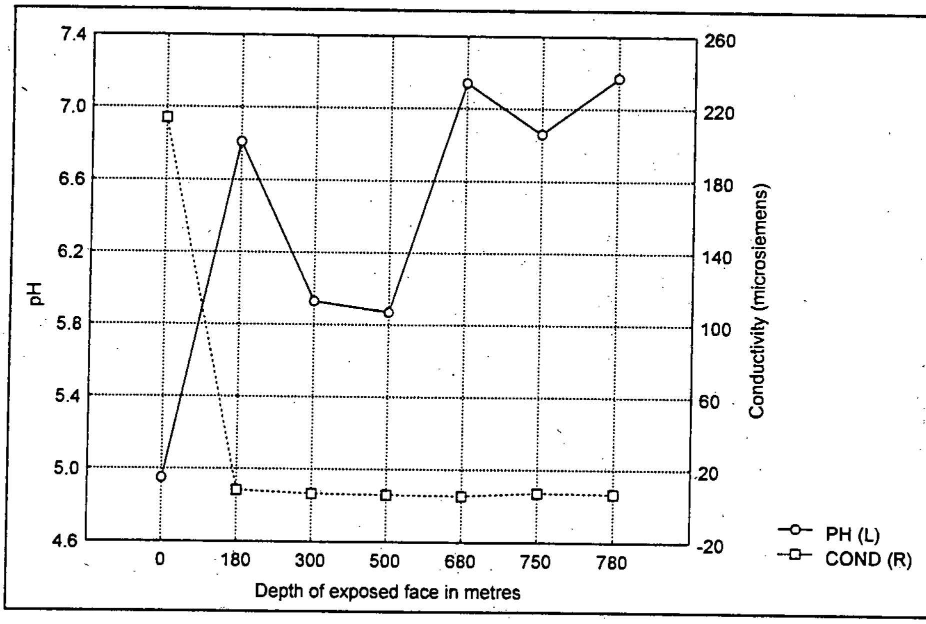


Figure 5.12 pH and conductivity readings for the Sandput exposed face.

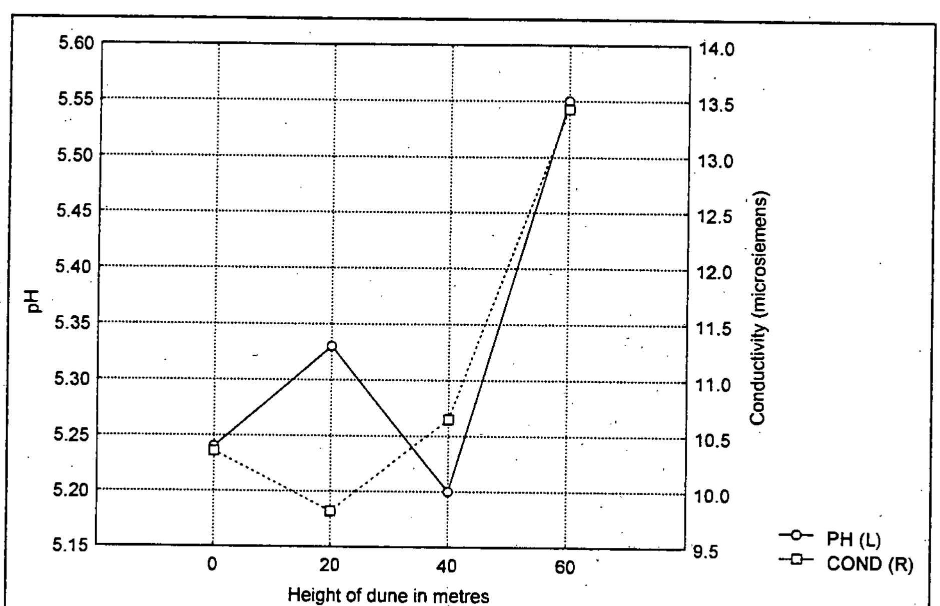


Figure 5.13 pH and conductivity readings for the Sandberg topographical dune.

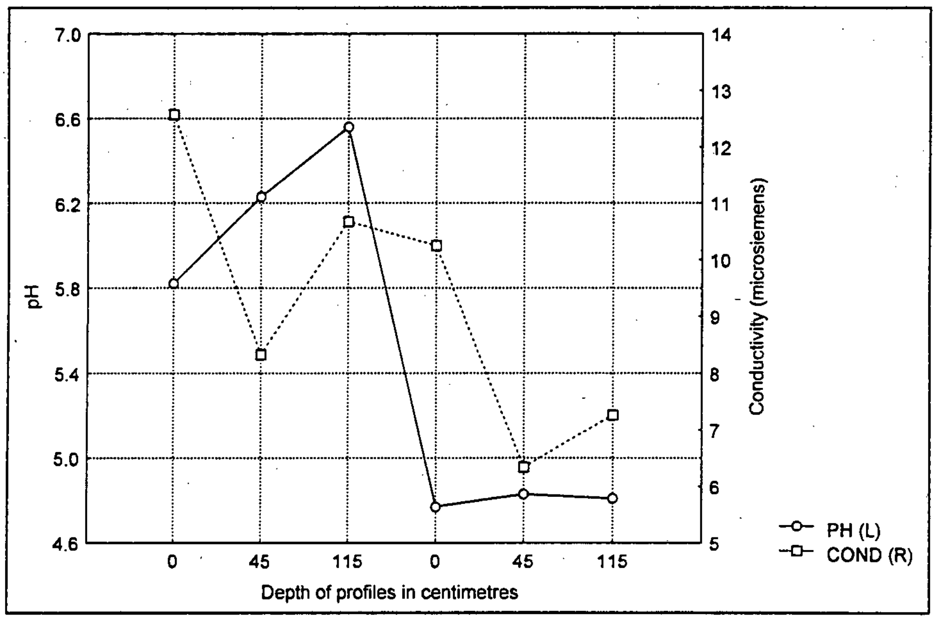


Figure 5.14 pH and conductivity readings for the Moddergat pits.

5.5 SCANNING ELECTRON MICROSCOPY

5.5.1 Chemical Composition Analysis

CHEMICAL COMPOSITION TABLE (Weight %)												
Sample	**C**	**O**	**Mg**	**Al**	**Si**	**K**	**Ca**	**Ti**	**Fe**	**Cu**	**Sn**	**Hg**
PRP5	25.64	35.45	0	0.64	37.33	0	0	0	0.21	0.13	0.08	0.54
PYP4	0	44.34	0	0.73	52.43	0	0	0	0.46	0.48	0	1.56
PRS6	0	45.58	0	5.04	45.65	0.51	0.16	0.28	1.87	0.28	0	0.62
PYS6	0	49.48	0.3	2.07	44.31	0.26	0.08	0.13	1.88	0.26	0	1.23
KA4	0	44.09	0	1.46	51.29	0	0	0	1.51	0.29	0.1	1.25
KN4	0	44.86	0	0.91	52.33	0	0	0	0.51	0.15	0	1.25
S4	0	42.83	0	0.55	55.48	0	0	0	0	0	0.17	0.98
MM1	0	31.35	0	0.69	54.93	0	0	0	2.37	3.31	1.19	6.16
MM3	0	45.19	0	0.78	52.17	0	0	0	0.64	0.19	0	1.04
SP1	0	43.61	0	1.26	53.57	0.5	0	0	0.22	0	0	0.84
SP5	0	36.35	0	0.81	61.58	0	0	0	0.5	0	0.3	0.47
SP7	0	50.15	0	0.46	47.38	0	0	0	0.52	0	0	1.49

Table 5.5 Summary of the weight (in percentage) of the elements found within the sand grains. One sample from each topographical dune or pit was analysed.

The chemical composition analysis results (Table 5.5) clearly show that silicon and oxygen are the two prominent elements found within the grains. Aluminium and iron are two secondary elements which are also present, but in small quantities. Silicon and oxygen are the two dominant elements in quartz sand grains and therefore the results of this chemical composition analysis indicate that the grains were derived from a quartz parent material. It is also interesting to note that mercury is found in all the samples that were analysed (this will be discussed in greater detail in chapter 6).

5.5.2 Scanning Electron Micrographs

The micrographs (a few examples are shown below) all show evidence of upturned plates as described by Krinsley and Doornkamp (1973). The grains vary in size and shape, from angular to spherical, and they also vary greatly in roundness. Figure 5.15 is a good example of a well rounded and spherical sand grain which shows upturned plates. Figure 5.16 is a well rounded grain with upturned plates, but it is not spherical. Figures 5.17 and 5.18 both show grains with large conchoidal breakage surfaces. Most of the sand grains have been smoothed by abrasion, but a few show evidence of sharp, angular surfaces.

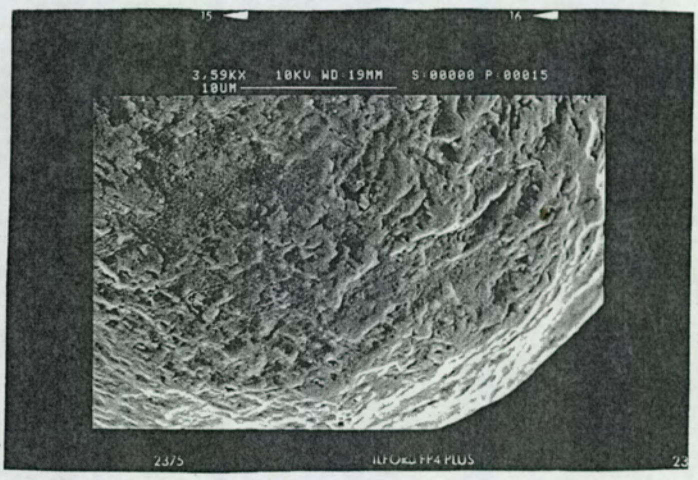


Figure 5.15 A sand grain from the Prynnsberg 1 topographical dune in the southern Kalahari. Note the smooth surface and rounded grain covered with upturned plates.

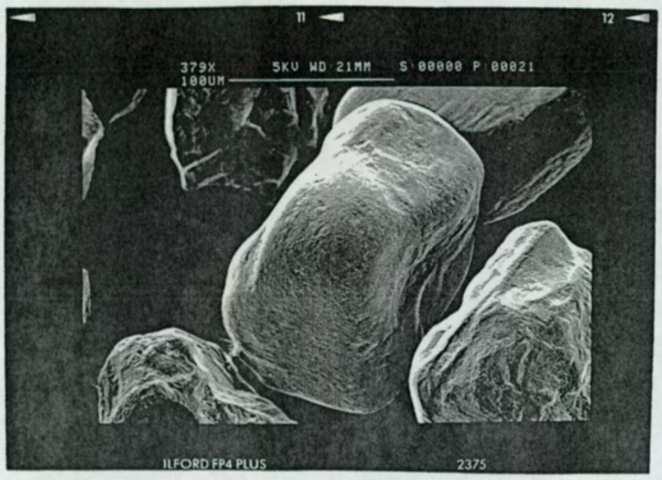
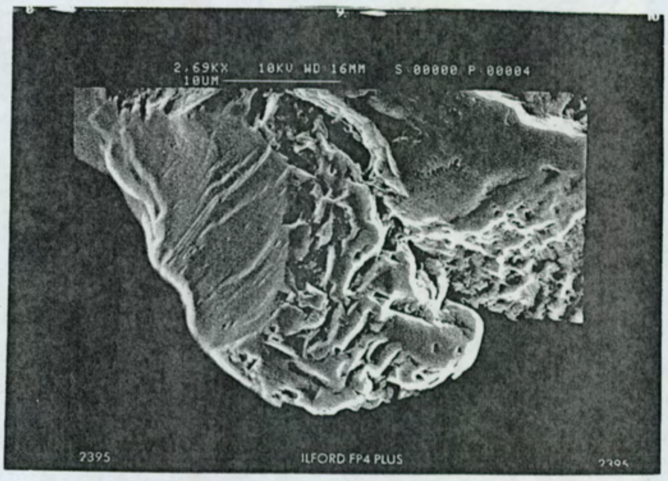
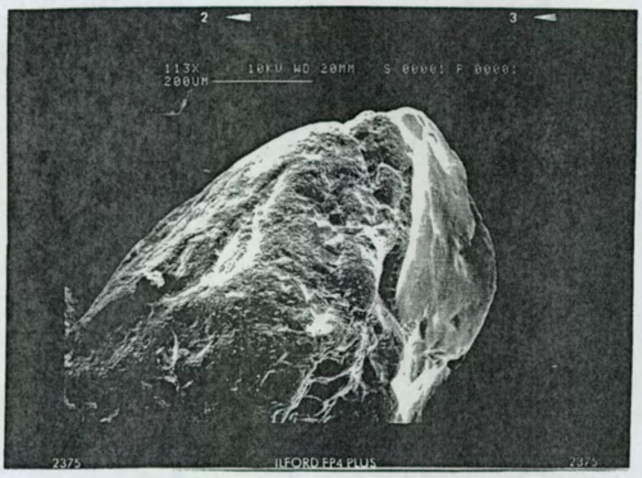


Figure 5.16 A sand grain from the Prynnsberg 2 topographical dune in the southern Kalahari. Although it is not as well rounded as the grain shown in Figure 5.15, it has a smooth surface with upturned plates.





Figures 5.17 & 5.18 A sand grain from the Prynnsberg 2 pit showing concoidal (dish-like) breakage features and upturned plates (left). A sand grain from the Sandberg topographical dune, also showing conchoidal breakage features and upturned plates (right).

5.6 OPTICALLY STIMULATED LUMINESCENCE DATING RESULTS

Six samples for optically stimulated luminescence (OSL) dating were sent to the Sheffield Centre for International Drylands Research laboratory in the United Kingdom for dating, three samples were taken from the Prynnsberg 2 topographical dune in the southern Kalahari and three were sampled from the Sandput exposed face in the Breede River Valley. Table 5.6 shows the results of this dating and lists the depositional ages which were derived for the samples. The Prynnsberg 2 samples are all approximately 100 years old. These samples all responded well to laboratory radiation, therefore implying recent sample exposure to light. This exposure could either be natural, implying that the dunes are active aeolian features, or it could have been accidental during OSL sampling or preparation, therefore making the ages incorrect (Bateman, pers. comm.). Due to the relatively shallow pit that was dug (only 1.4 m in depth) on such a large dune (225 m^3 volume of sand), it is probable that the ages are correct and that the exposure to sunlight was natural.

The Sandput samples, Breede River Valley, show an increase in age with depth. The sample SP-C has an age of 762.7 ± 104.5 ka is well beyond the normally considered limits of OSL (the limit being approximately 200 ka) and thus this age determination is, at best, a maximum age (Bateman, pers. comm.). The age determination of SP-B (28.8 ± 5.3 ka) displayed incomplete bleaching prior to deposition, thus leading to an over-estimation of age (Bateman, pers. comm.). SP-A has an age of 9.9 ± 0.7, and is considered a reliable age determination.

Sample Code	Laboratory Number	Depth (m)	ED (Gy)	Cosmic Dose (µGy/ka)	Total Dose (µGy/ka)	Age (ka)
PYP-A	Sxhfd98023	0.20	0.058 ± 0.017 †	223 ± 11*	796 ± 43	0.1 ± 0.02
PYP-B	Shfd98024	0.80	0.049 ± 0.011 †	205 ± 10	840 ± 44	0.1 ± 0.01
PYP-C	Shfd98025	1.30	0.049 ± 0.010 †	192 ± 10	738 ± 40	0.1 ± 0.01
SP-A	Shfd98028	1.80	5.18 ± 0.28	158 ± 8	525 ± 24	9.9 ± 0.7
SP-B	Shfd98027	6.80	15.77 ± 2.76 §	96 ± 4	547 ± 30	28.8 ± 5.3
SP-C	Shfd98026	7.80	375.60 ± 47.49 ‡	85 ± 4	492 ± 26	762.7± 104.5

Table 5.6 Optically stimulated luminescence dating results for two topographical dunes, Prynnsberg 2 (southern Kalahari) and the Sandput (Breede River Valley).

5.7 STATISTICAL RESULTS

Two main statistical analyses were performed on the results from the sedimentological laboratory analysis, namely, principal component analysis (PCA) and cluster analysis.

5.7.1 Principal Component Analysis

Table 5.7 shows the results of the first PCA test that was run on all the samples from both regions. It shows that most of the variance is explained by four factors and that factor 1, at 40%, explains most of this proportional variance. Table 5.7 indicates that the component loadings; coarse, medium, fine, mean and median, all display loadings of > 0.7. The PCA therefore shows that the variance in factor 1 is explained by parameters which are all related to grain size, therefore indicating that grain size is an important determining variable which is selected for in an aeolian environment. Factor 2, which explains 23% of the proportional total, highlights silt content and sorting as loadings of > 0.7. These loadings indicate that within a dryland environment, grain size as well as the degree of sorting are determining factors. Factor 3 has no loadings with scores > 0.7, while in factor 4 pH has a component loading of 0.751. pH is a measure of leaching within a soil or sand profile and thus leaching is considered an important selecting variable in arid and semi-arid areas.

When the unrotated PCA (Table 5.7) is compared with the rotated PCA (Table 5.8) there is very little difference between the two results, and therefore all the other statistical tests were conducted on the unrotated PCA results. In Tables 5.9 and 5.10, PCA's of the Kalahari and Breede River sites respectively, there was little difference between the unrotated and rotated PCA and thus the rotated loadings have not been presented. Coarse, medium and fine sand display loadings of > 0.7 in each PCA (with the exception of medium sand in the rotated PCA, Table 5.8), and mean is also considered important in factor 1 for all the PCA's. These results not only indicate that grain size, sorting and pH are an important factors that are selected for in a dryland environments, but also that there are no significant differences in the PCA results between the different sites.

	Factor 1	Factor 2	Factor 3	Factor 4
% COARSE	**0.743**	-0.428	-0.154	-0.187
% MEDIUM	**0.831**	-0.144	0.137	0.293
% FINE	**-0.898**	0.279	-0.019	-0.153
% SAND	0.624	0.684	0.159	-0.162
% SILT	-0.547	**-0.726**	-0.088	0.221
% CLAY	-0.645	-0.313	-0.326	-0.078
MEAN	**-0.907**	0.316	-0.012	-0.082
MEDIAN	**-0.916**	0.280	0.023	-0.095
SORTING	-0.148	**-0.810**	-0.077	-0.242
SKEWNESS	0.181	0.603	-0.453	0.428
KURTOSIS	-0.362	0.222	0.694	0.005
pH	-0.446	-0.069	0.047	**0.751**
COND	-0.047	-0.547	0.472	0.182
Expl.Var	5.202	2.924	1.101	1.081
Prp.Totl	0.401	0.225	0.085	0.083

Table 5.7 PCA unrotated factor loadings for all topographical dunes in the southern Kalahari and Breede River Valley.

