THE GEOMORPHOLOGY AND AEOLIAN DEPOSITS IN THE VICINITY OF FLORISBAD

By

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Abstract

The discovery of the Florisbad hominid prompted further archaeological and palaeoanthropological research in the Florisbad area. However, research that looks specifically at the geomorphology and aeolian deposits around Florisbad has been very limited, although aeolian processes and sand dunes have been widely recognized as being of significance in understanding past environmental conditions in this area. Geologists have also shown an interest in trying to explain the formation of the Florisbad spring and fossil site.

The Florisbad spring site has a complex stratigraphy because the deposits are lithologically variable due to the fact that they are the product of an unusual depositional environment. Many hypotheses have being proposed in trying to understand the complex depositional environment at Florisbad. This research suggests that, in order to better understand the complex depositional environment of Florisbad, there is a need to understand the surrounding geomorphological setting in terms of geohydrological and geomorphic processes and features.

The methodology comprises a review of current literature on lunette dunes, and previous work undertaken on the geomorphology and geology at and around Florisbad, an examination of aerial photographs to identify lunette dunes in the vicinity of Florisbad, and fieldwork to ground-truth the dunes. Field sampling, laboratory work (sedimentological techniques, pH, conductivity and geochemical analysis) as well as statistical analyses (principal component and cluster analyses) were employed to compare the characteristics of the lunette dune sediments with those at the spring site itself, and to assist in a general palaeoenviromental reconstruction.

The results of the laboratory analyses do not reveal any obvious differences with respect to sediment particle size and pH, between the lunette dunes and the spring site. However it was noted that there were minor differences when it came to dune structures, electrical conductivity and chemical composition. There is convincing evidence that the sediments are primarily wind-blown in origin. The geochemical results suggest the lunettes are older than the dune at the spring site. Two optically stimulated luminescence dates were determined for a lunette dune close to Florisbad. The samples were dated to 500 years, and it is suggested that this is because of reworking of sediments down the slope.

The overall geomorphology, as described in this study, suggests a shallow depression (Florisbad-Soutpan) in which both fluvial and aeolian processes have conspired to create a unique landscape which has promoted the formation and preservation of dune deposits and the unique archaeological site which is Florisbad.

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DECLARATION OF ORIGINALITY

I, Mulalo Rabumbulu, hereby declare that the research reported in this dissertation is a result of my own investigations except where acknowledged, and has not, in its entirety or in part, been previously submitted to any university or institution for degree purposes.

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M. Rabumbulu

May 2011

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CHAPTER 1: INTRODUCTION

1.1. INTRODUCTION

Geomorphology, by definition, is that branch of the earth sciences that focuses on the history of landscapes and landforms and the development thereof. The reconstruction of Quaternary geomorphic environments is based on the concept that changes in climatic variables, such as wind, temperature and precipitation have implications for the development of landscapes. Therefore an understanding of the influence that today's climate variables may have on aeolian landforms can facilitate the use of relict aeolian landforms to deduce the environmental (climatic) conditions that prevailed in the past.

Aeolian deposits occur globally. In certain areas, lengthy aeolian sedimentary sequences provide a basis for Quaternary correlation between aeolian deposits and global record of climatic changes, perhaps the best published examples being the loess deposits around Prague, Brno and Nitra in the former Czechoslovakia (Czech Republic and Slovakia), and near Krems in Austria (Lowe and Walker, 1984). Within aeolian deposits, there are often sequences of soil horizons that contain records of paleoclimatic conditions going back into the Quaternary period. Additional paleoenvironmental information can also be obtained from the rich faunal and floral remains found in the deposited material, and dating of deposits is possible through the use of dating methods such as radiocarbon dating in more recent sediments and magnetostatigraphy in older deposits (Lowe and Walker, 1984; Meadows, 2001).

This dissertation looks at aeolian deposits and specifically, lunette dunes. The aim and specific objectives are given below. In the more arid parts of southern Africa, lunette dunes are closely associated with pans.

Therefore, pans and lunette dunes are defined, and their importance, as well as their potential use as paleoenvironmental indicators is examined in this Chapter. The Chapter ends by giving a clear description of the specific aims and objectives of this research.

1.2. DEFINITION OF PANS AND LUNETTE DUNES

Since the primary focus of this research is aeolian processes and aeolian landforms, it is important that clear definitions for both terms are provided. Aeolian processes may be described as those processes which involve wind action (i.e. erosion, transportation and deposition), as a result of movement of air over the earth’s surface. Pye and Tsoar (1990) refer to erosion, transportation and sedimentation as the main three groups of aeolian processes.

Erosional processes include the deflation of loose sediment by impacting grains in the wind stream and abrasion of hard surface by particles entrained in the flow. It is difficult to draw a clear distinction between transport and depositional processes because they can occur simultaneously. However aeolian transport processes include movement of individual grains by creep, saltation or suspension and migration of landforms, while sedimentation processes also involve individual grains that are involved in the stabilization of bedforms.

Many different types of aeolian landforms exist and have been described in detail, *inter alia* by Pye and Tsoar (1990). It is important to understand the similarities and differences between these land forms in order to have a clear understanding of how they formed and how they interact with one another presently, as well as how they interacted in the past.

Since it is not within the scope of this dissertation to discuss the various types of aeolian landforms in detail, only those landforms that are of relevance to this research will be examined here. Although aeolian landforms result from aeolian processes, some of the deposits found in these features may include fluvio-aeolian deposits. Fluvio-aeolian deposits are interbedded or reworked mixtures of fluvial and aeolian sediments. They result from either partial aeolian reworking of the upper surface of exposed fluvial deposits or by partial fluvial reworking of the upper surface of exposed aeolian deposits (Pye and Tsoar 1990).

1.2.1 PANS

Pans are products of aeolian erosion which form when the force of wind is concentrated on a particular spot in the landscape. In brief, pans may be defined as closed depressions found in arid and semi-arid regions of the world, where mean annual rainfall is low and the evaporation rate is at least three times the mean annual rainfall. These features are widespread in the summer rainfall zones of southern Africa (Seaman *et al*, 1995; Lawson and Thomas, 2002; Holmes *et al*, 2008).

1.2.1 LUNETTE DUNES

A lunette dune is a crescent shaped depositional feature, typically anchored to the leeward side of a pan. Although they are similar to ordinary parabolic dunes, lunette dunes are formed transverse to the prevailing wind, and their arms point upwind. The arms, however, are much shorter than those of parabolic dunes because lunette dunes are composed of cohesive materials deflated from the adjacent pan floor. Their size is usually relative to the size of the pan from which they grow. Lunettes dunes are widespread in semi-arid regions such as Texas and New Mexico (USA), southern Africa, and central Australia (Sabin and Holliday, 1995; Bullard, 2004).

Lunette dunes can be easily identified on aerial photos because of their relatively bright reflectivity, arcuate shapes in plan view, and proximity to the downwind borders of pans. Because of their low relief, they can be difficult to distinguish on the ground. In South Africa, lunette dunes are most common in the southern Kalahari, the Northern Cape and the Western Free State. In most instances there may be inner and outer dunes with different sedimentary characteristics; however triple dunes have been identified at Koes pan in Namibia (Thomas and Shaw, 2002).

The orientation of most lunettes suggests that outer lunettes generally contain a higher sand content than their inner lunette counterparts, and are formed during dry seasons, which are dominated by windy conditions. Inner dunes generally contain high clay content, and are formed during dry hot conditions and may have being active until fairly recently (Bowler, 1978; Moon and Dardis, 1988). Characteristic of lunette dunes, especially those found in southern Africa will be discusses in more details in Chapter 3.

1.3. The Importance of Pans And Lunette Dunes As Paleoenvironmental Indicators

Geomorphology and landforms have a direct influence on human activities, so it is important that the relationship between the landforms and the processes that shape them is fully understood. For example, aeolian landforms are closely linked with desertification, which implies that an understanding of aeolian processes has cultural and economical implication, especially for agricultural areas being overrun by sand or undergoing deflation (Nickling, 1986).

Soil formation also plays an important role in the reconstruction of paleoenvironments, because some features of sediments and soils reflect the state of the atmosphere at the time they were formed and can therefore be used to facilitate the reconstruction of such environments.

Studies of pan level variation, particularly in arid and semiarid regions, can provide valuable insight into paleoclimatic condition in those regions (Hugget, 1991; Bradely, 1999). In South Africa, a number of studies that specifically look at the origin of pans as well as their physical and chemical properties have been carried out (Le Roux, 1978; Beaumont *et al*, 1984).

Although research on pans has been conducted in South Africa, few studies have been utilised as paleoenvironmental indicators. An exception is Kathu pan in the Northern Cape where dateable materials have been encountered (Tooth, 2007). The reason why pans are not generally used as paleoenvironmental indicators is because of the complexity of the ground water and surface water interface in the pan environment. Furthermore, as a result of their hydrological characteristics, there is often a discontinuity in their sediment record (Holmgren and Shaw, 1996).