	Factor 1	Factor 2	Factor 3	Factor 4
% COARSE	**-0.783**	0.141	-0.143	-0.375
% MEDIUM	**-0.867**	-0.230	0.057	0.092
% FINE	**0.944**	0.104	0.035	0.068
% SAND	-0.251	**-0.880**	-0.041	-0.262
% SILT	0.151	**0.870**	0.108	0.302
% CLAY	0.478	0.603	-0.181	0.047
MEAN	**0.950**	0.069	0.032	0.141
MEDIAN	**0.946**	0.098	0.0741	0.130
SORTING	-0.132	**0.809**	0.108	-0.243
SKEWNESS	-0.004	-0.524	-0.595	0.394
KURTOSIS	0.386	-0.214	0.673	0.114
pH	0.197	0.193	0.079	**0.830**
COND	-0.232	0.395	0.563	0.172
Expl.Var	4.626	3.161	1.221	1.298
Prp.Totl	0.356	0.243	0.094	0.100

Table 5.8 PCA rotated factor loadings for all topographical dunes in the southern Kalahari and Breede River Valley regions.

	Factor 1	Factor 2	Factor 3
% COARSE	**0.860**	0.202	0.073
% MEDIUM	**0.749**	-0.476	-0.140
% FINE	**-0.855**	0.345	0.173
% SAND	-0.294	**-0.901**	0.086
% SILT	0.401	**0.840**	0.006
% CLAY	-0.167	0.692	-0.330
MEAN	**-0.909**	0.300	0.033
MEDIAN	**-0.886**	0.345	0.075
SORTING	0.429	**0.797**	-0.197
SKEWNESS	-0.246	**-0.770**	-0.185
KURTOSIS	-0.335	0.114	**0.702**
pH	**0.723**	-0.213	0.349
COND	0.691	0.335	0.399
Expl.Var	5.277	3.991	1.025
Prp.Totl	0.406	0.307	0.079

Table 5.9 PCA unrotated factor loadings for all topographical dunes in the southern Kalahari.

	Factor 1	Factor 2	Factor 3	Factor 4
% COARSE	**0.801**	-0.468	0.115	0.130
% MEDIUM	0.446	**0.741**	0.018	0.102
% FINE	**-0.950**	-0.081	-0.107	-0.173
% SAND	0.137	**0.885**	-0.122	-0.120
% SILT	-0.250	**-0.786**	0.326	0.291
% CLAY	0.306	-0.352	-0.559	-0.467
MEAN	**-0.939**	0.129	-0.130	-0.184
MEDIAN	**-0.944**	0.148	-0.144	-0.132
SORTING	-0.589	**-0.703**	-0.147	-0.086
SKEWNESS	**0.818**	-0.189	0.159	-0.305
KURTOSIS	-0.483	0.635	0.298	0.231
pH	-0.448	-0.103	**0.755**	-0.146
COND	-0.162	-0.116	-0.454	**0.819**
Expl.Var	5.166	3.297	1.408	1.274
Prp.Totl	0.397	0.254	0.108	0.098

Table 5.10 PCA unrotated factor loadings for all topographical dunes in the Breede River Valley.

5.7.2 Cluster Analysis: Single Linkage

Two types of tree cluster analyses were undertaken, namely single linkage and Ward clustering. In the single linkage cluster analysis, three main clusters were evident in all of Euclidean distance tree diagrams. In Figure 5.19, SP1, MB3, and KA1 have been identified as outliers, and this is also reflected in Figure 5.20 and Figure 5.21. In Figure 5.20, PYS4 and KA3, in addition to KA1, have been identified as outliers. In Figure 5.21, SP1, MB3 and S1 are outliers within the data set. The strongest clustering is evident in Figure 5.19.

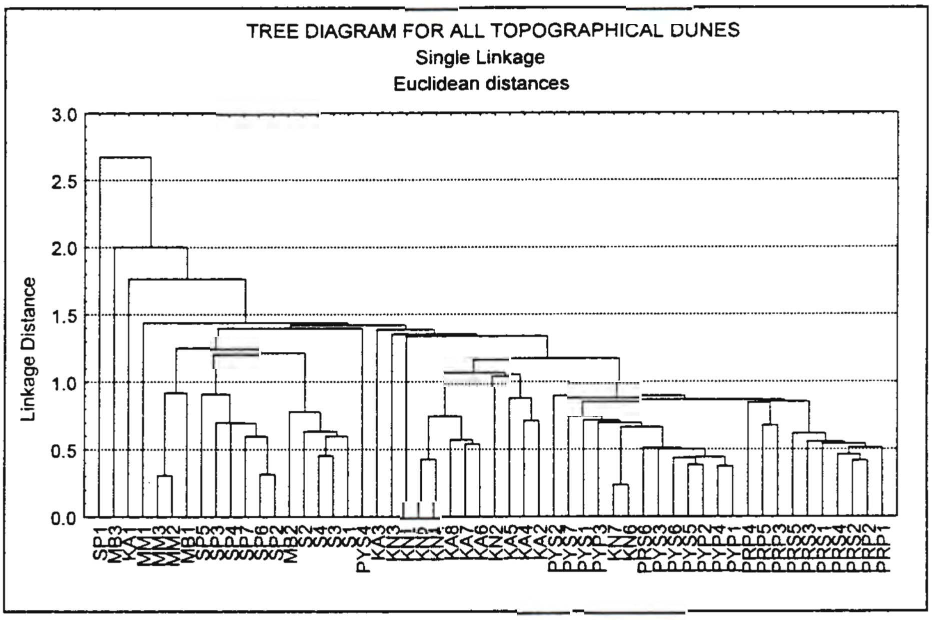


Figure 5.19 Clustering of the diagram for the samples from the southern Kalahari and the Breede River Valley regions.

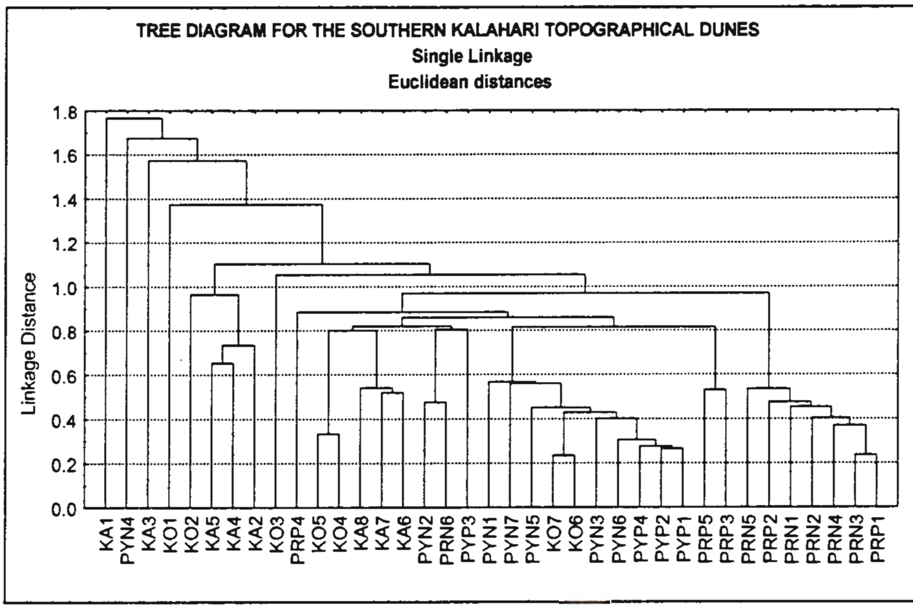


Figure 5.20 Clustering of the southern Kalahari samples.

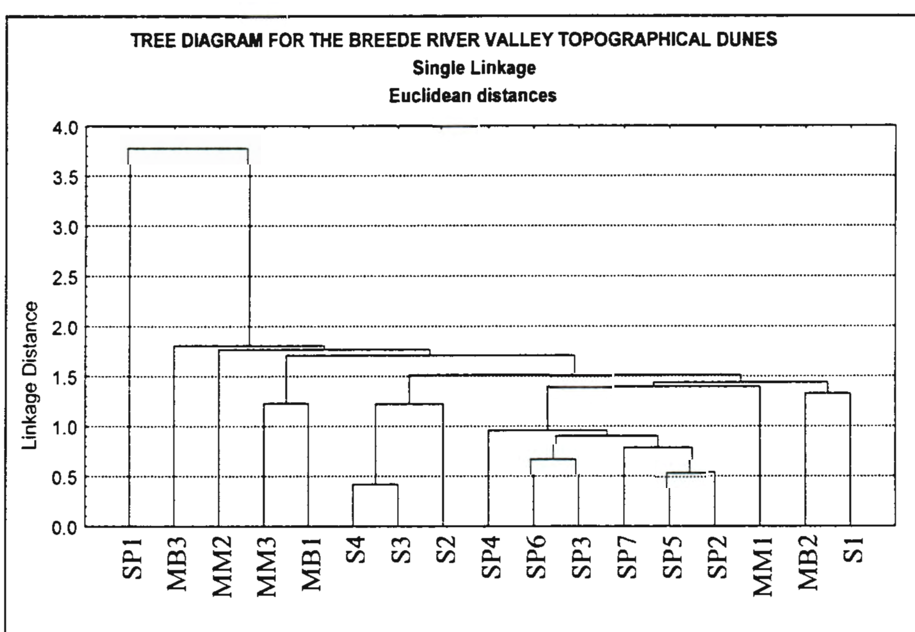


Figure 5.21 Clustering of the Breede River Valley samples.

5.7.3 Cluster Analysis: Ward's Method

A Ward's method cluster analysis was run on the three PCA tests in order to identify groups rather than outliers. It is evident from Figure 5.22 that Ward's method has highlighted three groups within the data set. In general, one group represents the Kanoneiland topographical dunes, the second group represents the Breede River Valley dunes and the final group represents the Prynnsberg topographical dunes. Figure 5.23 illustrates Ward's method on the southern Kalahari topographical dunes. Two groups are evident from this cluster analysis, although no distinguishable patterns can be seen within the groups. Figure 5.24 highlights that there are two main groups within the Breede River Valley Ward's clustering. The first group contains samples from the Sandput topographical dune, while the second group contains the Moddergat and Sandberg topographical dunes.

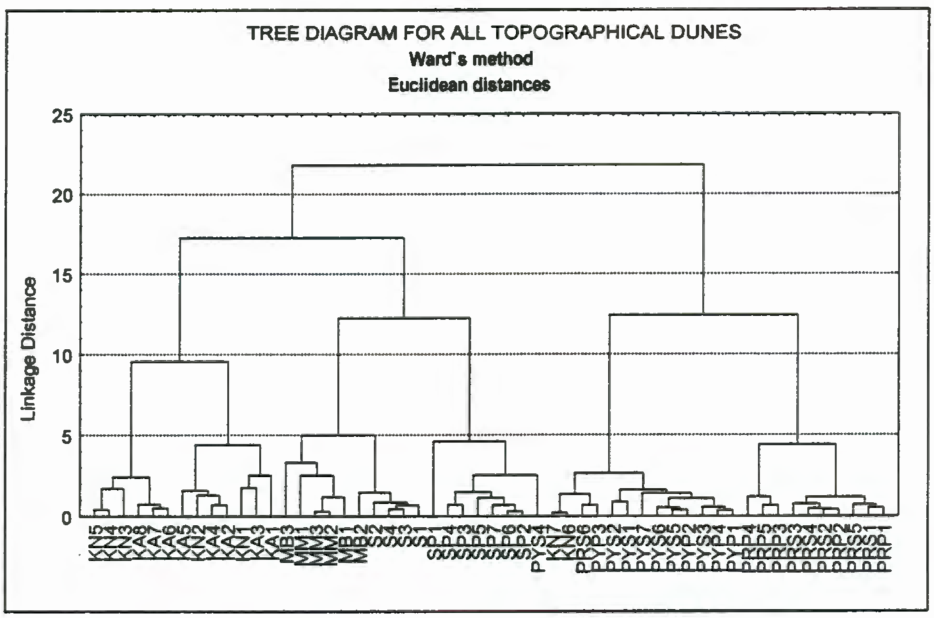


Figure 5.22 Ward clustering of the samples from both study regions.

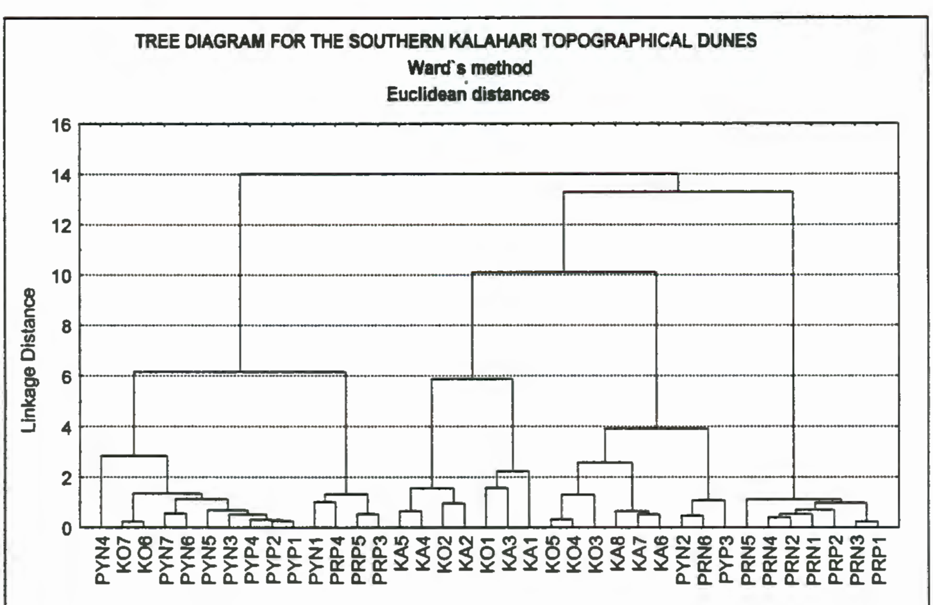


Figure 5.23 Ward clustering of the southern Kalahari samples.

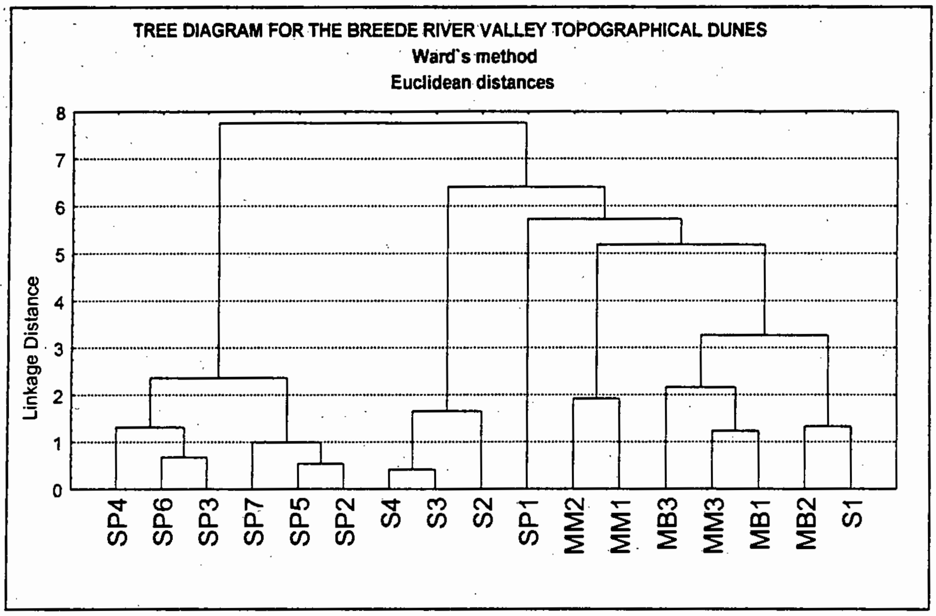


Figure 5.24 Ward clustering of the Breede River Valley samples.

5.8 SUMMARY

In this chapter, through the use of graphs, tables and ternary diagrams, the results of the study have been presented. They show that the topographical dunes from the southern Kalahari and Breede River Valley regions are very similar with respect to slope angle, particle size, pH, conductivity, chemical analysis and micro-morphology (as identified by SEM).

In summary, the topographical dunes comprise pure sand to medium sized sand. The Folk and Ward (1953) distribution of the topographical dune samples are, on the whole, mesokurtic, symmetrical, and are well sorted. No major trends are apparent in the pH and conductivity measurements, although the Breede River Valley dunes tend to be more acidic in pH than the southern Kalahari dunes. The chemical composition analysis shows that silicon and oxygen are the dominant elements found in the sand grains, and an interesting feature is that all the sand grains contain mercury. The SEM micrographs show typical windblown sand grains which have characteristic aeolian etchings on their surfaces. The PCA and cluster analysis indicate that statistically there is very little significant difference between the sand samples. What variance there is between the samples, is best explained in terms of grain size.

In the following chapters, the above results are compared with topographical dunes in the literature and then discussed in terms of their implications for environmental change. The information is then used to determine the usefulness of topographical dunes in South Africa as indicators of environmental change. In addition, the results are compared with current scenarios of Quaternary environmental change in South Africa.

CHAPTER 6: DISCUSSION

6.1 INTRODUCTION

In the previous chapter the analytical results of the field, laboratory, and statistical procedures were presented, showing that all the topographical dunes were relatively uniform with respect to structure, particle size, pH, conductivity, chemical composition, and surface texture of the sand. In this chapter the question as to whether the topographical dunes are climbing dunes or sand ramps is addressed, and secondly the palaeoenvironmental significance of these dunes is discussed. An important component of this chapter is the environmental reconstruction of the dunes that were sampled for dating. These dunes are not only discussed in terms of their local significance, but they are also placed in context in terms of global environmental change trends.

6.2 SAND RAMPS OR CLIMBING DUNES?

One of the main aims of this study was to determine whether the southern Kalahari and Breede River topographical dunes are climbing dunes or sand ramps. The particle size results show the features sampled in the southern Kalahari to comprise medium sand (slightly positively skewed towards the fines) with sorting coefficients of 0.3 ϕ - 0.76 ϕ (i.e. moderately to well sorted), while the Breede River Valley examples comprise medium sand (slightly skewed to the coarse grains) with sorting coefficients of 0.27 ϕ to 0.68 ϕ. The dominance of well sorted, medium sized sands strongly suggests that they were in all likelihood transported by wind. The scanning electron microscope results show that the chemical composition of the grains comprised mainly silicon and oxygen, therefore implying a quartz-rich parent material. The evidence of upturned plates, conchoidal breakage surfaces as well as smoothing, combined with angular surfaces (caused by abrasion when the sand grains hit against each other during transport by wind) all support the notion that the grains were transported by wind (Krinsley and Doornkamp, 1973). The PCA shows that grain size is an important determining and limiting factor in the dune environment, suggesting that the grains were transported by wind. The cluster analysis shows that although the data did not vary significantly, there were regional differences as it grouped the Breede River Valley dunes separately from the southern Kalahari dunes.

In general, the southern Kalahari and Breede River Valley topographical dunes therefore contain homogeneous quartz sand that was transported by wind and deposited against a topographical barrier. When the definitions of sand ramps and climbing dunes (given in Chapter 1) are reviewed, i.e. that sand ramps are an amalgamation of aeolian sands, talus material, fluvial and colluvial sediments as well as palaeosols which were formed during geomorphically more stable periods (Lancaster and Tchakerian, 1996), whereas climbing dunes consist entirely of aeolian material (Thomas *et al.*, 1997a) then it is probable that these aeolian depositional features are in fact climbing dunes. The columnar structures (see Table 4.2 and Fig. 4.8), however, might indicate incipient soil formation, so this assertion that these are climbing dunes is made with caution.

Studies on climbing dunes (see Chapter 1) are few, and hence there is a need to investigate them (Thomas, pers. comm.). Most of the literature on climbing dunes tends to focus on the mechanics of climbing dune formation, and although it was not seen as part of the scope of this dissertation, they will be briefly compared with the dunes directly investigated here. Evans (1962), and White and Tsoar (1998) have shown that there is a decrease in particle size up the climbing dunes, and that the dunes are generally poorly sorted with coarse material at the base of the dune and fine material at the dune crest. The dunes from this investigation do show a slight decrease in particle size up the dune (except for Kanoneiland in the southern Kalahari where particle size increases, the Sandberg dune which shows no discernible pattern and the Sandput where surface samples were not taken), but they are well rather than poorly sorted. Evans (1962), however, researched coastal climbing dunes and it has been shown (Reynhardt, 1980) that sorting of particles on coastal dunes is not as good as for desert/ semi-arid inland dunes. In addition, other factors such as vegetation (Helstrom and Lubke, 1993), height and steepness of the topographical barrier (Tsoar, 1983), as well as wind speed and direction (Marsh and Marsh, 1987) cause differing effects on the grain size distribution of climbing dunes.

The slope data (Figs. 5.1 and 5.2) also suggest that these topographical dunes are climbing dunes. The mean slope value for the southern Kalahari dunes is 11.25° and for the Breede River Valley dunes, 16.3°. In Chapter 1 it was noted that the slope of sand ramps in the Mojave Desert varied between 3° and 25° although those ramps with slopes greater than 25° were classed as falling ramps (Lancaster and Tchakerian, 1997). In the Ardakan Desert, however, the sand ramp slopes were found to be between 5° and 10° (Thomas *et al.*, 1997a). The slopes of climbing dunes are much steeper, with the sand often lying close to its angle of repose (Thomas *et al.*, 1997a). Although the mean slopes of the topographical dunes in this study are not particularly steep (i.e. 11.23° and 16.3°), individual slopes tend to be quite steep (e.g. the Sandberg has a slope of 23,5°) and are generally steeper than the 5° to 10° sand ramps that have been identified by Thomas *et al.* (1997a).

6.3 SOURCES OF SAND

The nature of the Kalahari sediments from the southern Kalahari topographical dunes is difficult to define due to the considerable reworking of sediments that has taken place in the Kalahari (Thomas and Shaw, 1991b). The dunes comprise homogeneous quartz sand which is mesokurtic, well sorted medium to fine sand and pure sand. It is therefore proposed, particularly in the absence of any other potential sources, that the original source of sand from these dunes is the red, ocherous Kalahari Sand that has been reworked from the extensive southern Kalahari linear dune field. It is also possible that the sands have been deposited in the Orange River and have been fluvially transported downstream until they become deposited and are once again available for transport by wind. This reworked Kalahari Sand is then transported by aeolian processes and deposited against the windward flanks of mountains forming climbing dunes.

The sand which comprises the Breede River Valley topographical dunes, like the southern Kalahari dunes, is homogeneous quartz sand which is mesokurtic and well sorted. It differs from the southern Kalahari dunes in that it comprises medium to coarse pure sand. It is proposed that the sand source of the Breede River Valley climbing dunes is the Breede River. It is suggested that weathered Table Mountain Sandstone (TMS) was transported by the Breede River and deposited on its banks during flooding. The low pH of the Breede River sands are supportive of this assertion. Sand was then transported by wind and deposited against the flanks of mountains causing the Breede River topographical dunes to form.

6.4 PALAEOENVIRONMENTAL SIGNIFICANCE

A secondary objective of this dissertation was to evaluate, against the opportunities and limitations of using topographical dunes as palaeoenvironmental indicators, the potential use of these South African dunes as indicators of environmental change. It is proposed that these topographical dunes are climbing dunes rather than sand ramps. This implies that the dunes in this study are less useful indicators of palaeoenvironmental change than sand ramps due to the homogeneity of the climbing dune sediments as opposed to the multi-sedimented sand ramps which clearly highlight periods of environmental change.

Two topographical dunes, one from each study region, were dated using optically stimulated luminescence (OSL) dating, and despite the homogeneous nature of these sediments, some interesting issues arise. These are discussed in the following section. In the southern Kalahari, the Prynnsberg 2 climbing dune was dated, and in the Breede River Valley, the Sandput exposed face was sampled for OSL dating. Although only one dune per region was dated, the dates are tentatively interpreted as being representative of each region during the Quaternary and are placed into a regional as well as global context.

6.5 THE SOUTHERN KALAHARI

6.5.1 Prynnsberg 2

The low slope angle of Prynnsberg 2 (Chapter 4, Fig. 4.2) topographical dune facilitated sampling as an inspection pit could be dug. Although it is classified here as a climbing dune, other sedimentary layers may be present below the aeolian layer which was sampled in the pit. In Chapter 5 it was shown that all the samples from the Prynnsberg 2 pit were dated to have been deposited approximately 100 years ago. Two scenarios are suggested which could explain the similarity in ages. Firstly, the OSL sampling in the field or during the OSL sample preparation in the laboratory caused the samples to become contaminated or exposed to sunlight. Sampling problems that were experienced in the field have already been discussed (Chapter 3), but is should be stressed that the continual collapse of the pit due to the steepness of the dune slope could potentially have caused younger material to contaminate the OSL sample. This is unlikely as the face was cleaned each time before hammering a tube into it in order to secure a sample.

Secondly, the reworking of the sand could have caused older material to be displaced or contaminated by younger aeolian sands. Reworking of sands in the southern Kalahari is a well recognised problem, and Thomas and Shaw (1991b) stated that it is very difficult to determine the true age of the original emplacement of Kalahari sands due to extensive reworking within this area. This scenario therefore implies that the southern Kalahari climbing dunes are still episodically active, thus accounting for the very young OSL dates that were obtained at Prynnsberg 2. The claim by Thomas and Shaw (1991a) that the presence of vegetation on a dune does not necessarily indicate dune stability nor infer relict dune status (therefore indicative of a former phase of aridity) is thus supported by this scenario.

It is the belief of the author that the dune at Prynnsberg can be explained by the latter scenario. It was noted during field trips that the sands on the surface of the dunes are still relatively mobile, and thus contemporary reworking of sands occurs frequently. Unfortunately, however, due to the sampling problems that have already been described, an age determination of dune formation cannot be given. Only 1.4 m of a 17 m high dune has been sampled and thus the dates obtained are not representative of the whole dune. The results also do not allow for the determination of the formation process of the dunes, i.e. whether the dunes were formed over multiple periods of aridity, or whether they are the result of a single period of dune formation.

Previously, researchers attempts to establish phases of aridity from the southern Kalahari linear dunes have not been very successful mainly due to the misunderstanding of dune functioning, along with the simplification of dune responses to climatic factors such as wind and rainfall (Shaw and Thomas, 1996). Despite the sampling problems that were faced in the southern Kalahari during this study, it is believed that the topographical dunes in this region are very similar to the linear dunes in that they comprise homogeneous aeolian quartz sand which have previously not been particularly useful in determining changes in climate. Due to more advanced dating techniques (OSL), better insights into periods of dune emplacement, as distinguished from undated episodically active surface sands, are emerging (Thomas, pers. comm.). According to Shaw and Thomas (1996) a period of aeolian activity occurred from 22 kyr to 28 kyr, and this is supported by Stokes *et al.* (1997a) who state that at the last glacial maximum (i.e. ± 20 000 ka) cold dry conditions prevailed in the southern Kalahari region. New information from Stokes *et al.* (1997b) confirmed that there were three arid dune building phases during the Late Pleistocene: 28 - 23 ka, 17 - 10 ka and around 5.5 ka. In addition, the lack of structure or palaeosols in the linear dunes, as well as the homogeneity of the sediments, indicates that there was a single-phase dune emplacement. The last glacial arid phase is also supported by palaeohydrological studies at palaeo-lake Makgadikgadi and speleological studies from Drotsky's Cave (Shaw and Cooke, 1986).

6.5.2 The Klipkraal Sand Deposit

A Pleistocene sand deposit in the Great Karoo (Marker and Holmes 1993; Holmes, 1998), offers the possibility of assisting in the interpretation of the southern Kalahari climbing dunes as it has recently been realized that this deposit could in fact be a sand ramp. The aeolian deposit is situated in the Buffelsfontein Basin, in the Stormberg region of the Great Karoo, and has been called the Klipkraal Sand Deposit (Fig. 6.1). Details of the Klipkraal sands can be found in Marker and Holmes (1993) and Holmes (1998). Tables 6.1 and 6.2 , as well as Figures 6.2 and 6.3 summarise the sedimentological data from the Klipkraal Sand Deposit. Table 6.3 shows the results of the thermoluminescence (TL) and OSL dating that was conducted on the samples. From the data it can be seen that the samples are textually relatively homogeneous, medium to fine grained loamy to pure sand. They are moderately well sorted to well sorted with a Munsell colour of yellowish red (5YR range) and a geochemical composition that indicates that they are derived from a quartz parent material (Holmes, 1998). Marker and Holmes (1993) found that the Clarens Formation sandstone comprised finer grained material with no red patina covering the grains (it was evident, under an optical microscope, that the Klipkraal Deposit sands were covered with a red translucent patina). Marker and Holmes (1993) concluded that the sands were emplaced as a result of aeolian activity and that the footslope fan, which overslies the stratified sand deposit, was characterised by colluvial debris reworked from the Klipkraal Sand Deposit. It is thus likely that the Klipkraal Deposit is a remnant of a more extensive aeolian deposit and its location (i.e. on a north facing slope) suggests that its sand was derived from a source to the north. The source of the Klipkraal sands is possibly reworked Kalahari sand deposits (Marker and Holmes, 1993). The Klipkraal Sand Deposit is indicative of an arid phase, with strong aeolian activity over the interior of southern Africa (Marker and Holmes, 1993).

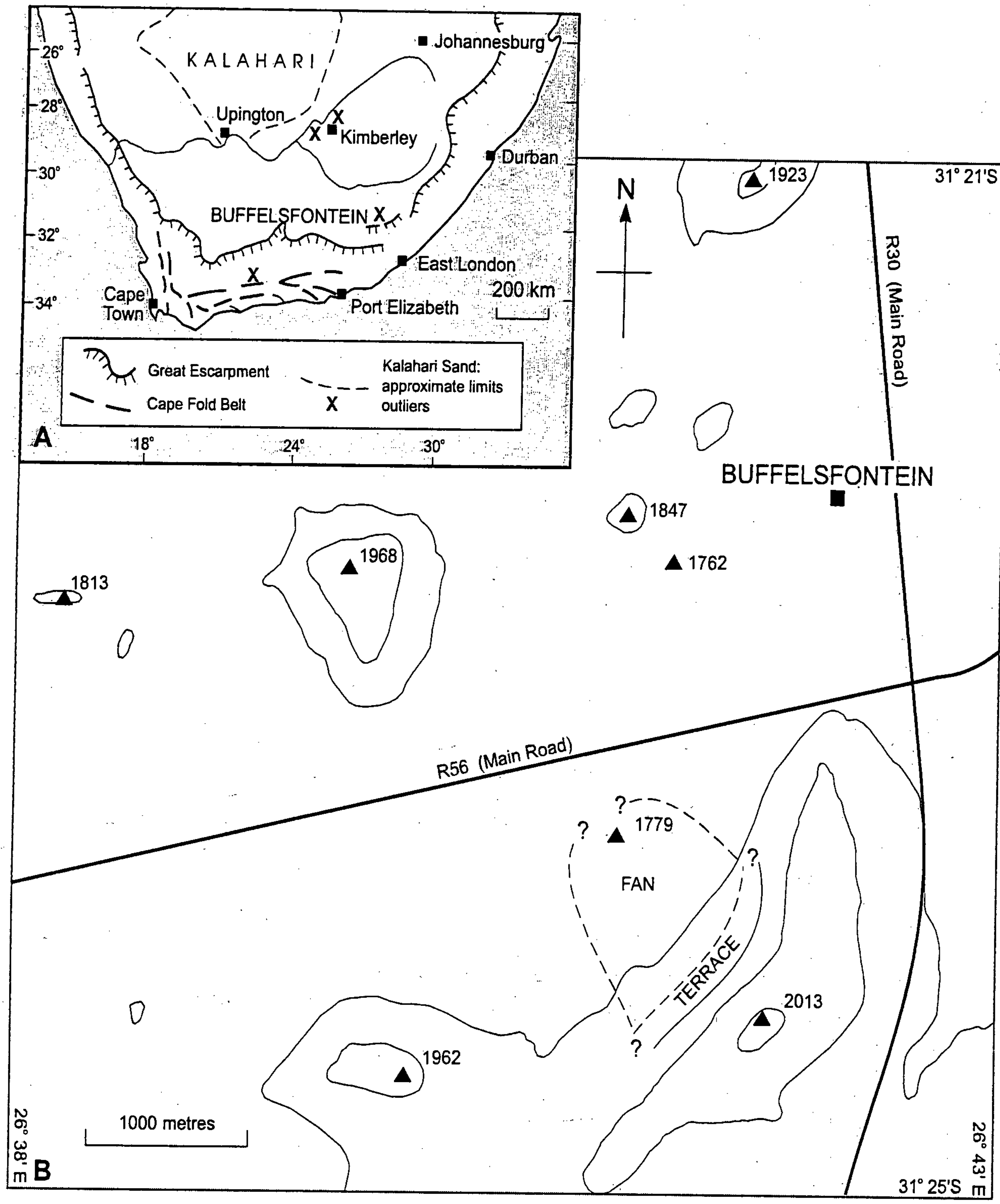


Figure 6.1 (a) The location of the Buffelsfontein Basin.
(b) The Buffelsfontein Basin and the Klipkraal sand deposit (after Marker and Holmes, 1993: p. 480).

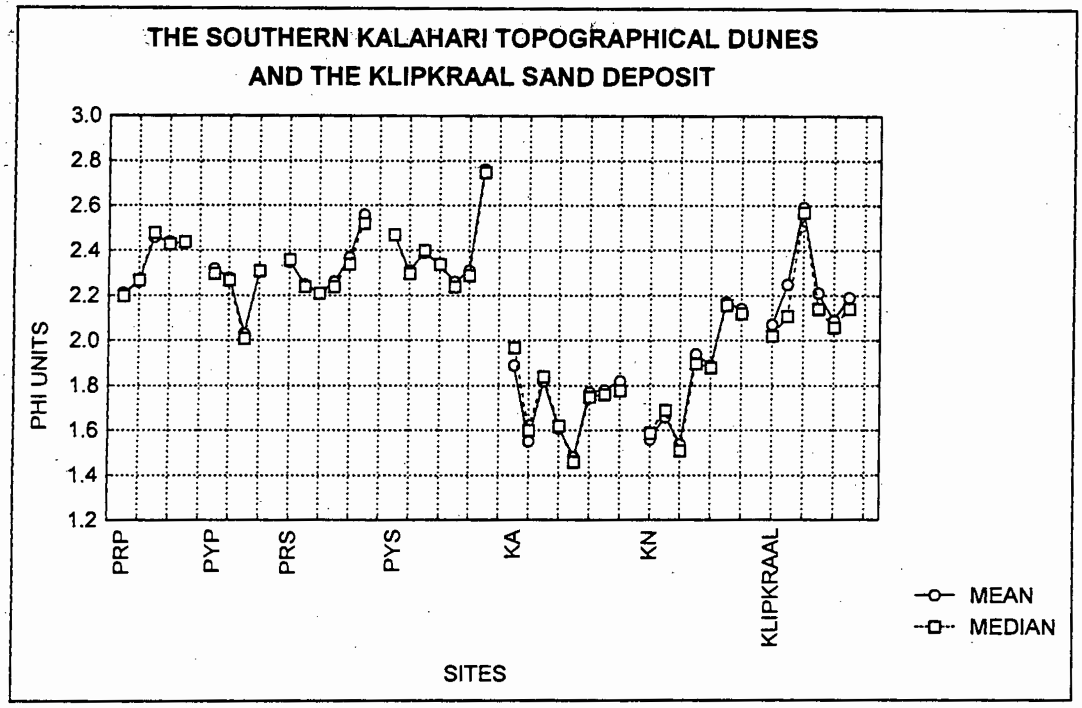


Figure 6.2 A comparison of the mean and median grain sizes between the southern Kalahari topographical dunes and the Klipkraal Sand Deposit.