Since the primary focus of this research is aeolian landforms, this section will focus on their importance as paleoenvironmental indicators. Although a wide range of erosional and depositional landforms develops as a result of aeolian processes, this section will only discuss the importance of dunes, and specifically lunette dunes, as indicators of environmental change.

Aeolian deposits preserve evidence of former climatic conditions, for example the presence of palaeodunes may serve as an indicator of previous drier, or windier conditions, because inland sand dunes only form under arid conditions (Moon and Dardis, 1988; Marker and Holmes, 1995).

Lawson and Thomas (2002) have indicated that the potential use of pan-lunette complexes with more than one lunette dune for paleoenvironmental reconstruction has long been recognized since such lunettes may preserve evidence of episodic or multiple episodes of aridity, with differences in dune orientation also indicating changes in the dominant wind direction and therefore changes in atmospheric circulation.

Within the palaeosol stratigraphy, pollen may be found, and therefore a further indication of the type of environment and, possibly, climate experienced in the region during soil formation, can be provided through pollen analysis. In addition a well resolved chronological sequence of lunette dunes may be obtained by dating of quartz and feldspar using luminescence dating techniques (Meadows, 2001).

Although lunette dunes have great potential, they also have limitations as paleoenvironmental indicators. One of the major limitations is that the degree of aridity of the landscape is often uncertain since the transportation and deposition of sediments may occur under a variety of arid and semi-arid conditions. Marker and Holmes (1995) have noted that dune formation does not necessary indicate a decrease in precipitation, it may result from an increase in windiness. Bowler (1973, 1986) and Lancaster (1978) have concluded that lunette dune development indicates the availability of sediments to wind and conditions that allow sediment to be moved from the pan and accumulate on its downwind margin, rather than the degree of aridity.

Significant advances in dating techniques such as optically stimulated and infra-red luminescence dating (OSL and IRSL) has largely solved the problem highlighted by previous researchers (Lancaster, 1981) of a lack of detailed chronologies in dryland regions.

1.4. AIMS AND OBJECTIVES

Florisbad is an important archaeozoological site, situated ~ 45 km north west of Bloemfontein, Free State Province, South Africa (Figure 1.1 and 1.2). This site is important for three reasons: the discovery of the Florisbad hominid by Prof T Dreyer in 1932, the existence of a collection of artefacts and an enormous number of faunal fossil remains representing the Florisian Land Mammal Age, with an age of ~ 400 Kyr (Klein, 1984) and, lastly, the excavation and identification of Middle Stone Age tools and faunal remains (Brink, 1987; Brink and Henderson, 2001).

Figure 1.1 The location of Florisbad, Free State Province, South Africa.

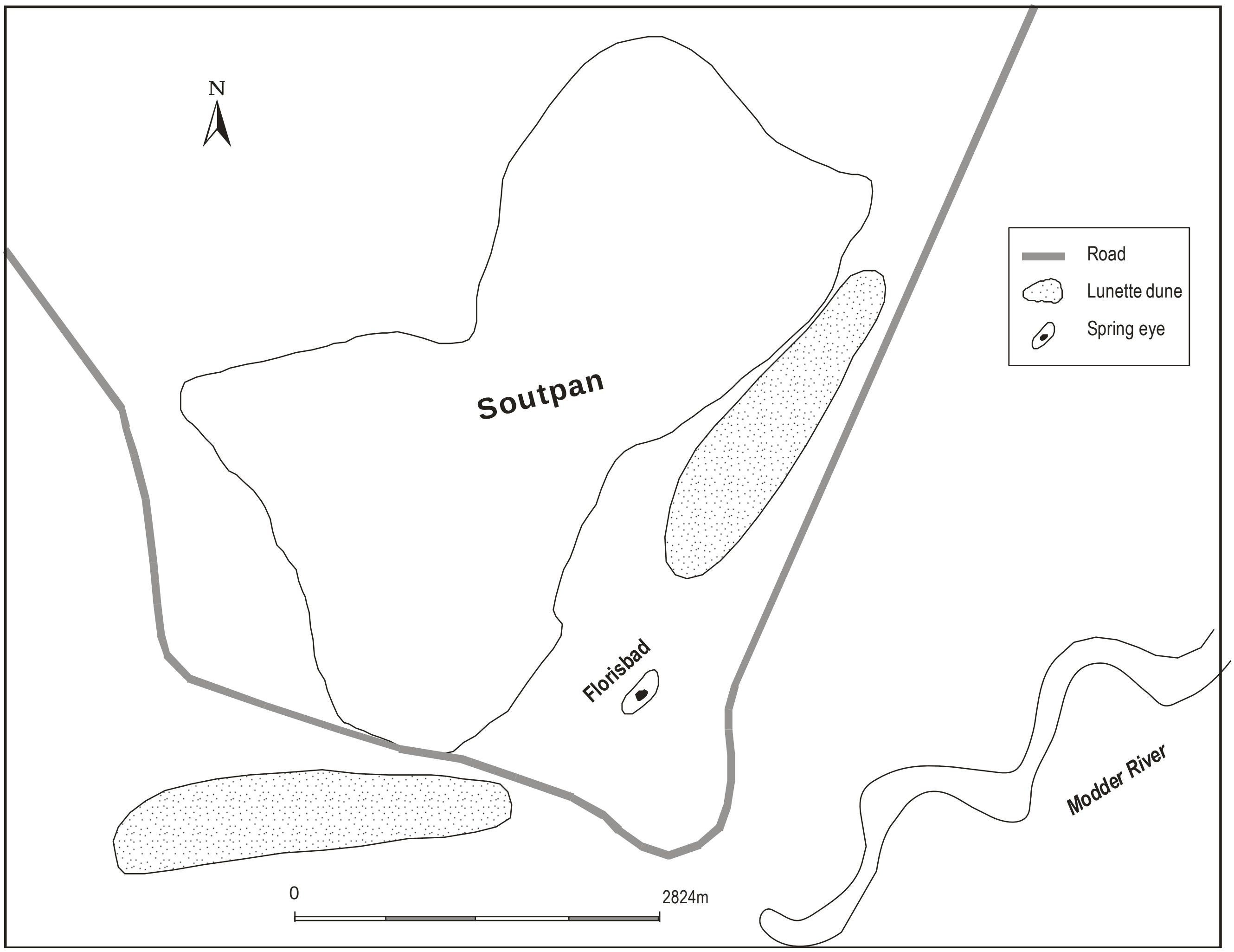

Figure 1.2 Florisbad pan and fringing lunette dunes

Although considerable research was conducted at Florisbad after the discovery of the Florisbad human skull (refer to the literature review in Chapter 3), no research that specifically looks at the surrounding geomorphology and aeolian deposits has, as far as can be ascertained, been published.

A number of researchers have shown an interest in trying to explain the formation of the Florisbad spring and fossil site (Van Zinderen Bakker, 1989; Marshall and Harmse, 1992; Grobler *et al*, 1988).

Douglas (2006b) proposed an alternative hypothesis for the formation of the Florisbad spring and fossil site, where he believed the development of the western Free State Panfield was a key factor in the formation of the Florisbad site. Douglas (2006b)'s model for formation of the Florisbad spring and fossil site will be discussed in more details in Chapter 3.

Douglas (2006b)'s hypothesis is based on an assumption that a sand dune, which was formed on the southern shore of Soutpan, migrated towards the Florisbad spring site, and then covered the spring pan. This research will elaborate on the geomorphic context of the area immediately surrounding the site.

The Florisbad spring site has a complex stratigraphy because the deposits are lithologically variable, probably due to the fact that these deposits are the product of an unusual depositional environment. Thus, the primary aim of this research was to reconstruct the paleoenvironmental conditions which prevailed around Florisbad, to gain a better understanding of the geomorphologic landscape of Florisbad, and to try to explain some of the landforms (which, in this case, are primarily dunes) in terms of the geomorphological processes that shaped them. Below are five specific objectives that have been pursued in order to achieve the aim of this research. They are to:

- determine the relationship between the stratigraphy and textural composition of the outer lunette (or lunettes) and the spring site deposits
- compare the composition and morphological aspects of the Florisbad outer lunette and other lunettes in South Africa
- determine the age of the outer lunette at Florisbad
- determine whether there has been migration of the dune toward the spring pan

- ascertain whether there is any relationship between topography and depositional sites, since studies of modern dune fields has shown that, when large dunes form, they create a topographically irregular surface and later occurrence of aeolian activity commonly fill the low-lying areas between the older dunes, resulting in beds that are laterally discontinuous (Langford *et al*, 2008).

1.6 STRUCTURAL OUTLINE

This dissertation is divided into eight Chapters. In Chapter 1 a broad overview of this research is provided.