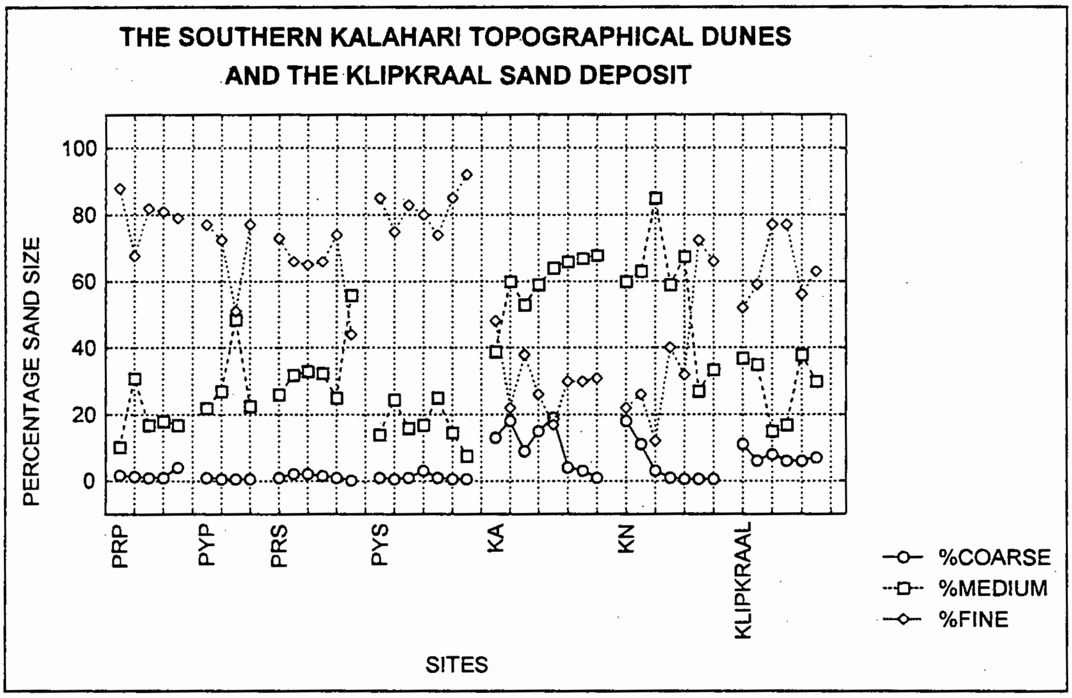


Figure 6.3 A comparison of the sand texture between the southern Kalahari topographical dunes and the Klipkraal Sand Deposit.

Sample	Location	General Description
1	Horizontal strata - quarry face	Friable
2	Resistant strata - quarry face	Partly lithified
3	Cross bedded strata - quarry face	Friable
4	Horizontal basal strata - quarry face	Friable
5	Lens in gully perpendicular to quarry face	Friable
6	Footslope fan	Unconsolidated

Table 6.1 Klipkraal Sands, situation of samples and general description (after Holmes, 1998: p. 81)

Sample	Texture			Textural Class	Munsell Colour
	% Sand	% Silt	% Clay		
1	81	16	3	Loamy sand	5YR 4 / 8 Yellowish Red
2	84	15	1	Loamy sand	5YR 5 / 8 Yellowish Red
3	83	16	1	Loamy sand	5YR 5 / 8 Yellowish Red
4	87	12	1	Sand	5YR 4 / 6 Yellowish Red
5	77	20	3	Loamy sand	10YR 5 / 3 Brown
6	96	4	0	Pure sand	5YR 4 / 8 Reddish Yellow

Table 6.2 Klipkraal Sands; textural and colour properties (after Holmes, 1998: p. 82).

Sample Site/ Number	Sample Position	OSL (Single)	OSL (Multiple)	TL
Klipkraal Sands				
-	A (90 cm depth)	13.3 ± 0.67	15.4 ± 1.96	
-	A (3.3 cm depth)	13.75 ± 0.5	33.0 ± 1.55	11.72 ± 0.6
-	B (~70 cm depth)	34.18 ± 1.91	52.59 ± 5.45	20.5 ± 1.0
W 1407	B (basal)			20.5 ± 1.0

Table 6.3 Luminescence dates (ka) with one standard deviation (after Holmes, 1998: p. 85).

6.5.3 Discussion

The dates (Table 6.3) from the Klipkraal sand deposit are, with the exception of W1407, unpublished. They indicate that this feature was active early in the Late Pleistocene Hypothermal (20 500 ± 1 000 BP). During the Late Pleistocene cold phases, stronger anticyclonic circulation led to phases which were more arid than present (Tyson, 1986). The significance of the Klipkraal sand deposit lies in its homogeneity, and more importantly in its isolation as an aeolian deposit, possibly derived from the Kalahari Group Sands, and it is therefore proposed that during this Late Pleistocene Hypothermal, conditions in the southern Kalahari were also dominated by stronger anticyclonic conditions. It is possible that the Klipkraal Sand Deposit can be correlated to the three dune building phases identified by Stokes *et al.* (1997b), viz. 28 - 23 ka, 17 - 10 ka and around 5.5 ka, , and it is thus proposed that the southern Kalahari topographical dunes were probably emplaced during the first dune building phase due to the extensive aridity which seems to have effected the summer rainfall regions of South Africa during this time. It is probably that after this extensive dune building period, the dunes were subjected to a series of active (arid) and inactive (humid) phases which were analogous with the oscillating dry and wet phases that have been described. In addition, the climbing dunes, due to their lack of structure and the homogeneous nature of the dune sediments, *might* have been emplaced during a single event rather than during multiple phases of development.

6.5.4 Summary and Conclusions

The southern Kalahari topographical dunes are homogeneous quartz climbing dunes of which the surface is still currently active. Due to field sampling difficulties, a pit of only 1,4 m was excavated and its material has been dated to 100 years ago. A basal date of dune formation is therefore not possible and age determination and sequence of events for the dunes are also not possible. The aeolian sand deposit in the Stormberg Locality of the Great Karoo indicates an extensive widespread arid phase occurred in the summer rainfall regions of Southern Africa at 20 500 kyr. This date coincides with the arid dune-building phases that have been identified in the southern Kalahari by Stokes *et al.* (1997a and 1997b), Shaw and Cooke (1986) and Shaw and Thomas (1996). Even though there is no direct correlation of dates between these sites, and although the southern Kalahari dunes in this study do not indicate these changes, they also do not exclude them. It is tentatively proposed from the comparison of research that the southern Kalahari dunes might have been emplaced during a single dune building phase at some stage between 28 - 22 kyr. They are currently episodically active climbing dunes.

6.6 THE BREEDE RIVER VALLEY

6.6.1 The Sandput

As stated previously, the Sandput (Chapter 4, Fig. 4.6), as well as Sandberg and Moddergat, are all homogeneous aeolian quartz sand dunes which have been classified as climbing dunes. Due to sampling limitations, shallow pits were dug and only surface samples were taken at Moddergat and the Sandberg respectively. Three samples for OSL dating (Chapter 5, Table 5.6) were taken from the Sandput exposed face, the basal date at the stone line, the middle date at the greyish brown horizon and the top date in the columnar structure layer (Fig. 4.8).

6.6.2 Basal Date: 762.7 ± 104.5 kyr

The magnitude of this date is well beyond the limits of OSL dating, and thus should be interpreted as an indicator of maximum age rather than an age of exact formation. This maximum age of formation implies that the dune is an exceptionally old feature that probably dates to the early to middle Pleistocene. It should be noted that because it is not a precise date, it cannot be compared to literature with respect to absolute dates, bur rather as a relative date of dune formation which was probably initiated around the middle Pleistocene. The middle Pleistocene is not well documented in the Western Cape. Tufa deposits from the Gaap Escarpment in the Northern Cape and the lower Vaal River terraces indicated that the middle Pleistocene reflected alternating semi-arid and humid conditions (Maud and Partridge, 1987). From analyses of tufa carapaces at Taung in the Transvaal, Partridge (1985, after Maud and Partridge, 1987) deduced that tufa depositions were characterized by semi-arid episodes and tufa erosion occurred during the more humid phases. A tufa depositional sequence was found at Taung (Maud and Partridge, 1987) and dates to approximately 760 000 kyr, therefore implying that this period was drier than the preceding and antecedent humid interludes. Due to the poor resolution of the date, however, as well as the lack of detailed chronological studies in South Africa, and more specifically the Western Cape, suggestions of a more arid phase in South Africa on the sub-regional level at this time should be treated with caution. The sample for dating was taken on the white stone line horizon (Fig. 4.8) and it is proposed that this line could be an indication of rather a more humid period where colluvial slope processes, driven by higher energy conditions, emplaced the quartz pebbles. This horizon may therefore indicate a period of stasis after which dune building was initiated. The implications of this interpretation, given the broad scale of the dating and lack of information regarding this period, evoke thoughts of a differing response in the summer and winter rainfall regions to glacial and interglacial phases.

6.6.3 Middle Date: 28.8 ± 5.3 kyr

Although this date, due to possible incomplete sunlight bleaching prior to sand deposition, may be an over-estimation in age, it is considered a relatively reliable date (Bateman, pers. comm.). Above the stone line, an ancient surface on which accumulation of sediment has taken place, a greyish brown horizon (10YR 5/2) was dated to 28.8 ± 5.3 kyr. This date falls into the period spanned by Oxygen Isotope Stage 3, the period prior to the Last Glacial Maximum (LGM) (Adams, 1997). According to Partridge (1997) the period at approximately 30 kyr was wetter than today (evidence for this comes from summer rainfall sites at the Pretoria Saltpan, Wonderkrater and coastal freshwater lakes in Kwa-Zulu Natal). Evidence from a stalagmite in the Cango Cave, Oudtshoorn, (in Partridge, 1997) also indicates that the temperatures were 3 - 4 °C cooler than the present day, therefore implying a cooling trend towards the LGM. By 28 kyr conditions were more arid than today and in northern Botswana evidence from linear dunes indicates that extensive dune building activities were initiated (Stokes *et al.*, 1997a), therefore suggesting aridity across the summer rainfall regions of southern Africa (Adams, 1997). Evidence from the Makgadikgadi basin and Drotskey's Cave in Northern Botswana (Shaw and Cooke, 1986) also indicate the end of a humid phase by about 30 kyr and an increase in aridity. A recent study conducted by Shaw *et al.* (1998) on Dias Beach, Cape Point, Cape Town, found that colluvium facies at Cape Point were emplaced at 31 kyr as a result of combined run-off events due to more moist Late Pleistocene climatic conditions.

Conflicting interpretations of the moisture levels during this pre-LGM period makes interpretations of the Breede River Valley environment difficult. Also, a lack of sites in the winter rainfall region, as well as poor chronological resolution, makes correlation between sites problematic. Despite these limitations, and the absence of organic matter in the greyish brown horizon of the Sandput, it is postulated that this horizon is indicative of a more humid phase as incipient soil formation may have begun to take place. The basis for this interpretation is twofold. Firstly, it supports the study by Shaw *et al.* (1998) who found that the more moist conditions caused colluvium facies to become emplaced. Secondly, it is supportive of the study by Baxter (1996) who found that the summer and winter rainfall regions have not responded synchronously to changes in global circulation which lead to periods of cooling or warming. Tyson (1986) found that there was a gradual cooling from the beginning of Oxygen Isotope Stage 3 until the LGM, and studies by, *inter alia*, Partridge (1997) and Cockroft *et al.* (1987) found that in the summer rainfall region of South Africa, this glacial cooling is coupled with increased aridity. Cooling in the winter rainfall region of South Africa would therefore be coupled with an increase in precipitation, causing dune activity to be reduced. This study therefore supports the Cockroft *et al.* (1987) model for dry and wet phases in South Africa. The model (Figure 6.4) is based on the Tyson (1986) model which explains present day extended (near-decadal) wet and dry spells on the basis of variation in surface and upper atmospheric circulation. Cockroft *et al.* (1987) applied this model to Quaternary climates and found that changes in general atmospheric circulation which evoke cooler spells (such as during the LGM) lead to a decrease in rainfall in the summer rainfall region and a concurrent increase in rainfall in the winter rainfall region (the mechanics of these dry and wet phase oscillations will be explained later).

Interpretation and dating of the Sandput exposed face therefore suggests an overall trend of Late Pleistocene hypothermal conditions where cooler temperatures and increased moisture from 30 kyr reached a peak at the LGM.

6.6.4 Top Date: 9.9 ± 0.7 kyr

The top date from the Sandput sequence was sampled at the base of the columnar depositional layer (Chapter 4, Fig. 4.8) and is the most reliable date that was obtained from this sequence. The importance of this date, and therefore the columnar depositional layer, lies in its positioning at the beginning of the Holocene (a period which is characterised by rapid sea level rises and temperature ameliorations). The columnar "organ pipe" structuring represents a period of stability evoked by more humid climatic conditions. According to Partridge (1990) the phase between the LGM and the Holocene was representative of a warming phase, associated with increased moisture availability in the summer rainfall region. If one concurs with the work of Baxter (1996) and Cockroft *et al.* (1987) it is likely that this post-glacial warming phase in the Western Cape was accompanied by increased aridity rather than an increase in moisture.

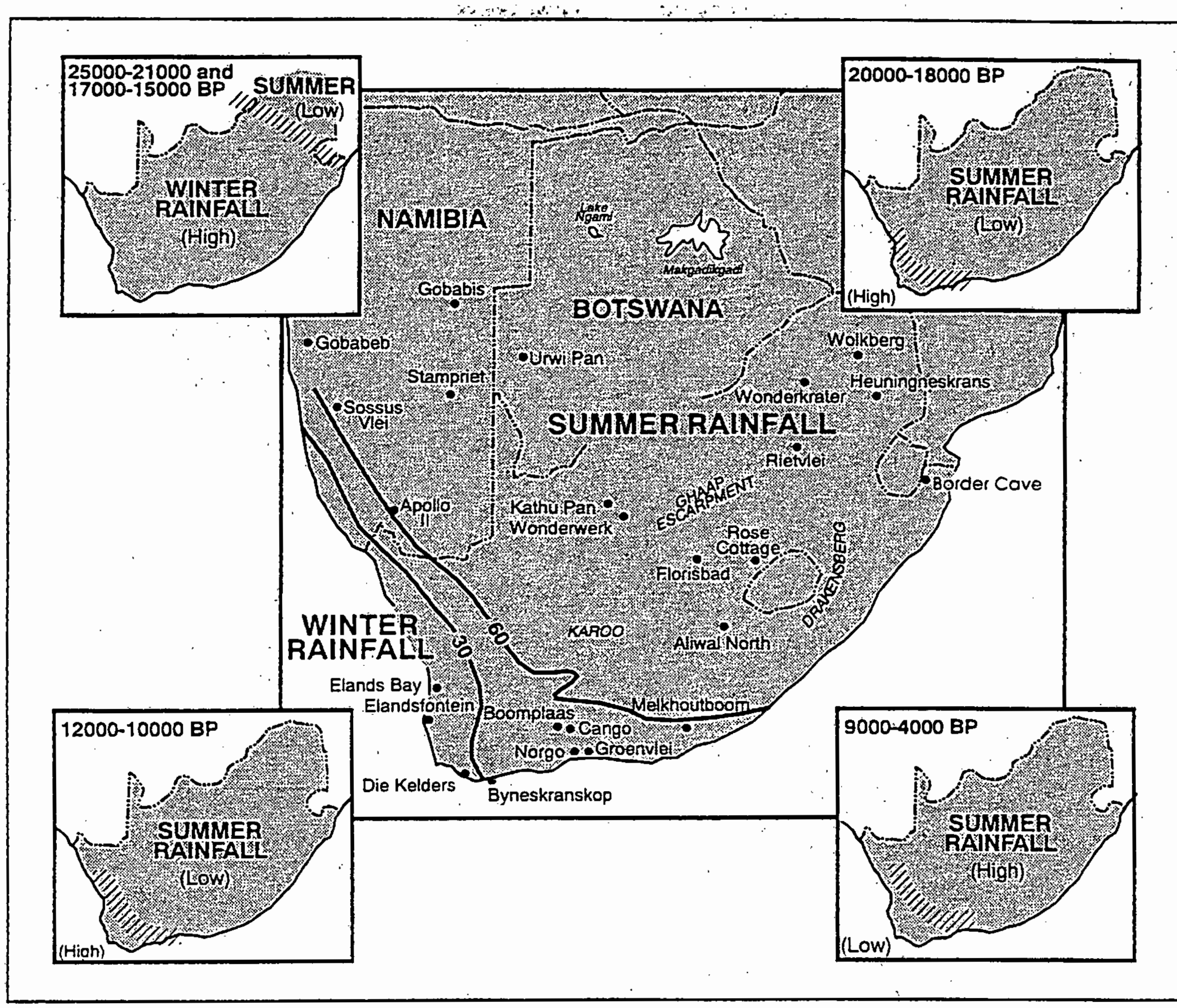


Figure 6.4 Climatic model of the regional rainfall variation in southern Africa. This shows the present-day distribution, and summer and winter rainfall regions in southern Africa (isolines give percentage annual rainfall received in summer), together with hypothesised positions of the summer-winter rainfall boundary at different times of the year (After Cockroft *et al.*, 1987: p. 103).

The warming of the terminal Pleistocene was then interjected by the Younger Dryas between 11 000 and 10 000 years ago. The Younger Dryas was a global cooling event which has been documented in the South African fossil record by means of isotopic variations in shells off the Atlantic coast and work by Partridge on ostrich eggshells (Adams, 1997). These studies, as well as the reactivation of dune building to the north of the Orange River, all support a cooler, more arid climatic phase (Adams, 1997). Unfortunately, the period between 10 500 and 6 800 BP was not represented in Baxter's (1996) fossil pollen sequence at Verlorenvlei, but the fossil mollusc and sedimentary record do indicate that hypsithermal conditions were evident. These warmer temperatures were associated with drier conditions. It can therefore be postulated that after the LGM the Breede River Valley was subjected to temperature amelioration accompanied by increased aridity. It is tentatively suggested that at approximately 9 kyr this region reflected the delayed impact of the Global Younger Dryas cooling event, accompanied by an increase in moisture. This moisture increase can be seen in the stability of the climbing, dune where a columnar sand structure was able to form. The Holocene hypsithermal followed, where temperatures began to once again rise and increased aridity evoked the reactivation of aeolian processes and thus dune building was able to recommence.

6.6.5 A synthesis of the Breede River Valley Environment during the Quaternary

Three significant periods of stasis followed by active dune building phases have been identified at the Sandput sequence. OSL dating supports the scenario. Although it is likely that other oscillations of dry and wet phases may also have occurred during the Quaternary, due to the coarse resolution of the chronology and lack of OSL dates, only these three phases were identified.

Phase 1: 760 kyr

Studies from this period in South Africa are few and thus it can only be concluded tentatively that the stone line from the Sandput sequence, which was dated to 762.7 ± 104.5 (Shfd98026) kyr as a maximum age, is an ancient surface that was emplaced by colluvial slope processes. This period is therefore indicative of a more moist phase which was followed by a phase of aeolian activity causing dune building to become initiated.

Phase 2: 28.8 kyr

This phase (analogous with Oxygen Isotope Stage 3) is characterised by gradual cooling and therefore increased moisture until the peak was reached at the LGM. The greyish brown horizon of incipient soil formation supports the findings of Baxter (1996) at Verlorenvlei and that of Shaw *et al.* (1998) at Dias Beach, and is in contrast to the until recently accepted view that general atmospheric circulation that evoked cooler temperatures were universally associated with drier conditions in southern Africa. The work of Partridge (1997) has shown that the summer rainfall region experienced cool dry climatic conditions at the LGM and thus it can be concluded tentatively that the summer and winter rainfall regions responded uniquely to the global atmospheric systems responsible for global cooling during the last glacial phase. Orbital (insolation) forcing as well as sea surface temperatures were responsible for changes in aridity on the subcontinent (Meadows, 1998), and Cohen and Tyson (1995) have emphasised the dichotomous response of the winter and summer rainfall regions to these factors. During this cooler phase at the LGM, weaker tropical easterlies and therefore Walker circulation coupled with a displacement of the South Atlantic High Pressure and South Indian High Pressure equatorward would lead to drier conditions over the interior of South Africa and its associated summer rainfall regions (Fig. 6.5b). In addition, strengthened westerlies coupled with a northward shift of the circumpolar vortex would lead to increased rainfall over the winter rainfall region (Cohen and Tyson, 1995). As can be seen from Figure 6.5a, the exact opposite would occur during an interglacial, thus leading to warm dry conditions in the winter rainfall areas and warm wet conditions in summer rainfall regions. The last glacial phase at Breede River Valley was therefore characterized by cooler, wetter conditions which lead to incipient soil formation.

Phase 3: 9.9 kyr

Phase 3 represents a period of cooler, more moist conditions in the Breede River Valley, possibly as a result of a delayed reaction to the Younger Dryas cooling event. This phase is preceded by temperature amelioration after the LGM and enhanced aridity which initiated extensive aeolian activity and dune building. By the beginning of the Holocene, however, a short global cooling (the Younger Dryas) caused aeolian activity to be slowed and a more moist climate allowed for the sand to become partly lithified in the form of columnar structuring. Following this short cooling phase (± 1 - 2 ka) the Holocene hypsithermal indicated maximum warm periods and once again enhanced aridity and thus aeolian activity recommenced (Partridge, 1993). The Western Cape climate was then characterized by a gradual cooling towards the climatic conditions which are experienced today (Baxter, 1996).

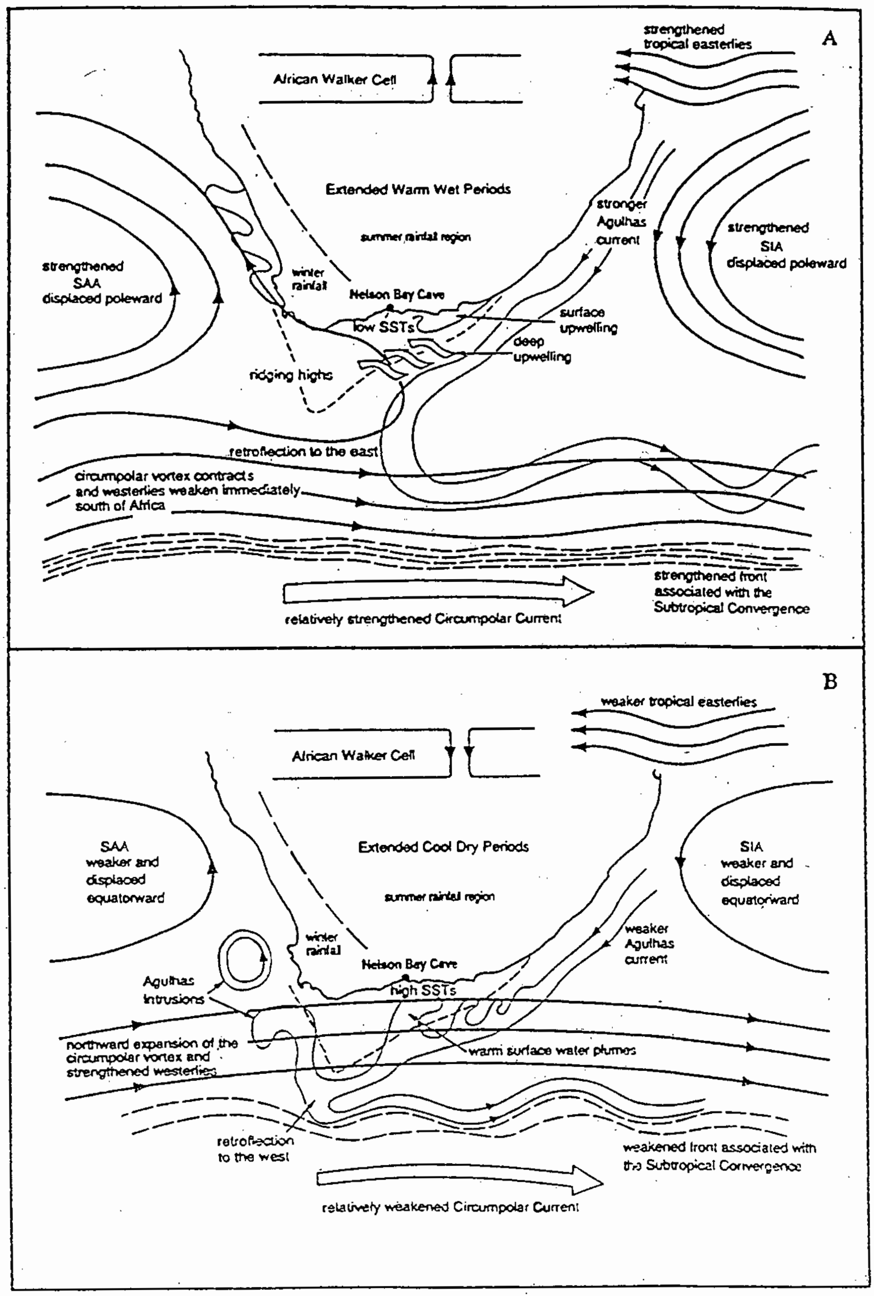


Figure 6.5 A conceptual model of the response of oceanic circulation and coastal sea surface temperatures to atmospheric circulation anomalies responsible for extended wet spells in the summer rainfall regions and extended dry spells in the winter rainfall regions (A), and extended dry spells in the summer rainfall regions and extended wet spells in the winter rainfall regions (B) in South Africa (after Cohen and Tyson, 1995: p. 305).

6.7 IMPLICATIONS FOR FUTURE CLIMATE CHANGE

Notwithstanding the limitations posed by the study, its importance lies in the implications it has for semi-arid regions for future climate change. In addition, despite concerns regarding the validity of Quaternary analogues for future global warming (i.e. enhanced warming evoked by modern technology) (Scott, 1993), it is assumed in this study that the global circulation patterns would probably react in the same way to warming as they have in the past, merely on a greatly accelerated time-scale. Semi-arid areas are transitional in nature (i.e. from more humid areas to more arid areas), and thus due to their high habitat diversity, the species diversity of these types of dryland regions is high. Furthermore, they are also sensitive to climatic changes and interference by humans could lead to processes such as desertification.

As has been shown, the summer and winter rainfall regions respond differently to changes in global atmospheric circulation, and that warming in the winter rainfall regions of South Africa is coupled with drier conditions than present. Mid-Holocene warming phases are characterized by weaker (and more southerly) westerly circulation and strengthened South Atlantic and South Indian high pressures which are displaced poleward (Partridge, 1993). The Tyson (1986) and Cockroft *et al.* (1987) models therefore imply that dry spells in winter rainfall regions (and wet spells in summer rainfall regions) are caused by general atmospheric circulation which lead to periods of warming. If this hypothesis holds for future climate changes, then global warming could lead to increased aridity in the winter rainfall regions of South Africa.

Further studies with increased chronological resolution should therefore focus on this issue in order to gain a more comprehensive understanding of the interplay between the global atmospheric phenomena which cause the Western Cape's enhanced aridity during warming events. These types of studies are necessary in order to aid the interpretation, improvement and evaluation of general circulation models (GCM's) which model future climate changes. These studies should also focus on becoming more outcomes-based in order to aid Western Cape, as well as National planners and decision-makers in policy formulation and mitigation measures to guard against water shortages in the future.

6.8 SUMMARY AND CONCLUSIONS

In this chapter, the results of the study have been discussed in terms of defining whether the southern Kalahari and Breede River Valley topographical dunes are sand ramps or climbing dunes, as well as their palaeoenvironmental significance. It has been tentatively concluded that the topographical dunes from both regions are climbing dunes rather than sand ramps due to their homogeneous aeolian sand composition and the absence of other types of sediment layers. The sand source of the southern Kalahari dunes is identified as being reworked Kalahari sands which were wind blown from the Orange River or from the vast linear dune field. The Breede

River Valley topographical dunes comprise wind blown sands from the Breede River which were deposited on its floodplain during flooding. However, due to the lack of differing sediments within climbing dunes and the homogeneity of aeolian sediments, it is proposed that they are less useful indicators of palaeoenvironmental change than the multi-sedimented sand ramps.

Palaeoenvironmental reconstructions, based on three OSL dates from each region were also presented. Due to the sampling limitation posed by the study, only a 1.4 m pit on the Prynnsberg dune was sampled. These dates proved to be 100 years old and it is tentatively proposed that they are not the result of contamination by sunlight, but rather as a result of reworking of Kalahari sands thus implying that the dune is still episodically active. In comparison with the Klipkraal sand deposit in the Great Karoo (Marker and Holmes, 1993 and Holmes, 1998) which comprises Kalahari sands, it was tentatively concluded that the feature was active during the LGM and thus cold dry conditions could possibly have been experienced over the interior or summer rainfall regions of southern Africa. This finding is supported by other palaeo-studies in the southern Kalahari, and Stokes et al. (1997b) confirmed that there were three dune building phases in the Late Quaternary, i.e. 28 - 23 kyr, 17 - 10 kyr, and around 5 kyr.

Data from the Sandput topographical dune exposed face suggest a different scenario. Here, three humid phases are proposed, i.e. 760 kyr (this period should be treated with caution as the date is well beyond the limits of OSL dating), 28.8 kyr and 9.9 kyr. The information from this site therefore confirms the view of Baxter (1996) that cold periods in the winter rainfall regions of southern Africa were coupled with an increase in moisture and thus the summer and winter rainfall regions responded differently to changes in general atmospheric circulation.

The study therefore has important implications for future climate change as it has been shown that, during warm phases, the winter rainfall regions experienced drier conditions. Future studies should focus on the use of GCM's coupled with palaeoenvironmental studies in order to determine the response of the landscape to this enhanced aridity under accelerated warming conditions. In the following chapter, a historic overview through aerial photographic analyses is undertaken in order to gauge the impacts that humans have already had on these unique aeolian depostional features.

CHAPTER 7: HUMAN IMPACTS ON TOPOGRAPHICAL DUNES

7.1 INTRODUCTION

Quaternary palaeoenvironmental studies of landforms are important as they elucidate the relationships between environmental change and geomorphic response to these changes. It is also important, however, to ascertain how humans have impacted on the landscapes which they occupy thereby possibly causing landforms to change. This study has primarily been concerned with investigating the response of topographical dunes to environmental change, however, the author recognises the importance of also studying the effects of human impacts on topographical dunes. This is particularly important as the results of the OSL dating on the southern Kalahari topographical dunes suggests recent activity and a possible episodic re-activation of the dunes, thus making them susceptible to human impacts. This chapter is thus concerned with the impacts of humans on topographical dunes during the historical period from 1942 to 1994. Aerial photographs from this period have been examined and conclusions as to the impact of humans on the southern Kalahari and Breede River Valley dunes are discussed.

7.2 HUMAN IMPACTS ON DUNE SYSTEMS

With the exponential increase in the world's population, the arid and semi-arid areas of the earth are highly susceptible to human impacts (Goudie, 1994). The patterns of human accelerated change in dryland regions reflects that of desertification, and the problem tends to be more severe on the desert margins where population pressures are high and climatic uncertainties are great. With respect to weather and soils, increased salinity levels of soils associated with irrigation (i.e. salinisation), erosion of the thin veneer of desert soils as a result of vegetation removal, and wind erosion all combine to desertify dryland areas (O'Hara, 1997). Forty percent of the world's drylands are susceptible to human degradation, and wind erosion of sparsely vegetated areas, moisture deficits and thin soils all combine to affect 39% of these susceptible drylands (Fig. 7.1) (O'Hara, 1997).

No studies with respect to human impact on topographical dunes have been found, and thus it is inferred that human impacts on other dunes (such as linear dunes) will be similar to, and have the same effects as on topographical dunes. Despite the complexities of desertification, Khalaf

(1989), identified three main causes of desertification of dune systems, i.e. agriculture, overgrazing and sand quarrying.

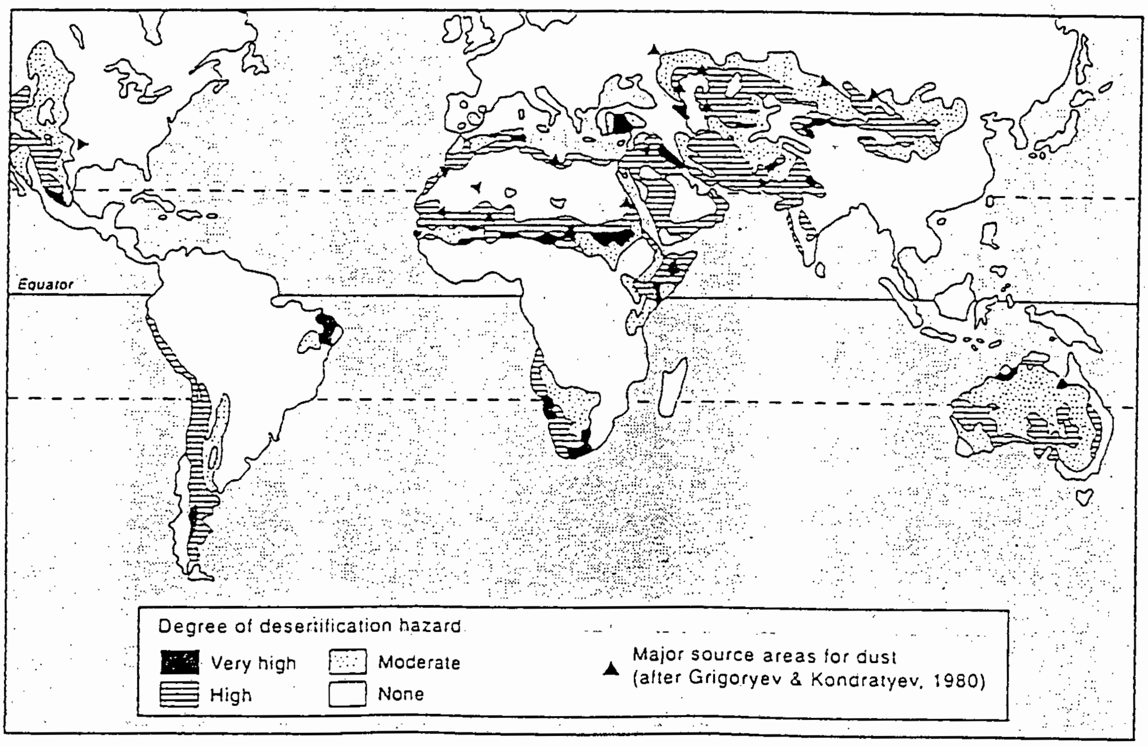


Figure 7.1 Major areas of desertification and major sources of dust (after O'Hara, 1997: p.643).

7.2.1 Agriculture

In many desert areas there is sufficient rain to support vegetation on dunes thereby resulting in these dunes becoming stabilized (O'Hara, 1997). In addition, the soils of these dunes generally support richer vegetation and thus the thin soils are more easily cultivated and are less prone to salinization than the low-lying areas (Pye and Tsoar, 1990). By removing the natural vegetation, the sandy surfaces of the dunes are exposed, thus increasing the erosivity of the system (O'Hara, 1997). Wiggs *et al.* (1994) showed that natural bush fires within the southwestern Kalahari linear dune field led to a three-fold increase in dune activity, and thus it can be inferred that agricultural burnings could also lead to increased sand movement.

7.2.2 Overgrazing

As previously mentioned, dunes support richer vegetation than the lower lying areas and thus they tend to be suitable areas for the grazing of cattle, sheep and goats. Overgrazing of these areas occurs because the carrying capacity of the environment with respect to grazing animals is exceeded. A study by Perkins and Thomas (1993) however showed that, despite the southern Kalahari being relatively resilient with respect to topography and soil characteristics and to degradation, the issue of overgrazing in semi-arid areas is more complex than previously perceived.

7.2.3 Sand Quarrying

Perhaps the most destructive activity of all human impacts on dunes, sand quarrying eliminates vegetation cover and the associated faunal communities (Khalaf, 1989). Sands are generally mined for their silica content for glass and ceramic manufacture, but some sands are mined for their heavy mineral content (Pye and Tsoar, 1990). Sand quarries are particularly hazardous as the process releases fines which can become airborne and the likelihood of sand and dust storms increases. These mobile sands not only present an environmental problem, but can also have adverse impacts on the economy and quality of life (Khalaf, 1989).

7.3 A REVIEW OF HISTORIC AERIAL PHOTOGRAPHY

One of the aims of this study is to examine the impacts that humans have had on topographical dunes in the past, and thus a review of aerial photographs for the period 1942 - 1994 has been undertaken. Furthermore, the southern Kalahari dune pit samples were dated to 100 years old, and it was concluded in the previous chapter that the dunes are still episodically active. It is for this reason that human impacts on the dunes are being studied so as to gain an understanding as to whether or not the reworking of the Kalahari sands can be attributed to natural causes or to anthropogenic changes. Due to the remoteness of both regions, a continuous record of each site using aerial photographs was not possible, and thus the sites are only examined for evidence of change for those years where the aerial photographs are available.

Each topographical dune was measured on the photograph and then using the appropriate scale, converted to meters in order to aid comparison. The footslope (base), west edge, east edge and tip to mid-base (Fig. 7.2) was measured and compared. The dunes were also examined for changes in vegetation and erosional features. Once the analysis was complete, the data was converted to percentage change since the base year and the results graphed. The main problem with using aerial photographs in order to compare dune morphometry is that the historical record of both study regions is not good, and over exposure of some of the older photographs made dune interpretation difficult. In addition, the season and time of day that the aerial photographs were taken differs, thus making interpretation difficult. The photographs do, however, allow for a relatively quick and easy surficial analysis of landforms due to the direct nature of the interpretation (Verstappen, 1977).