An overview of lunette dunes and pans, including definitions of terminology is then given. The importance, as well as the potential use of lunette dunes as paleoenviromental indicators, is discussed. Aims and objectives are described.

In Chapter 2 the physical setting of the study site is presented, together with a detailed description of the study area. A detailed literature review of Florisbad is provided in Chapter 3. Chapter 4 deals with the methodologies and research procedures used in this study. All the results of the study are given in Chapter 5 and, subsequently, the results of the study with respect to the aim and objectives that were set out in Chapter 1 are discussed in Chapter 6. In the last Chapter (Chapter 7) the conclusions of the study are discussed bringing together information and arguments (i.e. Chapters 5 and 6 that were presented in this dissertation.

CHAPTER 2 PHYSICAL SETTING OF FLORISBAD

2.1. INTRODUCTION

A comprehensive description of the characteristics of the physical environment of the study area will be undertaken before outlining the research procedure and methodology so that the reader can gain a clear picture of the environment in which this research was carried out. The influence of the physical environment on the formation and continued existence of lunette dunes cannot be over-emphasized. It is therefore imperative to look, in some detail, at a number of aspects of the physical environment. This Chapter describes the geology, macrogeomophology (site description), climate and vegetation of the study area. The description starts, in each section, with a general overview of the Free State Province, followed by a more detailed description that pertains specifically to Florisbad.

2.2. GEOLOGY

The landscape of South Africa was extensively impacted by the breakup of Gondwanaland. Since the Free State is situated in the geographic centre of the sub-continent, its geomorphology and geology has been particularly influenced by the breakup (Moon and Dardis, 1988; Holmes and Barker, 2006; Johnson *et al*, 2006). Unless otherwise stated, the following brief description is based on Moon and Dardis (1988) and Holmes and Barker (2006).

The geological evolution of southern Africa can be divided into five phases. The last phase is essential to the geomorphology and geology of the Free State, because many elements of its landscape evolved as a direct consequence of the geomorphic activity that took place during this phase.

The first stage of the geological evolution of the sub-continent, the Archean phase (up to 2600 Ma) saw the development of the granitic base of the subcontinent as manifested in the structural Kaapvaal, Limpopo and Zimbabwe provinces. The Supra-crustal development forms the second phase that occurred until 1200 Ma. It was characterised by burial of the granitic crust by sediments of the Pongola, Witwatersrand, Transvaal and Griqualand West Supergroups, and the formation of the Bushveld Igneous Complex.

The tectonic activity of the Proterozoic Orogeny up to 500 Ma comprised the third phase. The crystalline and cover rocks in the south and south west of the subcontinent were disturbed; intrusion of granitoid mantle material and crustal rifting occurred during this phase. Formation of the Proto-South Atlantic with the accumulation of geosynclinal deposits and subsequent convergence of crustal plates to close the rift were the result.

The fourth stage, which extended up to 150 Ma, was the Gondwana Era. The most significant element of the Gondwana Era is the deposition of the rocks of the Cape Supergroup, the movement of Gondwana across the southern polar region (continental glaciations) and the formation of the tillites of the Dwyka Formation. The activities that took place during the Gondwana Era, within the later part of this phase (and into the Post Gondwana Era) have profoundly influenced the geology of the Free State. The Karoo Basin was infilled by sediments and capped by the lavas of the Drakensberg Formation.

The final phase (Post Gondwana Era) led to the extensive intrusions of dolerite which, due to the enormous forces involved, also were associated with to the breakup of Gondwanaland. This has significantly influenced the landscape of the Free State.

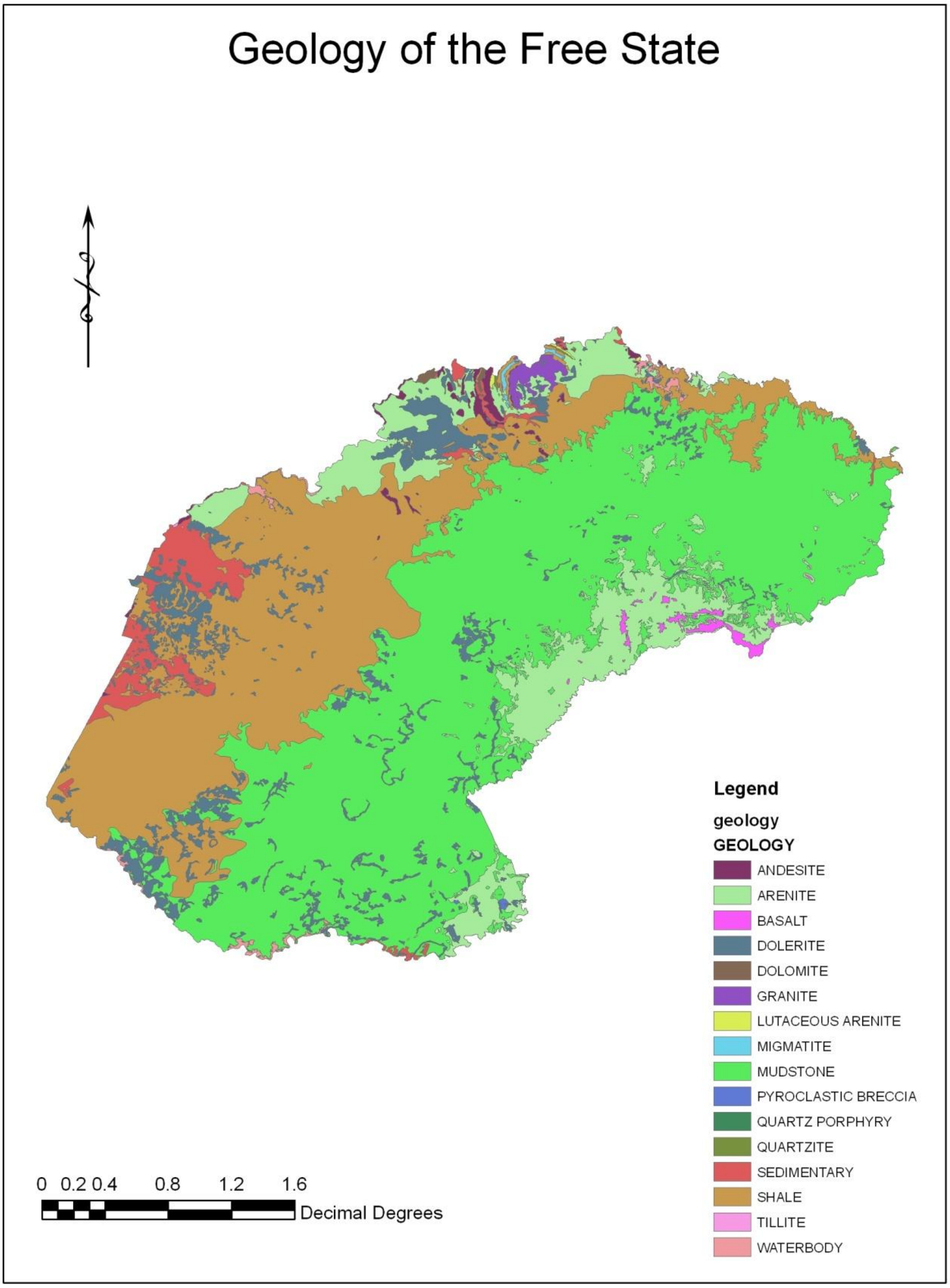

Figure 2.1 Geology (lithology) of the Free State Province (after Council for Geoscience, 2001).

2.2.1 Precambrian geology

The lithology of the whole of the Free State Province is briefly outlined below, because of the possible influence that this geology has had on aspects of Florisbad such as ground water control and sediment provenance. Put differently, it is insufficient to consider the lithological controls in the immediate vicinity of Florisbad in isolation; the geology of the region must be considered holistically.

The Precambrian geology is poorly represented in the Free State, but forms a part of the regional geology. “The ancient geology of the Free State is buried by Karoo Supergroup rocks” (Holmes and Barker, 2006; 3). The Precambrian strata are represented in the northern Free State province at the Vredefort dome. The Vredefort dome is a meteor impact site (Holmes and Baker, 2006). The oldest rocks in this area are Inlandsee Leucogranofels/gneiss and Parys granite of, Swazian age (>3100 Ma).

2.2.2 The Karoo Basin

The Karoo Basin covers approximately two third of the South African land surface, and Florisbad is situated within the Karoo Basin. The south-central African Karoo Basin was formed during the late Paleozoic to early Mesozoic (Visser, 1995). This is the time when the Pangaea supercontinent reached its maximum extent. Two factors were responsible for the formation of the south-central African Karoo Basin, namely tectonic mechanisms and shifts in climate (Cautunean *et al*, 2005).