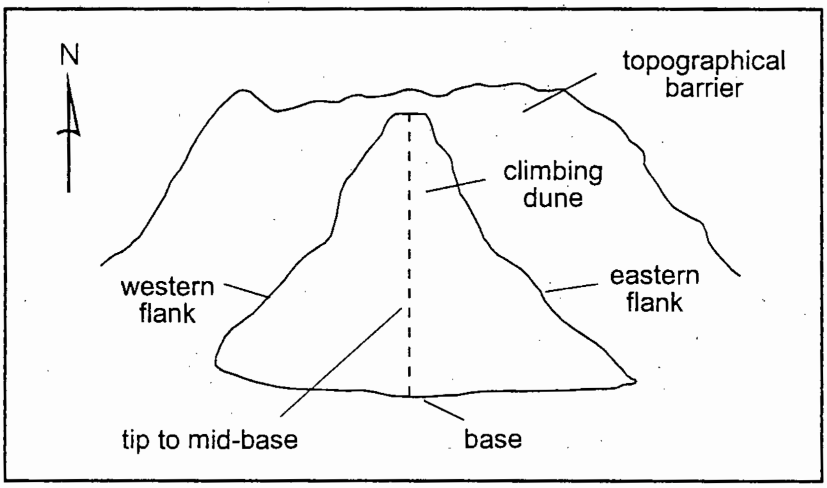


Figure 7.2 Schematic diagram showing the measured sides of the topographical dunes from the southern Kalahari and the Breede River Valley.

7.4 THE SOUTHERN KALAHARI TOPOGRAPHICAL DUNES

All four topographical dunes in the southern Kalahari were measured for changes in morphometry, although unfortunately a good historic aerial photograph archive of the region is not available. Figures 7.3, 7.4 and 7.5 shows the results of the study indicating that only 1976, 1982 and 1994 photographs are available for the Prynnsberg dunes, and only 1957, 1964 and 1994 photographs are available for the Kanoneiland dunes. The tabulated results from this analysis are presented in Appendix D.

7.4.1 The Prynnsberg and Kanoneiland Dunes

It is evident from Figures 7.3, 7.4 and 7.5 that there is very little change in the morphometric properties of the dunes with time. Differences in dune measurements could be due to the differences in scale, quality and seasonality of the aerial photographs. The Kanoneiland dunes (Plate 7.1) appear to be relatively well vegetated and there is no visible decrease in vegetation with time. The linear dunes, which are a possible sand source for the dunes, are also well vegetated. There does, however, seem to be a slight decrease in vegetation on the lower lying areas and this could be due to the grazing of cattle, sheep and goats in the area (Plate 7.2). The Prynnsberg dunes (Plate 7.3), on the other hand, are less well vegetated than the Kanoneiland dunes, but no discernible increase or decrease in vegetation cover with time is noticeable.

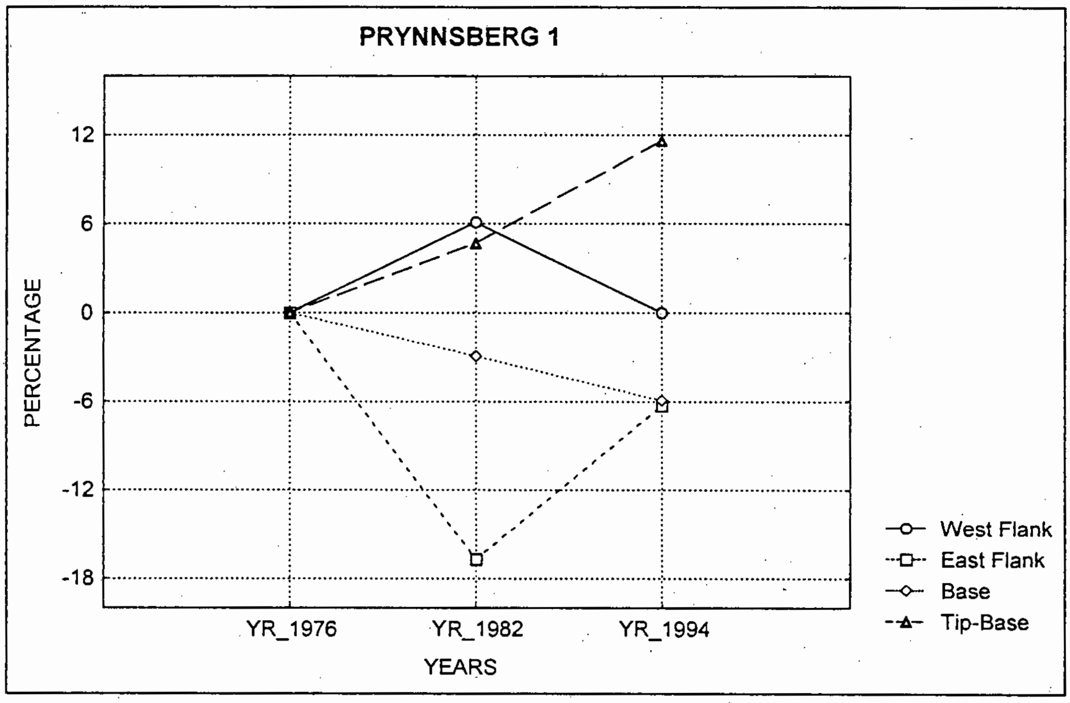


Figure 7.3 The change in dune size from 1976 to 1994 for Prynnsberg 1, southern Kalahari. The western flank, eastern flank, base and tip to mid-base of the topographical dune were measured.

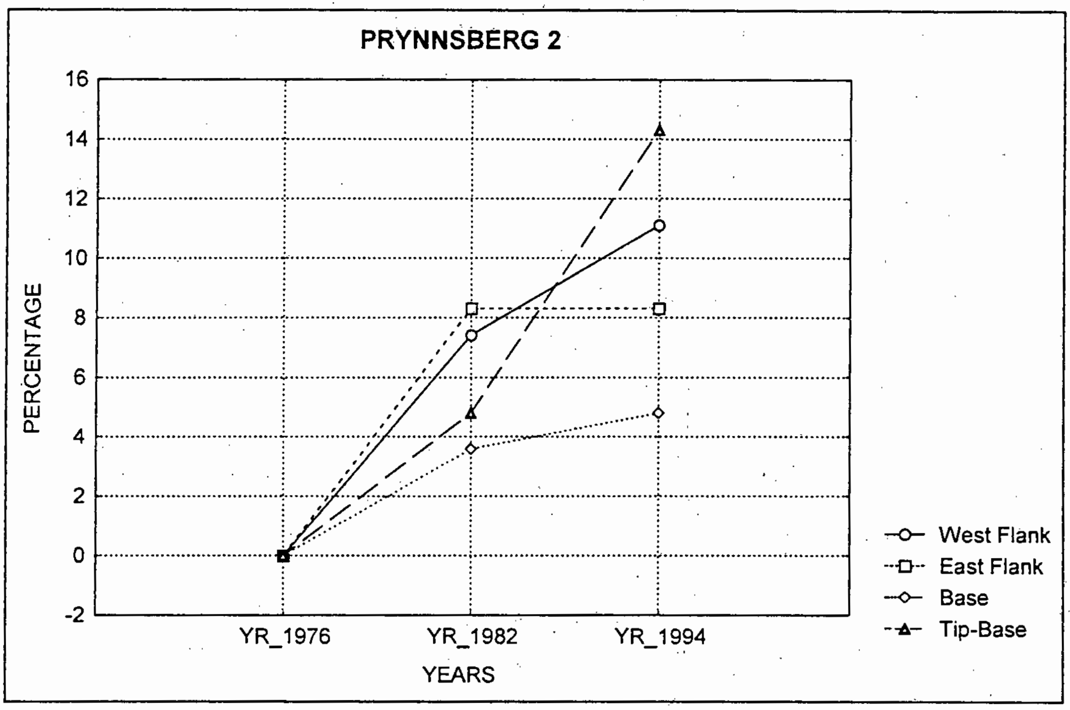


Figure 7.4 The change in dune size from 1976 to 1994 for Prynnsberg 2, southern Kalahari. The western flank, eastern flank, base and tip to mid-base of the topographical dune were measured.

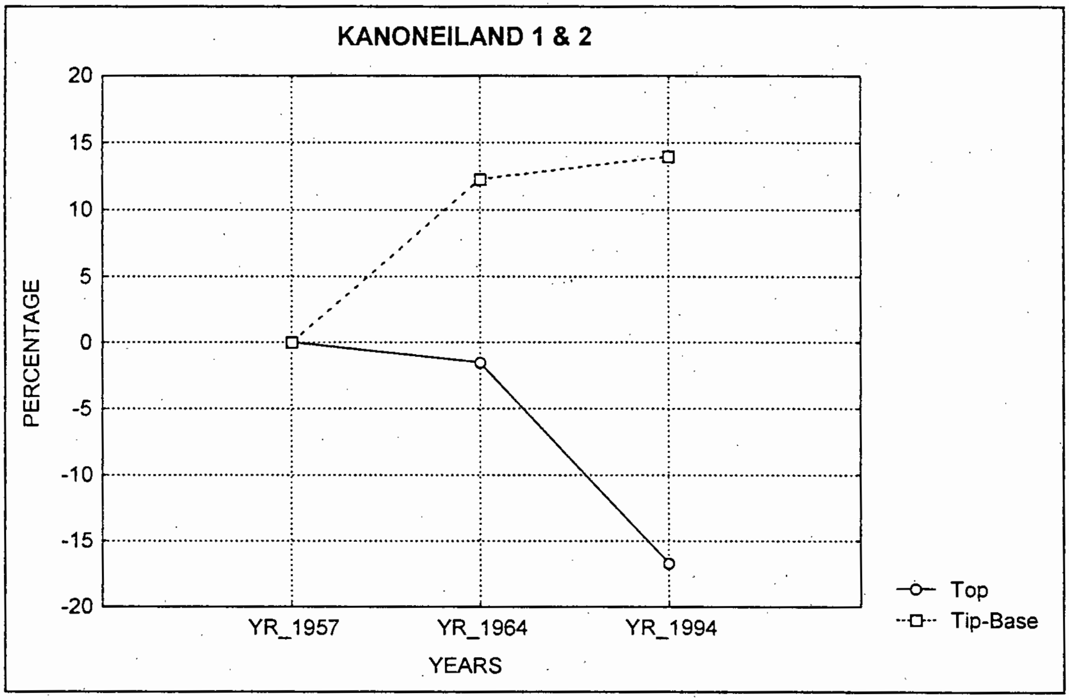


Figure 7.5 The change in dune size from 1957 to 1994 for Kanoneiland 1 and 2, southern Kalahari. Due to the nature and size of the dune, the top and tip to mid-base of the topographical dune were measured.

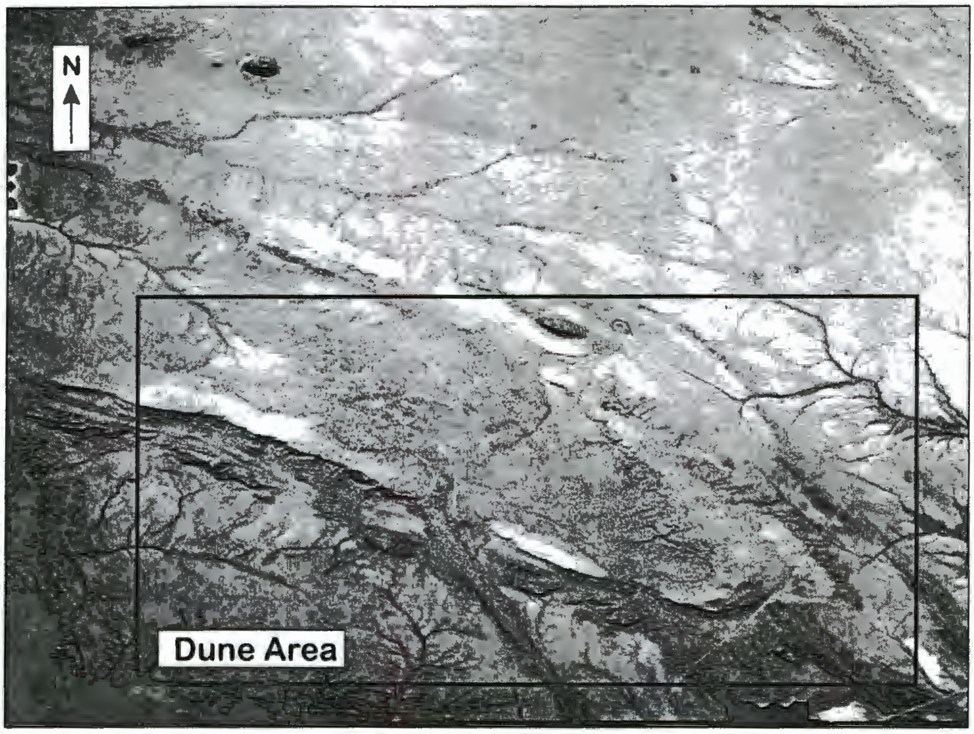


Plate 7.1 An aerial photograph of the Kanoneiland topographical dunes in the southern Kalahari, 1964 (Scale 1:50 000). Note the large linear dunes which feed the topographical dunes.

See Page 105 for **Plate 7.2**

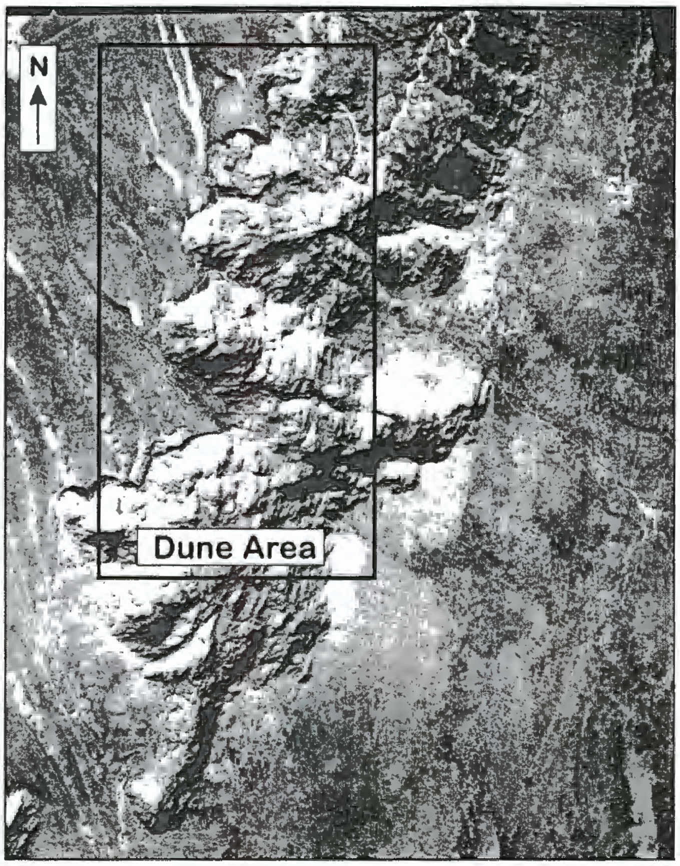


Plate 7.3 The Prynnsberg topographical dunes in the southern Kalahari, 1976 (Scale 1:20 000). These climbing dunes are also fed by large linear dunes.

e 7.2 Grazing by cattle, goats and sheep on the lowlands around the Kanoneiland dunes has caused a decline in vegetation in the area.

e 7.5 The Sandput is presently being used as a sand quarry.

e 7.6 Vineyards and orchards have been cultivated adjacent to the Breede River since 1942.

7.4.2 Discussion

As indicated by the preceding graphs (Figs. 7.3, 7.4 and 7.5) no general trends as to the increase or decrease in dune size of the southern Kalahari dunes are discernible. Unfortunately the study is restricted by the limited aerial photography record and a longer historic record is necessary in order to reach any definite conclusions. From the optically stimulated luminescence dates from the Prynnsberg dunes that were discussed in Chapter 6, it was concluded that there is still sand movement in the area therefore inferring a dynamic active system for the topographical dunes in the southern Kalahari. This active system could cause changes in the dune morphometry which would attribute the variations in dune sizes to natural variation rather than human interference. Impacts of grazing by cattle, sheep and goats are visible on the landscape, but these tend to be restricted to the lower lying areas. Perhaps with an increased population pressure on the land, animals will be forced to graze on the steeper dune slopes and overgrazing on the southern Kalahari topographical dunes may become problematic.

7.5 THE BREEDE RIVER VALLEY TOPOGRAPHICAL DUNES

Moddergat, Sandberg and the Sandput were all measured using aerial photographs in order to try to detect whether any changes in morphometry with time have occurred. For all three of the dunes photographs from 1942, 1966, 1975 and 1987 have been analysed (Figs. 7.6, 7.7 and 7.8). The tabulated results of this analysis can be viewed in Appendix D.

7.5.1 Sandput

The Sandput is a well vegetated topographical dune that is clear of vegetation near the base (Plate 7.4). There is no visible agriculture in the area and the dune is presently being used as a sand quarry (Plate 7.5). There is a slight increase in vegetation between 1942 and 1987, but the large deflated area at the base of the dune remains unvegetated. The dune is relatively stable with respect to size, except for a 50.06% decrease in the size of the base of the dune. This decrease, however, could be due to the vegetation cover of the dune which makes accurate measurement of the dune boundaries difficult (Fig. 7.6).

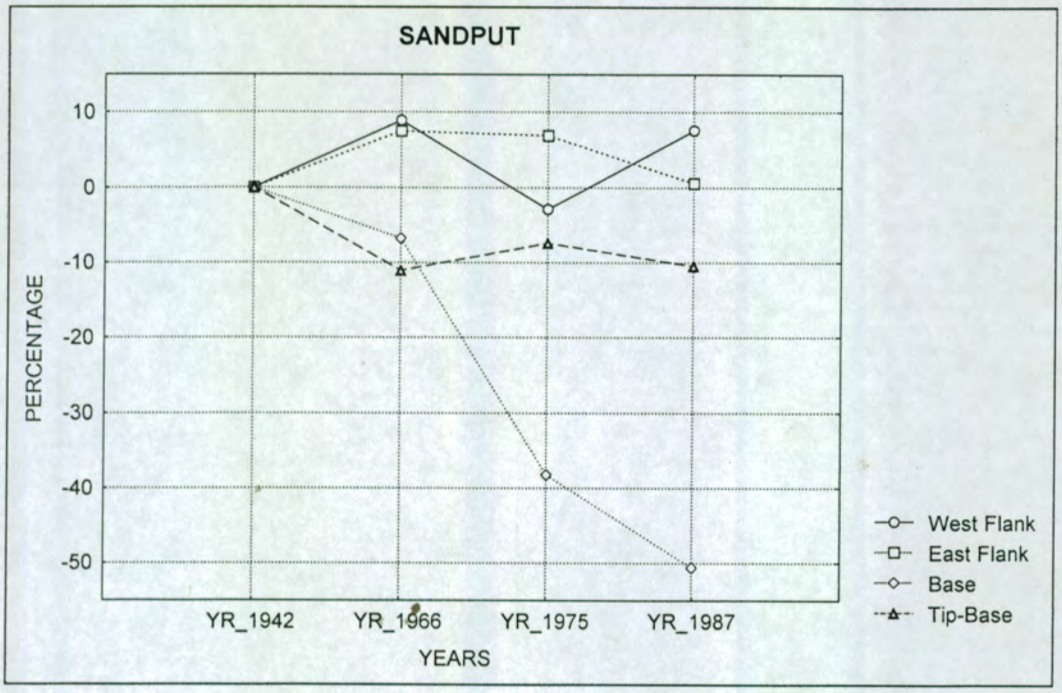


Figure 7.6 The change in dune size from 1942 to 1987 for the Sandput, Breede River Valley. The western flank, eastern flank, base and tip to mid-base of the topographical dune were measured.