2.2.3 The Karoo Supergroup

The Karoo Supergroup comprises a number of Groups and Formations, deposited within the Karoo Basin during the Late Carboniferous through to the Mid Jurassic (310 Ma - 185 Ma).

A brief discussion of these groups will be presented so as to provide a better understanding of the position of the Ecca Group rocks, on which Florisbad is situated.

The groups will be discussed in chronological order from oldest to youngest; "geomorphologically this implies an increasing altitudinal progression from south west to north east." (Holmes and Barker, 2006; 4).

2.2.4 Dwyka Group

The rocks of the Dwyka Group have had little impact on the geomorphology of the Free State landscape. The Dwyka Group rocks comprise glacially derived tilite which occurs only to the west of Kimberly, and west of Christiana in the Free State Province. Dwyka Group rocks consist mainly of diamictite that grades upward into conglomerate, mudstones and shales (Visser, 1955).

2.2.5 Ecca Group

Four of the Ecca Group Formations (i.e Volksrust, Vryheid, Tierberg and Prince Albert Formations) are dominant in the Free State Province. The Ecca sediments include mud, silt and other deltatic sediments, which were accumulated under brackish and fresh water conditions. The Ecca Group shales were accumulated in shallow intracratonic depression, which probably resulted from the preceding Dwyka glaciations (Visser, 1955). The Ecca Group rocks are well represented in the Free State.

The Ecca Group shales have weathered and eroded, producing a flat undulating landscape broken by flat-topped dolerite capped mesas and buttes (Holmes and Barker, 2006). The formation of the Ecca Group covered a timespan that extended from the late to mid Permian (i.e. 289-255 Ma) (Douglas, 2009).

2.2.6 Beaufort Group

Beaufort Group rocks were formed from fluvial and deltaic derived sediments. These rocks were deposited by north-flowing meandering rivers in which sand accumulated, flanked by large flood plains, where periodic flooding deposited mud (McCarthy and Rubidge, 2005; Douglas, 2009).

The Beaufort Group is dominant in the eastern and central Free State, the west being dominated by the older Adelaide Subgroup, comprising shale, siltstone and fine sandstone, with a thickness of up to 500m. The younger Tarkastad Subgroup consists of mudstone and sandstone with a thickness up to 200m; these rocks dominate in the east. These rocks cover a time span of 225 to 237 Ma (i.e. from the late Permian to the mid- to early Triassic).

2.2.7 Stormberg Group

The Stormberg Group comprises of three sedimentary formations, namely the Molteno, Elliot and Clarens. The timespan covered by the Stormberg Group extends from the mid Triassic to the late Jurassic periods (230-216 Ma) the rocks of the Molteno and Elliot Formations are sedimentary, and of fluvial origin.

Rocks of the Elliot Formation were deposited under drier conditions with loess type aeolian sedimentation of mudstone and siltstone and fluvial subordinate sandstone (Baran, 2003; Douglas, 2009). The Clarens Formation rocks (203-183 Ma) are of aeolian origin; they consist mainly of sandstone layers derived from sand dune deposits, and were formed under arid conditions (Holmes and Barker, 2006).

2.2.8 Drakensberg Group

This Group consists of horizontally stratified basaltic lavas, resulting from numerous flows of varying thickness (McCarthy and Rubidge, 2005). In the Free State, these basalts remain as remnant cappings, overlying the Clarens Formation rocks of the eastern Free State on the highest relief.

2.2.9 Post Karoo Intrusion

The Karoo dolerite which intruded the Karoo sediments to form dykes and sills represent a post Karoo sedimentation which is younger than the basalts of the Drakensberg Group. The intrusion of dolerite dykes and sills resulted in the creation of fracture zones within the host rocks themselves, and today form an important aquifer and the close positioning of boreholes for source of underground water (Baran, 2003; Douglas, 2009).

Dolerite dykes and sills also control second-order geomorphological features and drainage systems of the main Karoo basin. Other Post-Karoo intrusions include breccia plugs, volcanic vents and Kimberlites which are diamondiferous. The latter occur in the western Free State.

2.2.10 Quaternary deposits

These deposits are younger than ~2 Ma (Holmes and Barker, 2006), and they can be divided in to three broad categories, namely sand and soil, calcrete, and alluvial and colluvial deposits. Soil and sand formation is influenced by four factors, i.e. parent material, climate, topography and biological factors. Climate and parent material played a large part in the formation of soil and sand in the Free State (Hensley *et al*, 2006). Unconsolidated sand is a feature of many stream beds in the Free State (Holmes and Barker, 2006).

Based on the morphometric properties of the unconsolidated sand, Holmes and Barker (2006) suggested that they may well be of predominantly aeolian origin. Holmes and Barker (2006) also referred to the presence of lunette dunes and active aeolian processes along fence lines and roads in the western Free State.

Calcretes are widespread, either as surficial deposits or beneath soils or sand cover, in the semi-arid to arid western Free State. Two types of calcretes occur in the Free State. Nodular calcretes are often associated with unconsolidated sediments and hardpan calcretes, which have little or no surficial cover, also occur (Holmes and Barker 2006).

Alluvial and colluvial deposits are found along most of the rivers in the Free State. Holmes and Barker (2006) refer to evidence of aggrading conditions along some of the rivers in the Free State, with resultant river terrace formation.

2.2.11 The Geology of Florisbad

Florisbad is situated on geology associated with the Tierberg Formation (Loock and Grobler, 1998). The Tierberg Formation of the Ecca Group in the vicinity of Florisbad comprises well bedded shales and thin siltstones. They were deposited through suspension settling of fine mud and silt under reducing conditions in an inland sea (Loock and Grobler, 1998).

Beaufort Group rocks have been recorded 3 km south west and 14 km south east of Florisbad. In both cases approximately 4 m of Beaufort Group rocks overly the Ecca Group rocks (Loock and Grobler, 1998). An unconsolidated covering of red-yellow and pale bleached aeolian sand of varying depth occurs at the surface in the vicinity of Florisbad (Loock and Grobler, 1998). To the west and through to the north of Soutpan, dolerite intrusion intermixed with Ecca Group rocks are visible (Douglas, 2009).

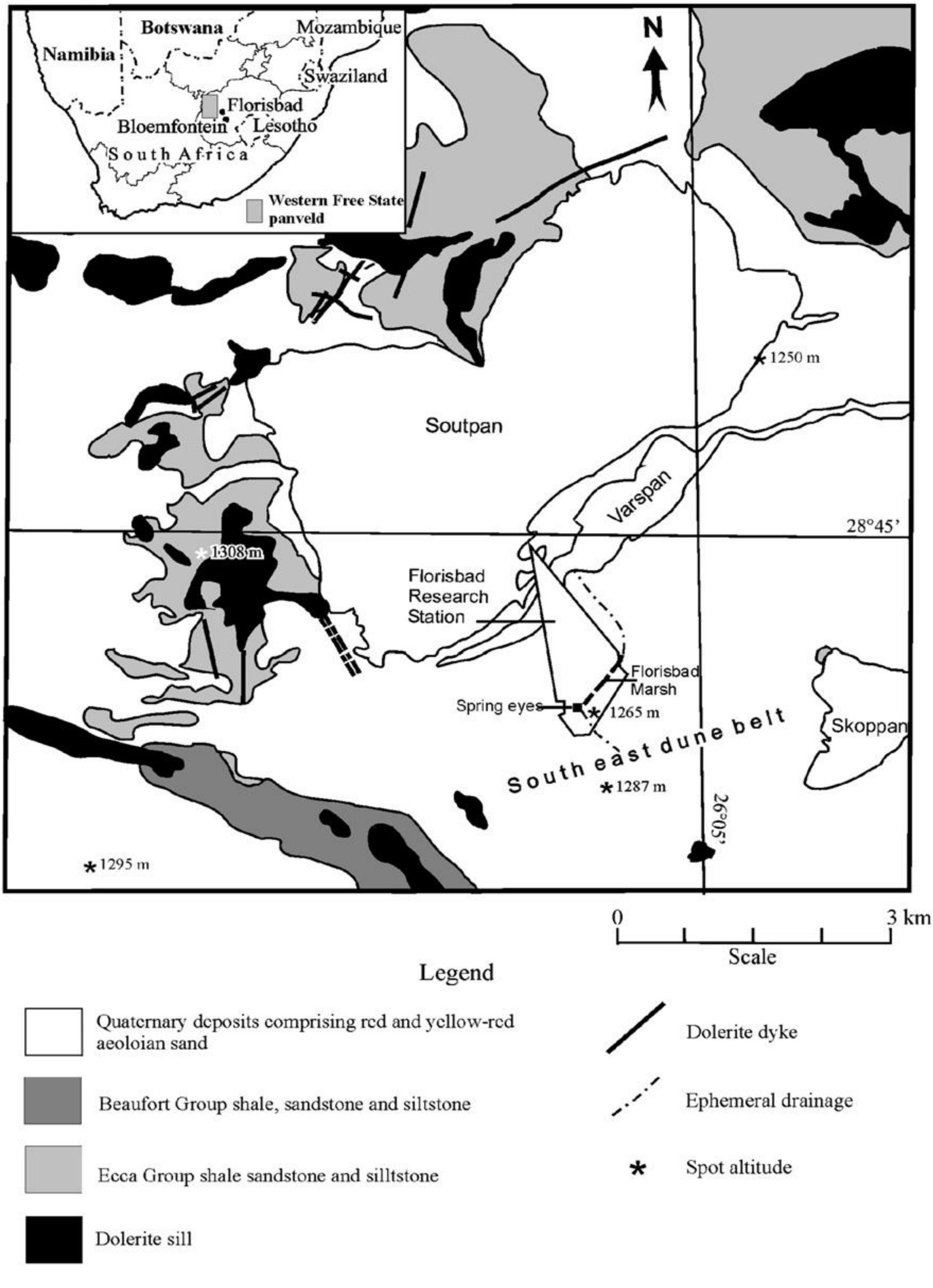

Figure 2.2 Geology of Florisbad (after Grobler and Loock, 1988; Douglas, 2009 and Douglas *et al*, 2010).