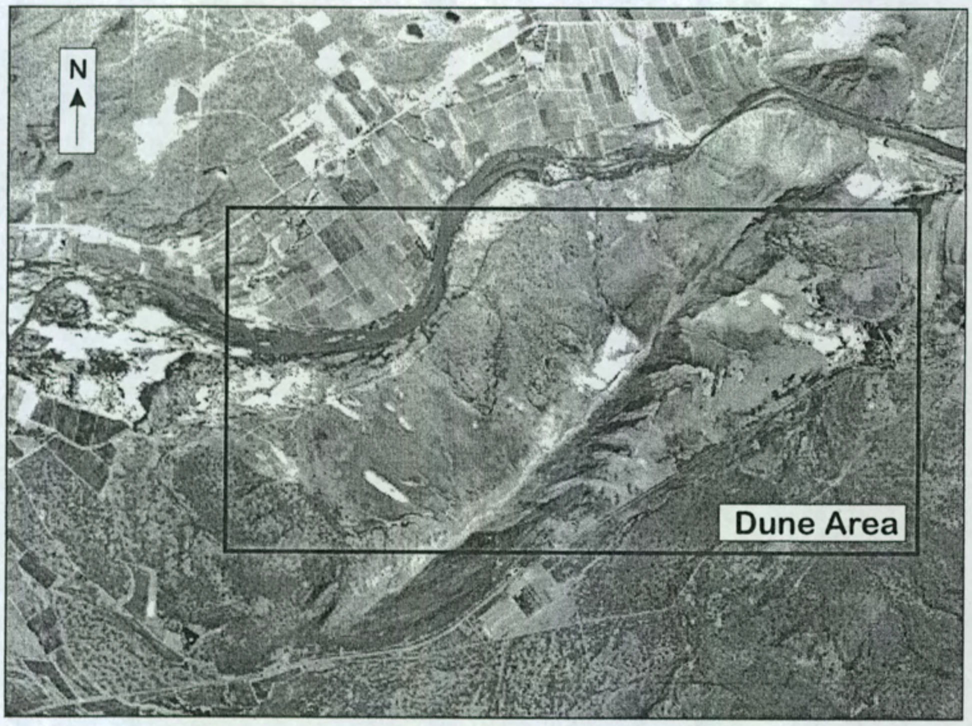


Plate 7.4 A aerial view of the Sandput and Sandberg topographical dunes in the Breede River Valley, 1987 (Scale 1:50 000). The Breede River, which flows adjacent to these dunes are a likely sand source.

See Page 105 for **Plate 7.5** and **Plate 7.6**

7.5.2 Sandberg

The Sandberg topographical dune that was analysed as part of this study is part of a larger sand deposit on the banks of the Breede River (Plate 7.4). Throughout the historic study period this sand deposit is well vegetated with the exception of a few deflation hollows. There is, however, a slight (approximately 15%) increase in vegetation cover with time. The morphometry of the dune seems to be relatively stable with time (Fig. 7.7). Agriculture (Plate 7.6) is evident from 1942 adjacent to the Breede River, and a series of canals and weirs were built between 1898 and 1952 (Wiggens, pers. comm.) in order to provide water for irrigation and to regulate flooding. In 1942, the topographical dune is sparsely vegetated, and is almost clear of vegetation at the top. This lack of vegetation could be attributed to the steepness of the slope. By 1987, there was a noticeable increase in vegetation cover, especially on the steeper slopes and the top of the topographical dune (therefore implying a more stable, less active system). This increase in vegetation cover could either be attributed to a more stable climatic period with an increase in rainfall (or decrease in windiness) between 1942 and 1987, or it could be a result of the canalization of the Breede River upstream. Invasion by alien vegetation could also explain the increase in vegetation, although site visits showed the area to comprise relatively pristine Arid Fynbos and Karoo shrubs.

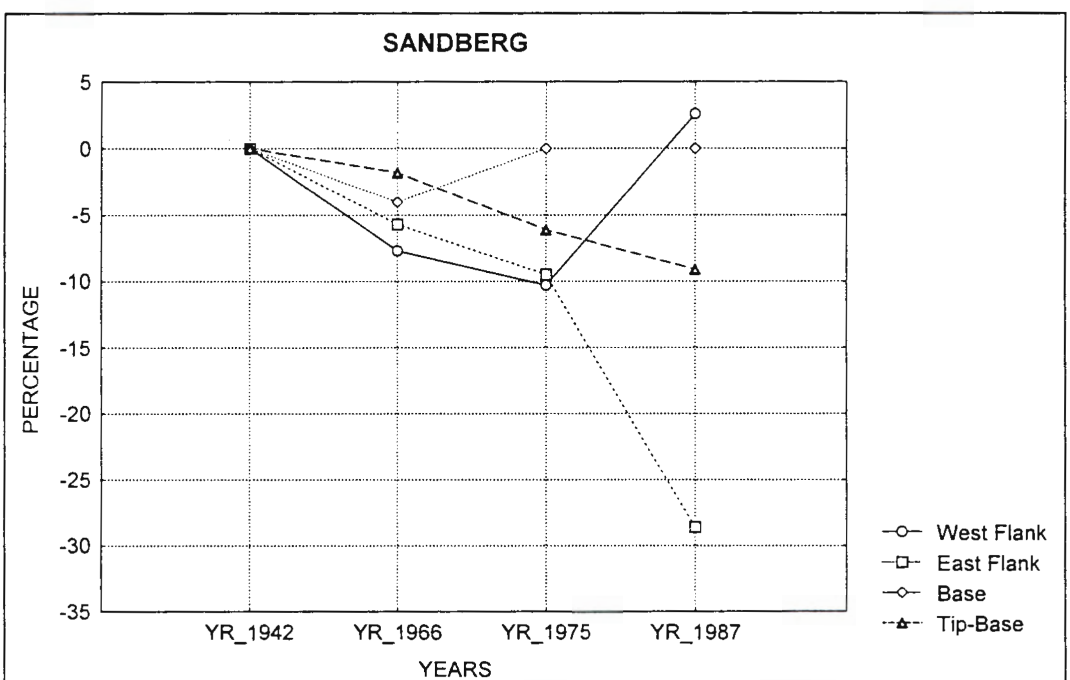


Figure 7.7 The change in dune size from 1942 to 1987 for the Sandberg, Breede River Valley. The western flank, eastern flank, base and tip to mid-base of the topographical dune were measured.

7.5.3 Moddergat

It is evident from Figure 7.8 that there is a general decrease in size of about 14% of the Moddergat topographical dune from 1942 to 1987. In 1942 (Plate 7.7a), agriculture (orchards and vineyards) were already established in the area and a road separates the base of the dune from these vineyards. The dune is sparsely vegetated except for a section on the eastern flank of the dune which is relatively well vegetated (approximately 40%). By 1966 (Plate 7.7b), more vegetation was present on the dune and the section on the eastern flank of the dune is covered by approximately 60% vegetation. It appears as if the morphology of the dune is changing as the road appears much clearer and the eastern flank spreads down the barrier towards the road. The 1975 aerial photograph (Plate 7.7c) is very similar to 1966, but it does appear as if there is a slight increase in vegetation. The "boundaries" of the dune and its morphology seem less clear than in previous photographs, although this could be a factor of stabilization by vegetation. By 1987 (Plate 7.7d) there has been another increase in vegetation and the original morphology of the dune is even less discernible. This continual increase in vegetation made it difficult to accurately measure the dune as the boundaries of the Moddergat topographical dune began to merge into the mountain.

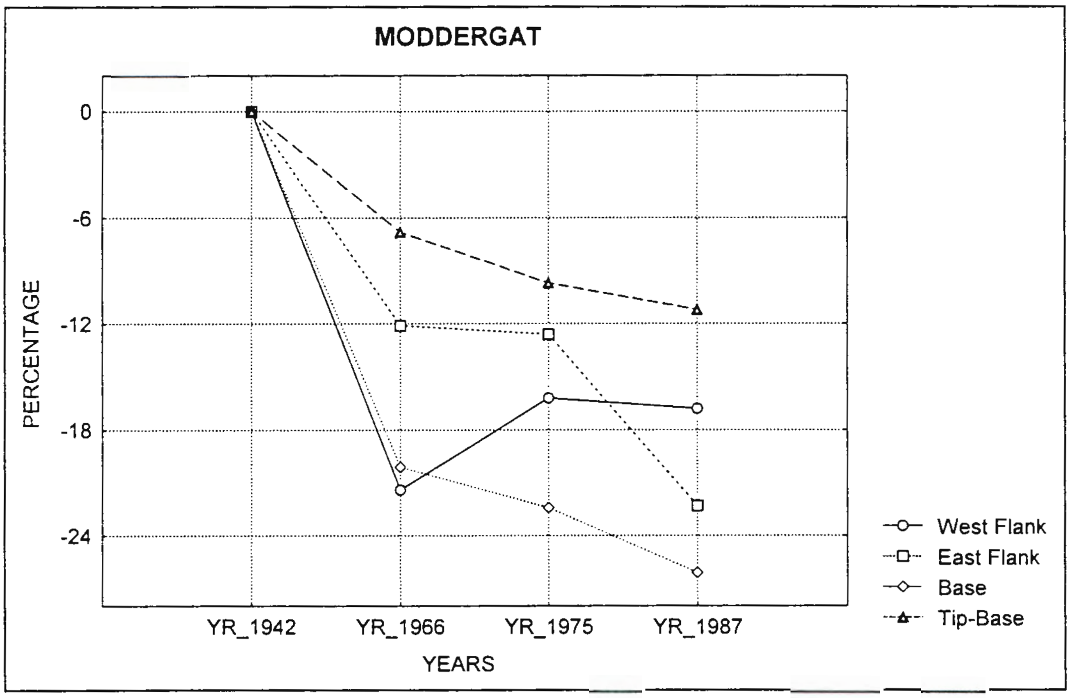


Figure 7.8 The change in dune size from 1942 to 1987 for Moddergat, Breede River Valley. The western flank, eastern flank, base and tip to mid-base of the topographical dune were measured.

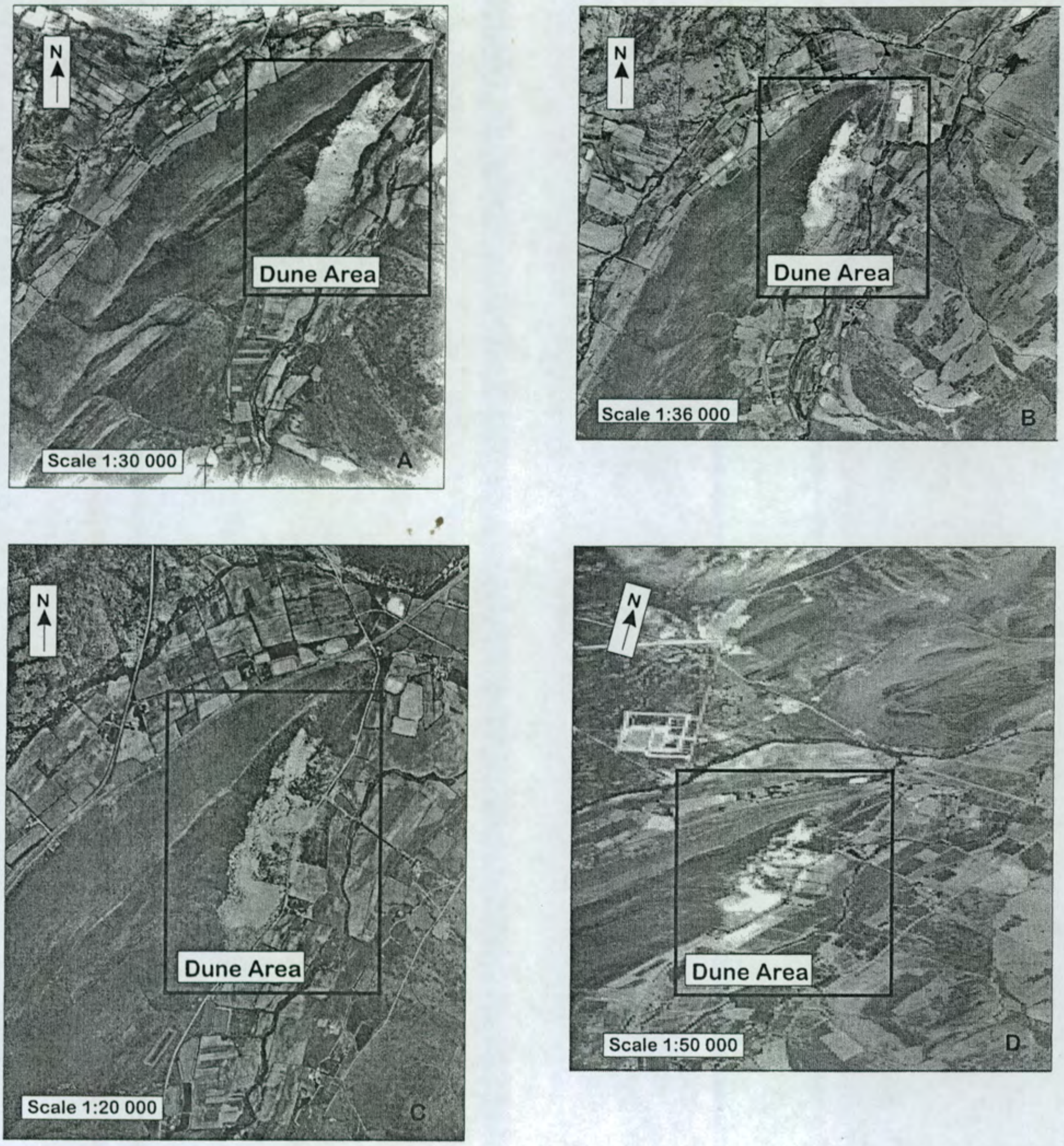


Plate 7.8 An aerial view of the Moddergat topographical dune as it has changed with time, 1942 (A), 1966 (B), 1975 (C), and 1987 (D). Note the decrease in dune size and increase in vegetation cover

7.5.4 Discussion

The Breede River Valley dunes show interesting changes in their morphometry and these changes are supported by a relatively good aerial photography record from 1942 to 1987. The Sandput dune (Fig. 7.6; Plate 7.4) shows a general decrease in size and increase in vegetation cover. The increase in vegetation cover could, however, be due to the seasonality of the aerial photographs, the more recent photographs being taken during and after the winter months. Quarrying activities only began three years ago (August 1995) and thus the disturbance of the dune by quarrying is not visible on the aerial photographs. It is suggested that the quarrying activities will cause a further decrease in dune size as well as devegetation of the dune therefore destabilizing the system and exposing bare sand surfaces to erosion by wind.

The Sandberg dune (Fig. 7.7; Plate 7.4) shows a general decrease in dune size with time, with an increase in vegetation. Farmers in the area (Pretorius and du Toit, pers. comm.) mention that there has been a definite decrease in the amount of sand on the mountain and they attribute this decrease to the canalization of the Breede River and the numerous weirs that have been built upstream of the Sandberg. The building of canals and weirs upstream has stablized the river by the regulation of flooding and therefore less sediment is available for transport and deposition on the river banks during these floods. This change in the river regime causes sandbanks to become less exposed and vegetation is able to grow, thereby decreasing the amount of sand available for transport and deposition by wind.

The Moddergat topographical dune (Fig. 7.8) shows the greatest morphological change with time, as can be seen in the series of aerial photographs from 1942 to 1987 (Plate 7.7). This change, like the Sandberg, can be attributed to the upstream construction of canals and weirs to regulate flooding. In addition, a great deal of water from the Hoek River (a tributary of the Breede River) is used for irrigation for the surrounding vineyards and this increase in irrigation could have a stabilizing effect on the dune (the dune lies adjacent to vineyard fields). The decrease in dune size and increase in vegetation on the dune slopes cannot be attributed to increased rainfall as the rainfall records (data obtained from the CCWR) show that precipitation has remained relatively constant between 1942 and 1987.

7.6 SUMMARY

In this chapter, background to a few potential problems caused by human impacts on topographical dunes were discussed. Agriculture, overgrazing and sand quarrying were highlighted as the main problems, and it was also noted that due to increased population pressures on arid areas, 40% of the world's drylands have now been declared as susceptible to desertification and degradation (O'Hara, 1997). More specifically, however, the aim of this chapter was to examine the southern African topographical dunes which have formed the basis for this investigation for changes in morphometry and vegetation cover during the historical period and to assess the extent to which humans could explain the patterns revealed.

It was found that the southern Kalahari dunes form a stable system that is still active in terms of sand movement. The impact of overgrazing on the landscape is visible, although this impact seems to be restricted to the lower lying areas rather than the steeper slopes of the topographical dunes. The Breede River Valley topographical dunes are more severely impacted by humans than the southern Kalahari dunes. All the dunes in this region show a minor decrease in size with time, coupled with an increase in vegetation cover. Canalization and the construction of weirs on the Breede River has caused a decrease in sand supply to the dunes and a change in the flooding regime of the river. Vineyards and orchards surround the dunes and the Sandput topographical dune is currently being used as a sand quarry. Despite topographical dunes being relatively stable with time and resilient to human impacts, increased population pressure in the regions could have more serious impacts on the landscape and lead to degradation of the topographical dunes in the southern Kalahari and Breede River Valley.

Historical studies are important as they indicate how topographical dunes have responded to human changes in the recent past and thus we can infer how they might respond to future human impacts and global warming. Future studies as to how topographical dunes react to human activities should focus on monitoring sand movement in order to investigate whether changes in dune size are seasonal or as a result of human impacts. Once researchers have an understanding of how topographical dunes respond to these changes, then the research can be used to inform decision-makers, therefore aiding planning procedures, environmental impact assessments and policy making to ensure that these unique features do not become degraded.