2.3. GEOMORPHOLOGY

This section will only briefly introduce the macro-geomorphology of Florisbad since the landscape of Florisbad will be discussed in more detail together with previous geological and geomorphological research conducted in the area, in the next Chapter. Florisbad is situated on the eastern boundary of the Western Free State Panfield (Holmes and Barker, 2006); with a lunette dune located on the lee side of Soutpan (Figure 2.3). The western Free State Panfield, the Florisbad sand dune and the pan fringing lunette dunes are the most important geomorphological features within the vicinity if Florisbad.

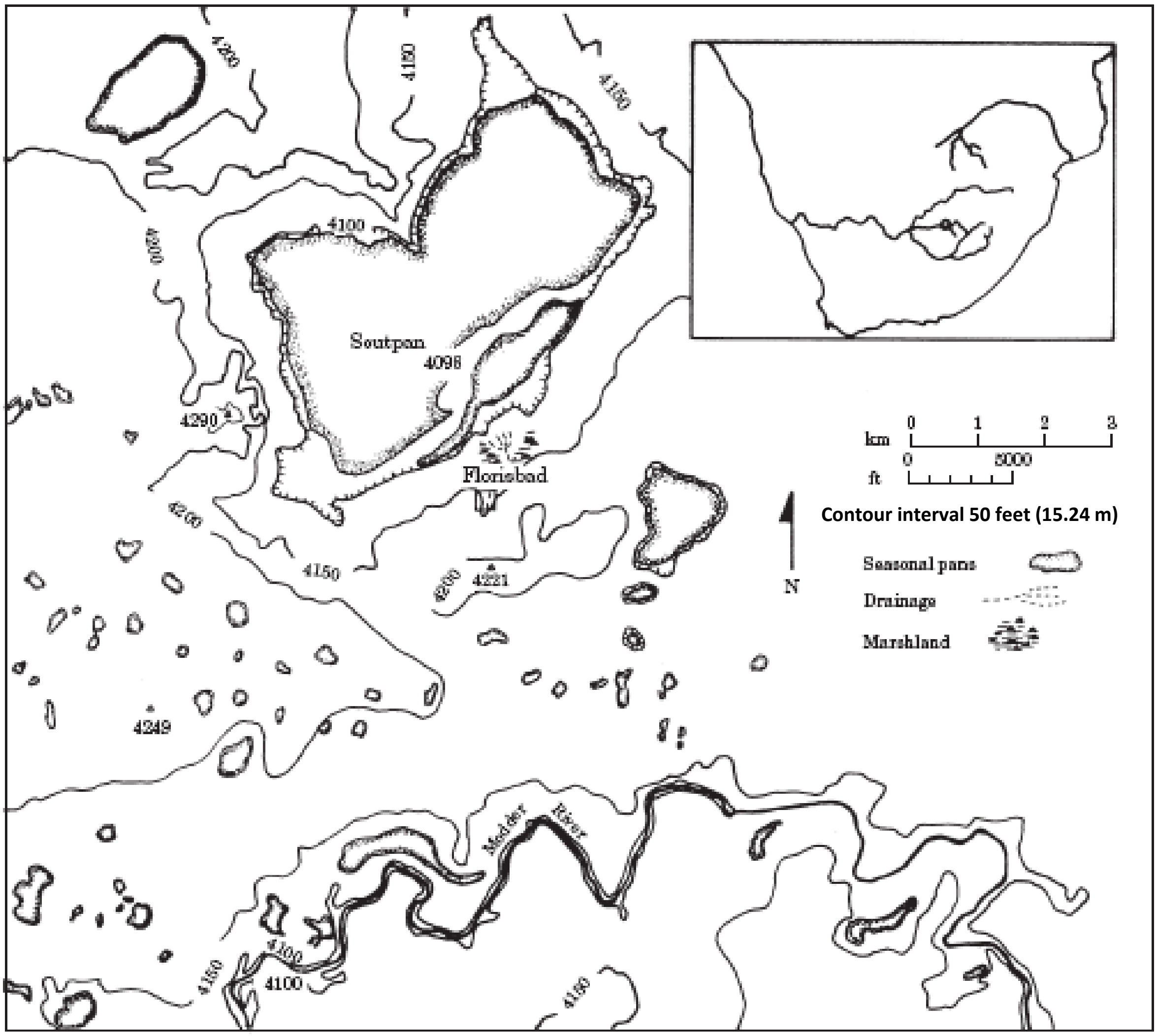

Figure 2.3 The location of Florisbad (after Kuman, 1999).

Since field studies play a vital role in all geomorphological investigations (King, 1966). Observations in the field are essential to formulate and/or to test hypotheses and theoretical calculations, which may also include modelled work. This section will also provides a detailed geomorphological description of the study area (Figure 2.4 and 2.5), with particularly reference to dunes. As part of this study, three dunes were identified; two outer lunette dunes on the southwest and eastern side of the Florisbad pan and a dune located at Florisbad proper. The following sub-sections will begin by describing each study site/dune individually, and then give an overview of the whole study area. For a clear understanding of each site, the description should be viewed in conjunction with the site sketches and photographs.

Figure 2.4 The Quaternary research station at Florisbad

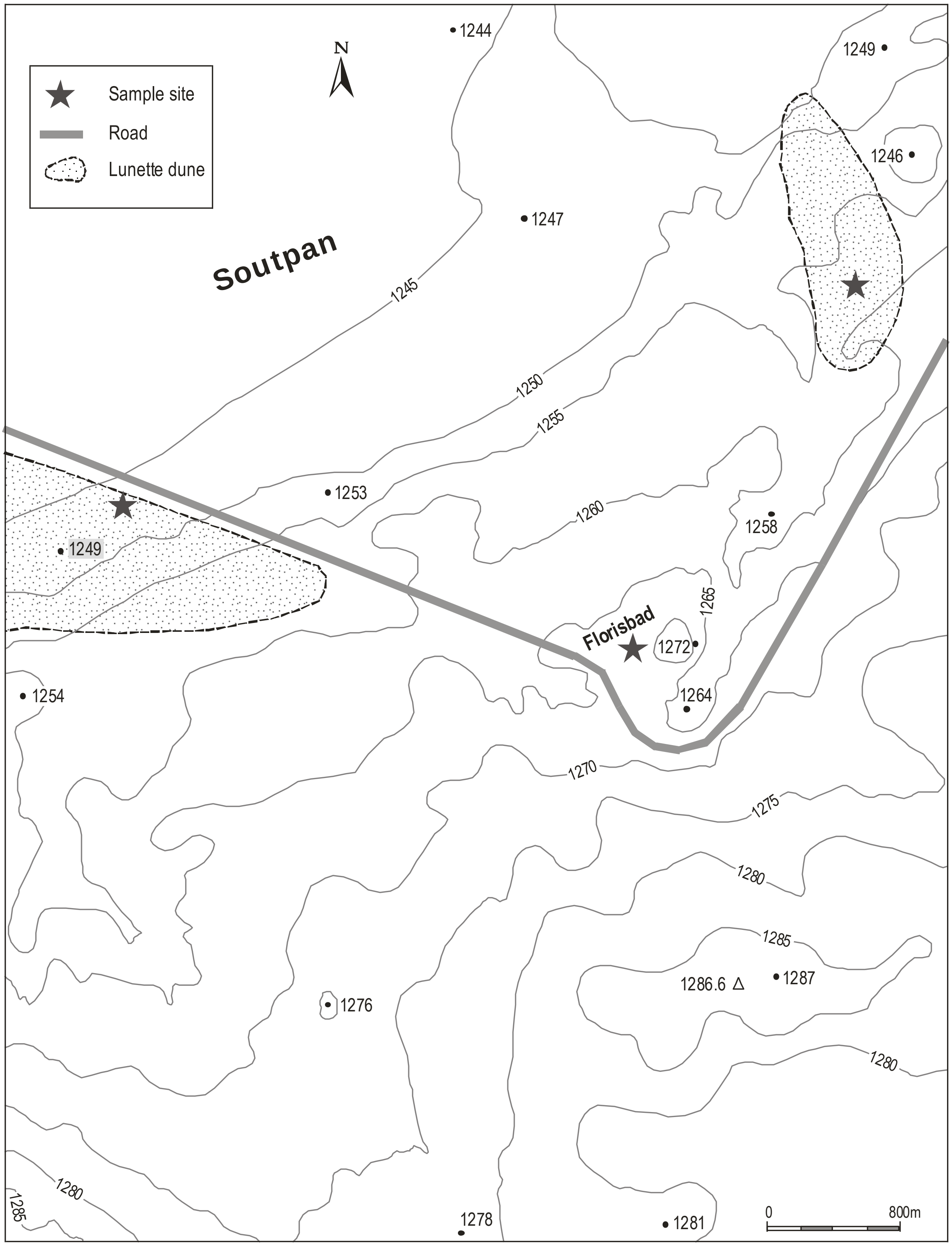

Figure 2.5 The Florisbad lunette dunes in the context of their surrounding environment

2.3.1 The South Western Lunette Dune

The south western lunette dune is situated on the south side of the Florisbad salt pan (28°45′ 45,5" S 26°03′12,9″E), approximately one hundred metres from the pan perimeter (Figure 2.5). The lunette dune is exceptionally well vegetated, the vegetation on the lunette comprises *Eragrostis obtusa-Eragrostis lehmaniana* grass. The surrounding land is used for farming and salt is mined from the pan. Within this dune there are no obvious stratigraphic units, but there are color differences down the profile.

There was evidence of colluvial action (sediment re-working down slope), e.g. a 20cm long angular sand stone clast embedded on the surface. Numerous small (± 8cm long axis) well rounded dolerite clasts were present at the base of the lunette profile.

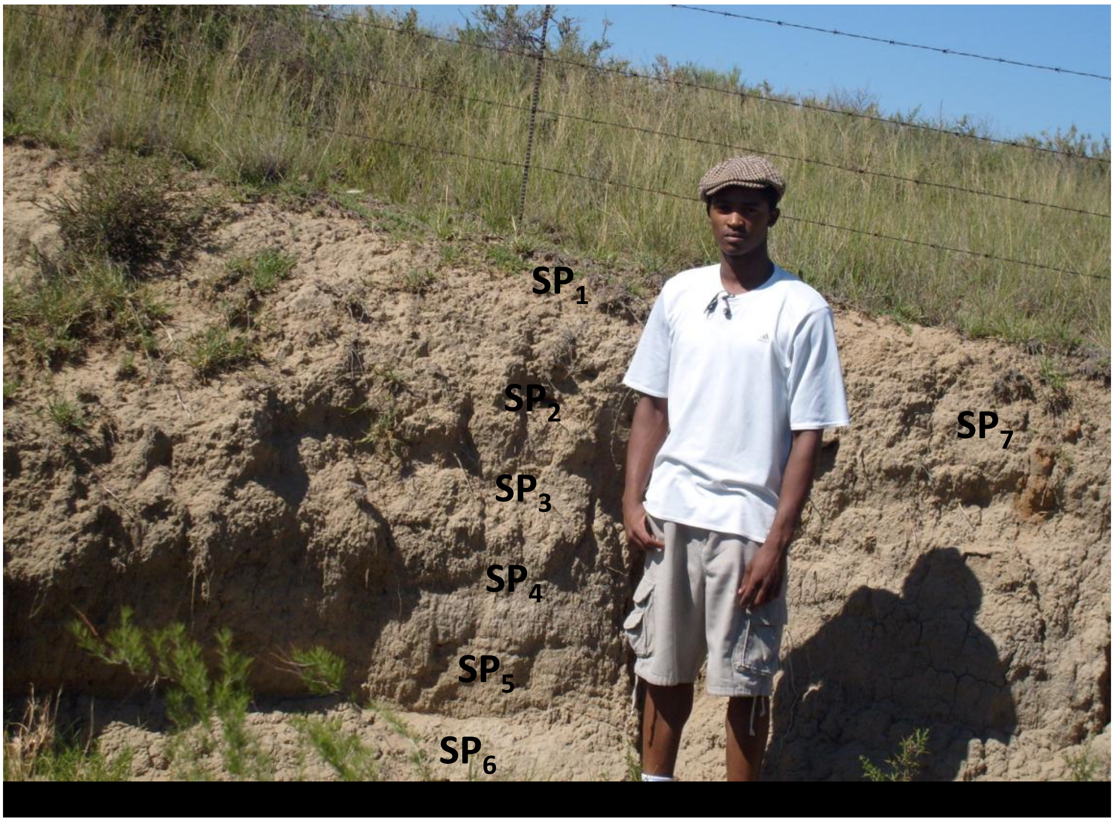

Figure 2.6 The south western lunette dune study site. Note the change in sediments colour down the profile

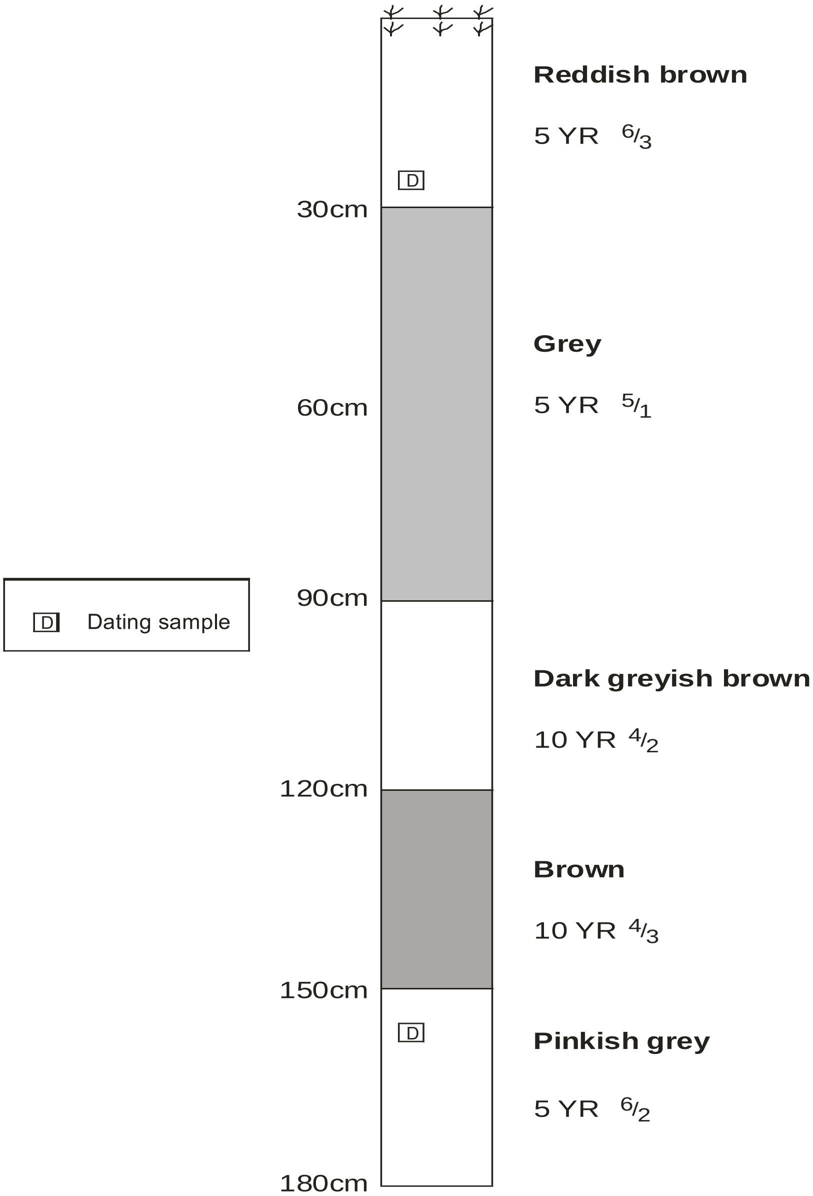

Figure 2.7 Profile of the south western lunette dune

2.3.2 THE EASTERN LUNETTE DUNE

The eastern lunette dune is situated on the eastern side of the Florisbad salt pan, extending to the north (28°45′ 50, 0’’ S 26°04′25, 0″E). This lunette dune is located next to a palaeo-drainage line, and extends to the northern side, where the road crosses the pan, on the palaeo-shore line of the pan (Figures 1.2 and 2.5).