CHAPTER 8: CONCLUSION

8.1 OVERVIEW AND SUMMARY

This study has been concerned with the identification of topographical dunes and their classification as either sand ramps or climbing dunes. These dunes were investigated in two dryland regions of South Africa, *viz.* the southern Kalahari near Upington in the Northern Cape, and the Breede River Valley near Robertson in the Southwestern Cape. A specific emphasis of the research was also placed on the potential use of these dunes as palaeoenvironmental indicators, as well as attempting a palaeoenvironmental reconstruction of both study regions. The research has contributed to an understanding of the morphology and sedimentology of topographical dunes as well as shedding light on the palaeoenvironmental histories of these dunes during the Quaternary. A further objective of the study has been to examine the dunes over a historical period with the use of aerial photographs in order to ascertain human impacts on the landscape.

Although there have been previous studies on sand ramps and climbing dunes which have researched their sedimentology, morphology and palaeoenvironmental history (e.g. Tchakerian, 1991; Thomas *et al.*, 1997a; Tsoar, 1983; Helstrom and Lubke, 1993; and White and Tsoar, 1997), no previous studies on dryland topographical dunes have been undertaken in South Africa. This study has therefore been pioneering in its attempts to classify topographical dunes in semi-arid regions of South Africa and to research their response to palaeoenvironmental changes during the Quaternary. The study has also attempted to expand on the debate surrounding the question of synchronous summer and winter rainfall regimes, and investigate whether these areas have differed in their responses to changes in global atmospheric circulation.

Aerial photographs have been used to identify topographical dunes in the southern Kalahari and the Breede River Valley. These dunes were then ground truthed and sampled for laboratory analysis and optically stimulated luminescence dating (OSL). In the field, Munsell colour of the dunes was recorded and detailed site sketches were drawn. In the laboratory, granular composition analysis, pH, conductivity, SEM for the surface texture of the grains and to analyse the chemical composition of the grains was undertaken. Principal component analysis (PCA) and cluster analysis were performed on the data in order to investigate their statistical relationships. The results of the study showed that the sand samples (and therefore the topographical dunes) are uniform with respect to structure, particle size, pH, conductivity, chemical composition and the surface texture of the grains. The southern Kalahari and Breede River Valley dunes both comprise medium sand that is moderately to well sorted. The dunes were emplaced as a result of aeolian processes and all comprise homogeneous quartz sand that was transported by wind and deposited against a topographical barrier. The dunes are therefore classified as climbing dunes and were assessed as being less useful indicators of palaeoenvironmental change than sand ramps due to their homogeneous texture.

The sources of sand for the southern Kalahari dunes are suggested to be the reworked Kalahari sands from either the Orange River or the extensive linear dunefield otherwise known as the Kalahari Dune Desert. It is proposed that the source of the Breede River Valley topographical dunes is weathered Table Mountain Group sandstone that was transported and deposited by the Breede River on its floodplain.

The samples from the southern Kalahari Prynnsberg 2 dune, which were subjected to OSL dating, all yielded dates of approximately 100 years. A number of possible scenarios were explained, but it was finally proposed that the young, and similar, dates are a result of the reworking of the Kalahari sands, thus implying that the dunes are still episodically active. The southern Kalahari climbing dunes were compared to the Klipkraal sand deposit (Marker and Holmes, 1993; and Holmes, 1998), as well as to other studies (e.g. Stokes *et al.*, 1997a, 1997b; and Shaw and Thomas, 1996), and it was concluded that there are three probable dune building phases that took place in the southern Kalahari which may have induced the formation of the topographical dunes. These more arid phases occurred during periods of cooler temperatures and took place at approximately 28 - 23 kyr, 17 - 10 kyr, and around 5.5kyr. It is likely that the southern Kalahari topographical dunes were formed during the first dune building phase between 28 - 23 kyr.

In the Breede River Valley, three dates from the Sandput exposed face may indicate three humid phases. The basal date of 762 ± 104 kyr (Shfd98026) is a maximum age of formation and this white stone line is probably related to a humid phase during which colluvial processes emplaced the quartz pebbles. The middle date, 28.8 ± 5.3 kyr (Shfd98027) spans Oxygen Isotope Stage 3, prior to the LGM. It is proposed that this period is also more moist due to the incipient soil formation which may have occurred. The top date of 9.9 ± 0.7 kyr (Shfd98028) is the most reliable date of the sequence and is important as it coincides with the beginning of the Holocene. The columnar structure of this layer is indicative of a more stable period, implying increased moisture which may have been the result of a delayed reaction to the Younger Dryas global cooling event. Following each of the three humid phases, dune building must have been initiated. The study supports Baxter (1996) by showing that increased warming in winter rainfall regions of South Africa are coupled with a decrease in precipitation. It thus also supports the Cockroft *et al.* (1987) model that states that summer rainfall regions have decreased precipitation in response to cooling while the winter rainfall regions experience a corresponding increase in precipitation. The findings from this investigation therefore have important implications for anthropogenically accelerated warming for the winter rainfall regions of South Africa.

A final aspect of this study was the investigation of the response of topographical dunes in South Africa to impacts on the landscape by humans. It was found that agriculture, overgrazing and sand quarrying are the major causes of topographical dune degradation. The southern Kalahari topographical dunes form a stable system that is still active in terms of sand movement, and although degradation of the landscape is visible, the steeper slopes of the topographical dunes appear to be less impacted. The degradation of the Breede River Valley dunes is more visible and they show a definite, although minor, decrease in size with time. Vineyards, orchards, sand quarrying, and the construction of dams and weirs along the Breede River are responsible for this degradation.

This study has been successful in its attempts to identify topographical dunes in two study regions of South Africa and to classify them as either sand ramps or climbing dunes. It has shown that the topographical dunes that were studied are climbing dunes and that although they are not as useful indicators of environmental change as sand ramps, they do still yield important palaeoenvironmental information. The present study has also presented a palaeoenvironmental reconstruction of both areas and has been able to shed more light on the summer vs winter rainfall synchronous controversy. Furthermore, it has been able to research the response of these depositional features to human impacts, thus having important implications for accelerated anthropogenic warming.

8.2 CONSTRAINTS AND CAVEATS

There are a number of limitations associated with the present study that should be taken into account when assessing the results. Perhaps the most obvious constraint is the sampling problems that were experienced during the field work phase. These have been described in detail in Chapter 3. In addition, the vast areas that had to be covered in the southern Kalahari and the fact that choices of site generally depended on being able to locate the landowners as well as receiving their cooperation, limited the study. Accessibility, even with a four wheel drive vehicle, was also a restricting factor in some cases.

8.3 RECOMMENDATIONS

This study has examined the palaeoenvironmental implications of using topographical dunes as indicators of environmental change as well as presenting palaeoenvironmental interpretations of these features during the Quaternary. An interesting complementary study would be to investigate the mechanics and formation of topographical dunes in order to gain a greater understanding of the conditions under which they form.

In addition, future studies on climbing dunes and sand ramps in South Africa should aim to become bounded by a rigorous chronology in order to increase the resolution of the studies. More sites should also be researched, thereby increasing the areal extent of the study area.

Finally, future research should focus on areas that are arid, but are more limited in terms of their sand supply, thus making topographical dunes more sensitive to changes in the environment, and possible forming sand ramps rather than climbing dunes.

As the population of southern Africa increases, more people are moving into previously considered remote arid and semi-arid areas such as the southern Kalahari. The present study has shown that topographical dunes in South Africa are unique features which are susceptible to impacts by humans and that these features have the potential to yield valuable information as to how aeolian depositional features have responded to changes in climate in the past. It is through researching past climatic changes, that future changes to these aeolian environments can be predicted, thereby aiding our understanding of the response of landforms to anthropogenically induced global warming. Studies such as this one should be continued so as to aid planners and decision-makers in mitigating against the possible consequences of global warming and the degradation of topographical dunes which may occur in the future.

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APPENDIX A: WIND DATA

MONTH	N		NE		E		SE		S		SW		W		NW	
	V	N	V	N	V	N	V	N	V	N	V	N	V	N	V	N
JAN	21.96	72	17.64	65	15.12	36	12.96	37	13.68	158	14.4	294	14.76	85	19.8	89
FEB	19.44	89	17.64	89	14.04	47	14.4	50	12.96	109	14.4	217	14.76	58	18.72	114
MAR	19.44	108	14.76	96	12.96	42	12.6	46	11.52	91	12.24	160	13.68	59	17.28	122
APR	19.44	126	14.76	109	11.88	37	11.16	30	12.24	51	12.96	109	12.6	61	17.64	124
MAY	20.16	149	14.4	97	10.08	36	10.44	29	11.88	36	12.96	91	12.96	60	17.28	146
JUN	21.6	176	16.56	134	11.52	39	12.24	27	12.6	31	13.32	68	13.32	59	18.72	156
JUL	22.68	184	16.56	128	9.72	37	10.8	27	12.24	41	12.96	85	14.04	51	19.8	153
AUG	23.76	141	18.36	99	12.24	34	12.24	36	12.6	52	12.6	129	14.76	83	20.16	127
SEPT	24.84	100	18.72	74	13.68	36	14.76	46	12.6	97	13.68	210	14.76	75	20.88	103
OCT	23.76	85	19.44	64	15.84	46	14.04	56	14.04	127	14.76	252	16.2	90	21.24	90
NOV	24.48	77	20.88	54	16.56	39	14.4	52	13.32	156	14.4	262	16.2	93	21.24	88
DEC	23.04	60	19.8	51	16.56	39	15.12	36	13.32	162	14.4	308	16.56	99	19.44	103
YEAR	21.96	114	16.92	88	13.68	38	13.32	38	12.96	83	14.04	182	14.76	80	19.08	118

KEY Average direction frequency per thousand (N), and the average speed (V = km/hr), for each of the eight main wind directions.

Table 1 Average wind direction and speed for the Upington weather station for a thirty year period.

MONTH	N		NE		E		SE		S		SW		W		NW	
	V	N	V	N	V	N	V	N	V	N	V	N	V	N	V	N
JAN	7.56	2	12.24	38	17.28	217	15.12	226	10.08	21	14.04	49	17.64	60	20.88	104
FEB	16.56	2	12.96	42	16.92	263	16.2	274	11.16	9	14.04	30	18.72	42	20.52	98
MAR	9.36	1	12.6	42	16.56	260	16.2	211	12.96	10	13.32	23	18	40	20.16	97
APR	8.64	1	12.6	49	15.48	176	13.68	145	9.72	5	14.04	31	19.44	59	19.8	143
MAY	12.96	6	11.16	34	13.68	103	12.6	82	7.92	3	12.96	34	18	70	20.16	235
JUN	18.36	7	11.16	38	12.24	60	11.88	43	9	5	12.6	26	20.52	82	20.16	236
JUL	16.56	4	10.08	48	12.24	73	12.6	56	10.08	3	14.04	25	18.72	78	21.96	236
AUG	18	4	11.52	47	14.04	119	14.76	63	9	10	14.04	30	20.16	77	23.04	252
SEPT	12.24	2	12.96	53	15.12	163	15.48	122	10.44	9	16.92	24	21.96	93	23.76	215
OCT	20.88	2	13.32	40	16.2	196	16.2	227	13.68	7	14.4	45	19.44	89	24.48	158
NOV	9.36	1	12.96	30	17.64	225	16.92	305	14.4	17	13.68	43	18.36	70	23.04	130
DEC	7.56	1	13.68	31	18	227	15.84	262	11.52	15	13.32	40	18.36	82	23.76	161
YEAR	15.12	3	12.24	41	16.2	174	15.48	17	11.16	10	14.04	33	19.08	70	21.96	172

KEY Average direction frequency per thousand (N), and the average speed (V = km/hr), for each of the eight main wind directions.

Table 2 Average wind direction and speed for the Robertson weather station for a thirty year period.

APPENDIX B: SAMPLE CODES AND NAMES

SAMPLE CODES	SAMPLE NAMES
PRP1	Prynnsberg 1 Pit 30 cm
PRP2	Prynnsberg 1 Pit 60 cm
PRP3	Prynnsberg 1 Pit 90 cm
PRP4	Prynnsberg 1 Pit 110 cm
PRP5	Prynnsberg 1 Pit 140 cm
PYP1	Prynnsberg 2 Pit 30 cm
PYP2	Prynnsberg 2 Pit 60 cm
PYP3	Prynnsberg 2 Pit 90 cm
PYP4	Prynnsberg 2 Pit 120 cm
PRS1	Prynnsberg 1 topographical dune sample 1
PRS2	Prynnsberg 1 topographical dune sample 2
PRS3	Prynnsberg 1 topographical dune sample 3
PRS4	Prynnsberg 1 topographical dune sample 4
PRS5	Prynnsberg 1 topographical dune sample 5
PRS6	Prynnsberg 1 topographical dune sample 6
PYS1	Prynnsberg 2 topographical dune sample 1
PYS2	Prynnsberg 2 topographical dune sample 2
PYS3	Prynnsberg 2 topographical dune sample 3
PYS4	Prynnsberg 2 topographical dune sample 4
PYS5	Prynnsberg 2 topographical dune sample 5
PYS6	Prynnsberg 2 topographical dune sample 6
PYS7	Prynnsberg 2 topographical dune sample 7
KA1	Kanoneiland 1 topographical dune sample 1
KA2	Kanoneiland 1 topographical dune sample 2
KA3	Kanoneiland 1 topographical dune sample 3
KA4	Kanoneiland 1 topographical dune sample 4
KA5	Kanoneiland 1 topographical dune sample 5
KA6	Kanoneiland 1 topographical dune sample 6
KA6	Kanoneiland 1 topographical dune sample 7
KA8	Kanoneiland 1 topographical dune sample 8
KN1	Kanoneiland 2 topographical dune sample 1
KN2	Kanoneiland 2 topographical dune sample 2
KN3	Kanoneiland 2 topographical dune sample 3
KN4	Kanoneiland 2 topographical dune sample 4
KN5	Kanoneiland 2 topographical dune sample 5
KN6	Kanoneiland 2 topographical dune sample 6
KN7	Kanoneiland 2 topographical dune sample 7

Table 1 Sample codes and names for the southern Kalahari topographical dunes.

SAMPLE CODE	SAMPLE NAME
S1	Sandberg topographical dune 1
S2	Sandberg topographical dune 2
S3	Sandberg topographical dune 3
S4	Sandberg topographical dune 4
MB1	Moddergat base pit 15 cm
MB2	Moddergat base pit 45 cm
MB3	Moddergat base pit 115 cm
MM1	Moddergat middle pit 5 cm
MM2	Moddergat middle pit 16 cm
MM3	Moddergat middle pit 75 cm
SP1	Sandput exposed face 30 cm
SP2	Sandput exposed face 180 cm
SP3	Sandput exposed face 3 m
SP4	Sandput exposed face 5 m
SP5	Sandput exposed face 6.8 m
SP6	Sandput exposed face 7.5 m
SP7	Sandput exposed face 7.8 m

Table 2 Sample codes and names for the Breede River Valley topographical dunes.

APPENDIX C: SLOPE PROFILE DATA

KANONEILAND 1		KANONEILAND 2		PRYNNSBERG 1		PRYNNSBERG 2	
Distance (m)	**Height (m)**	**Distance (m)**	**Height (m)**	**Distance (m)**	**Height (m)**	**Distance (m)**	**Height (m)**
0	0	0	0	0	0	0	0
15.0	1.1	14.6	3.4	15.0	0.4	14.9	2.1
29.9	2.1	29.1	7.1	30.0	1.2	29.7	4.2
44.9	2.9	43.4	11.7	45.0	2.0	44.5	6.5
59.9	4.2	57.5	16.9	59.9	2.9	59.2	9.6
74.8	6.1	71.4	22.5	74.9	4.0	73.7	13.5
89.6	8.4	85.3	28.4	89.8	5.3	87.6	17.8
104.3	11.3	99.0	34.5	104.8	6.6		
118.9	14.9	101.4	35.5	119.7	7.9		
133.4	18.8			134.7	9.2		
139.9	20.6			149.6	10.7		
				164.5	12.2		
				179.4	13.8		
				194.4	15.3		
				209.3	16.9		
				224.2	18.2		
				239.2	19.5		
				254.1	20.6		
				269.1	20.3		
				282.9	14.5		
				297.0	9.1		
				311.0	3.7		

Table 1 Slope profile data for the southern Kalahari topographical dunes.

SANDBERG		MODDERGAT		SANDPUT	
Distance (m)	**Height (m)**	**Distance (m)**	**Height (m)**	**Distance (m)**	**Height (m)**
0	0	0	0	0	0
20	55	20	45	20	10
40	170	40	120	40	19
60	260			60	43
				80	73
				100	123
				120	178
				140	218
				150	228

Table 2 Slope profile data for the Breede River Topographical dunes.

APPENDIX D: AERIAL PHOTOGRAPHY ANALYSIS DATA

AERIAL PHOTOGRAPHY ANALYSIS: SOUTHERN KALAHARI		
	PRYNNSBERG 1	**PRYNNSBERG 2**
	1976	1976
Western Flank	330 m	270 m
Eastern Flank	480 m	120 m
Base	670 m	420 m
Tip to mid-base	430 m	210 m
	1982	1982
Western Flank	350 m	290 m
Eastern Flank	400 m	130 m
Base	650 m	435 m
Tip to mid-base	450 m	220 m
	1994	1994
Western Flank	330 m	300 m
Eastern Flank	450 m	130 m
Base	630 m	440 m
Tip to mid-base	480 m	240 m
	KANONEILAND 1&2	
	1957	
Top of dune	1380 m	
Tip to mid-base	570 m	
	1964	
Top of dune	1360 m	
Tip to mid-base	640 m	
	1994	
Top of dune	1150 m	
Tip to mid-base	650 m	

Table 1 Changes in dune size over time using aerial photographs in the southern Kalahari study region.

AERIAL PHOTOGRAPHY ANALYSIS: BREEDE RIVER VALLEY			
	SANDPUT	SANDBERG	MODDERGAT
	1942	1942	1942
Western Flank	2370 m	390 m	1742 m
Eastern Flank	1740 m	420 m	1351m
Base	810 m	300 m	541 m
Tip to mid-base	1620 m	330 m	1351 m
	1966	1966	1966
Western Flank	2580 m	360 m	1370 m
Eastern Flank	1870 m	396 m	1187 m
Base	755 m	288 m	432 m
Tip to mid-base	1440 m	324 m	1259 m
	1975	1975	1975
Western Flank	2300 m	350 m	1460 m
Eastern Flank	1860 m	380 m	1180 m
Base	500 m	300 m	420 m
Tip to mid-base	1500 m	310 m	1220 m
	1987	1987	1987
Western Flank	2550 m	400 m	1450 m
Eastern Flank	1750 m	300 m	1050 m
Base	400 m	300 m	400 m
Tip to mid-base	1450 m	300 m	1200 m

Table 2 Changes in dune size over time using aerial photographs in the Breede River Valley study region.