This lunette dune is relatively well vegetated along the crest, the vegetation on the lunette comprises *Eragrostis obtusa-Eragrostis lehmaniana* grass. As with the south western lunette, the surrounding land is used for farming and mining of salt from the pan. The sediments comprising this dune display a blocky structure, with obvious colour differences. On the crest of the dune, the first 50cm is overburdened by a structureless top soil, followed by a calcrete inclusion at ~ 80cm followed by a sand layer with abundant plant rootlets. From ~ 120cm there is a transition from sand to a clay layer. There were several Stone Age tools and calcretenodules at the base of this lunette. There was also evidence of colluvial action this will be discussed in more detail in Section 2.3.5.

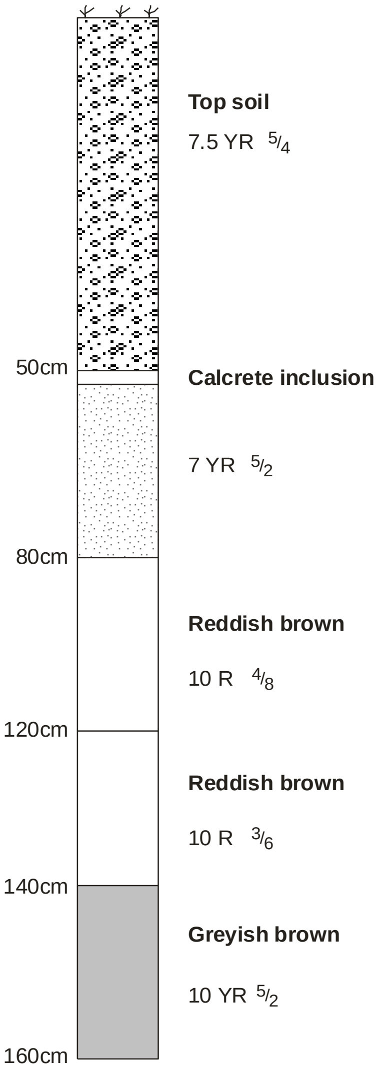

Figure 2.8 Profile of the eastern lunette dune

Figure 2.9 The innermost part of the Florisbad eastern lunette dune. The pan is to the immediate left of the photo.

Figure 2.10 A view of the Florisbad eastern lunette dune, The Florisbad sand dune is located to the north. Note the difference in vegetation density between the lunette and the Florisbad dune.

Figure 2.11 A view of the profile of the Florisbad eastern lunette dune, The dune overlain by reddish brown sand layer with abundant plant rootlets, and then there is a transition from sand to a clay layer. Note mallet for scale

2.3.3 THE FLORISBAD DUNE

A detailed, literature-based description of the Florisbad dune will be given in Chapter 3 (Section 3.4) of this dissertation. Only the horizontal stratigraphy of the eastern part of the dune, as it was observed during field work, will therefore be described here. This will then be compared to previous stratigraphical descriptions of the dune, as described by other researchers. However it is important to note that the stratigraphy that is outlined below only reflect the stratigraphy of the eastern part of the Florisbad dune. Douglas (2009) has indicated that, due to the complexity of the site, any cross section reflecting a specific section of the site would only reflect that particular sequence and would be of relative limited application in the context of the site as a whole.

Figure 2.12 provides the cross section of the eastern part of the dune, illustrating the major sequence as observed during field work. Figure 2.13 was taken from a pit dug next to an area of spring activity, and Figure 2.14 is logged sediments from the Florisbad dune to the east of the spring. It is noteworthy that these two profiles appear to have a similar stratigraphy. The lower portion of the Florisbad dune comprises grey sediments material, and is overlain by dark reddish brown sediments (Figures 2.12 and 2.13). It was also noted that there were no organic rich layers on the deposits that were far from the central part of the dune. However drilling of 31 boreholes to analyzes the deposits on and away from the spring mound had already confirmed that organic rich layers were limited to the central part of the site (Rubidge and Brink, 1985).

Although this site appears to be heavily vegetated as compare to the other two sites (Figure 2.10), it was also noted that most of the trees (Blue gums), are alien species (*Eucalyptus*) which were introduced to the area by humans for ornamental purposes. The next section will give an overview of the whole study area, with special focus on the differences and similarities, which were observed between different sites.

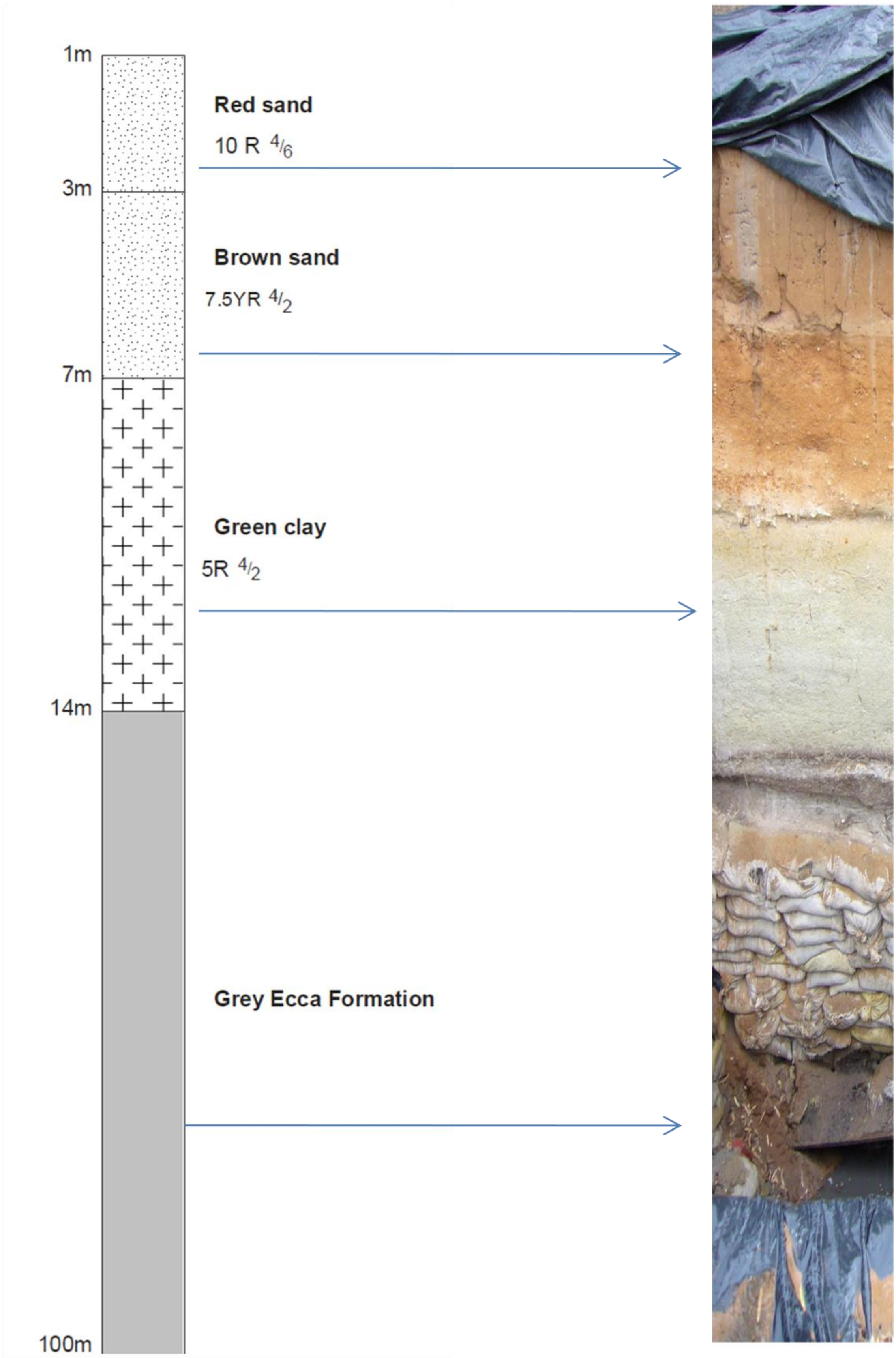

Figure 2.12 Profile of the Florisbad dune (borehole) comparing to Florisbad main pit (Figure 2.13)

Figure 2.13 The horizontal stratigraphy of the exposed face of the main pit at Florisbad (Photo,

Figure 2.14 logged sediments for every metre from the eastern part of the Florisbad dune

2.3.4 OVERVIEW OF THE STUDY AREA

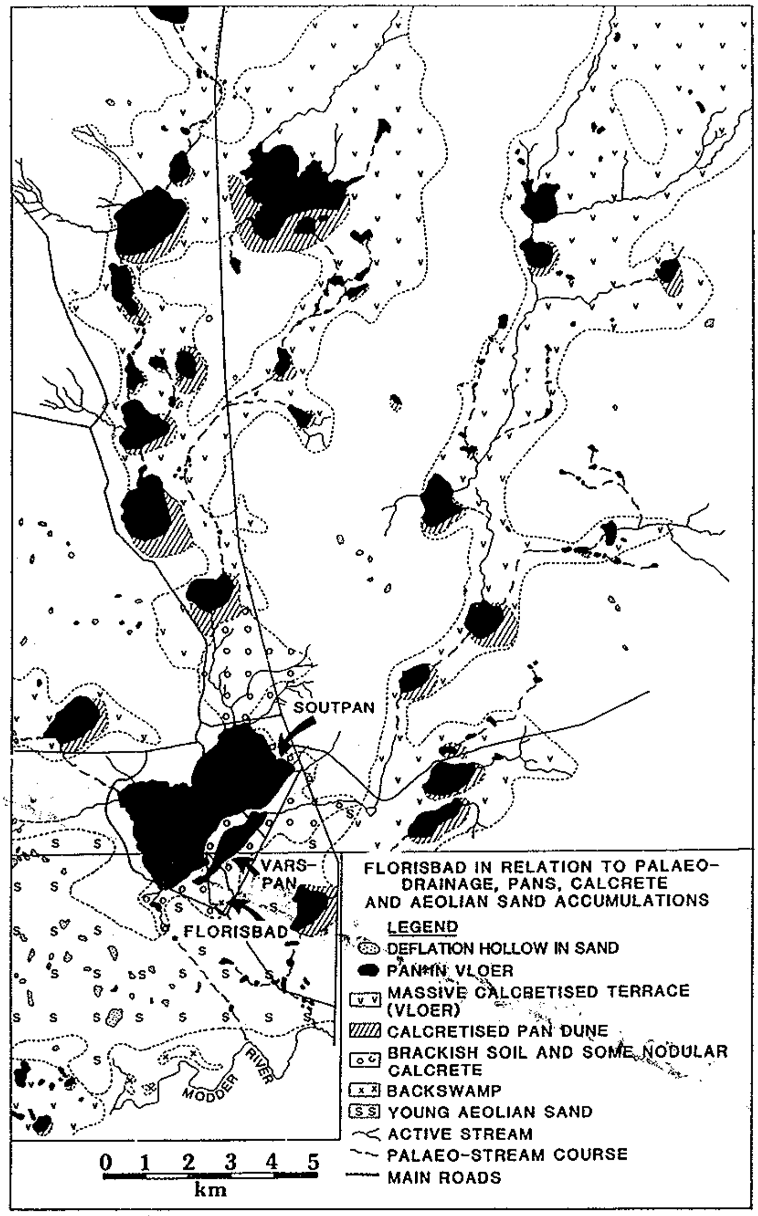

Figure 2.15 Florisbad in relation to palaeodrainage, pans, calcrete and aeolian sand accumulations (original figure from Grobler and Loock, 1988).

Through extensive mapping, Loock and Grobler (1988), demonstrated the existence of a large palaeodrainage system north, north-east and west of Florisbad, which today is evident as numerous pans associated with deflation hollows, aeolian sands and calcretized terraces and lunette dunes (Figure 2.15).

Loock and Grobler (1988) argued that Soutpan, the very large pan north of Florisbad, owes its unusual large size and shape to the confluence of three streams. Since the prevailing wind direction is from the northwest, dunes in this region form on the south-eastern sides of pans through deflation of pan sediments during dry seasons. A separate, elongated pan, called Varspan (Figure 2.15) is located between Soutpan and Florisbad. Varspan's floor consist of green-grey gley (*sic*) (Loock and Grobler 1988).

The lunette dunes in the study area appear to be more severely eroded, as compared to the Florisbad dune; this will be discussed in more detail in Chapter 6. The south western lunette dune and the eastern lunette dune have similar vegetation cover, which comprises mainly grass, and the Florisbad dune is densely vegetated with trees. Although most of the trees on the Florisbad dune are alien species, due to the presence of the spring, it is quite evident that in the past there used to be luxuriant vegetation around the spring, which eventually formed the 'peat' (carbon rich sediments) on the central part of the Florisbad dune.

Several Stone Age tools and calcretes were present at the base of the eastern lunette dune. The calcretes on the lunette appear to have been washed into the lunette by water. However it was also noted that the eastern lunette dune is closest to the present pan and as a result material from the pan can easily get washed into this lunette, unlike the south western lunette which is further away from the present pan. Since Soutpan is linked to other pans in the western Free State, there is also a strong possibility that some of the material such as the Stone Age tools originated somewhere else, and were brought to the vicinity of Florisbad during wet period, by fluvial wash.

As previously mentioned, the surrounding area is used for agricultural purposes. Loock and Grobler (1988) noted that "the incursion of vegetation can be ascribed to the lowering of the groundwater table with its high brine content and possibly to fertilizer rich in N, P and K which was blown and washed into the pan from surrounding maize fields located in the red, apedal soils of aeolian origin" (Loock and Grobler, 1988; 167).

Loock and Grobler (1988) also indicated that the pan was originally devoid of vegetation. The vegetation started to develop in the form of vlei grass, low herbs and stunted trees in the north eastern corner of the pan (i.e. on the eastern lunette study site). Even today the eastern lunette dune is located close to a marshy area. It is important to note that this difference in vegetation cover could have led to different rates of sand accumulation and stabilization of dunes in the past. However the eastern lunette dune appear to have a similar, profile as the Florisbad dune, in terms of stratigraphy, which were both defined in terms of colour changes. A detailed comparison of the lunette dunes and the Florisbad dune will be given in Chapter 6.

2.4. CLIMATE

Climate controls are responsible for a number of processes that have contributed to the depositional environment at Florisbad. Climate plays a role in weathering digenesis, chemical reactions, aeolian deposition and the type of vegetation found in the area. The type of vegetation will then have an influence on the morphology of the area and, to an extent, it may influence sand dune mobility during long-term wet and dry periods. In the Free State, topography also has an influence on climate, with an increase in altitude from west (900 m) to east (3282 m). Florisbad is located almost in the centre of southern Africa on a plateau (Brink, 1987). This results in Florisbad experiencing extreme climatic conditions in the form of hot, wet summers, and dry, cold winters. This section on climate is subdivided into two subsections; the first subsection looks at the palaeoclimate in Florisbad, followed by the current climate of Florisbad. More emphasis will be put on atmospheric circulation because wind conditions, and an understanding of aeolian processes, are very important in this research.

2.4.1 Paleoclimate

Paleoclimate played an important role in determining aspects such as temperature, wet and dry periods and vegetation type when Florisbad and its surrounding environs were formed. Many different factors such as pollen, stalagmites temperature and lithofacies analyses, have been used at Florisbad to project paleoclimate (Van Zinderen Bakker, 1995; Scott and Nyakale, 2001 and Bamford and Henderson, 2003).

From the late Pleistocene through the Holocene, Nicholson and Flohn (1980), have identified three major episodes, in which Africa was experiencing climate conditions that differ significantly from the conditions experienced today. Van Zinderen Bakker (1995)'s analysis of paleoenvironments of three pollen record from Florisbad indicated that during the above mentioned period, considerable change in the environment has taken place.

The reconstructions at Florisbad were based on lithofacies analyses of palaeolake sediments, on micro- and megafaunal remains, on pollen data and on archaeological evidence from the late Earlier Stone Age onward. The sequence at Florisbad indicated that radical changes took place from the last cold stage of the penultimate ice age onward, ranging from alpine to temperate and periodically to cold desert conditions. However, setting up of an absolute time scale was prevented by lack of dating beyond the radiocarbon limit (Van Zinderen Bakker, 1995).

According to Nicholson and Flohn (1980), the first episode falls between c. 20 000 to 12 000 BP, this is the period when the Sahara was advancing southwards. Aeolian sand dunes were forming and expanding along the Sahara margins. This episode was followed by two wetter lacustrine periods, c. 10 000 to 8 000 BP and c 6 500 to 4 500 BP which were only interrupted by drier conditions 3 millenia ago.

In most instances the projection of paleoclimate is based more on speculation than on certainty, because of a lack of correlation in the broader interpretation of paleoclimate. Therefore to obtain a precise projection of paleoclimate, it is important that intense and detailed research is carried out for a specific region. Mid- to late-Holocene pollen data from Florisbad in the central Free State, South Africa, reveals a number of moisture fluctuations (Scott and Nyakale, 2001). However the data from Florisbad are complemented by previously published results on environmental change from the nearby Deelpan site to the west which is principally an aeolian deposit (Holmes *et al*, 2008).

Based on evidence presented by previous researchers, Florisbad experienced variations in terms of its palaeoclimates (Brink and Lee-Thorpe, 1992; Joubert and Visser 1991). These authors suggested that Florisbad previously experienced more humid periods in comparison to the relatively dry climate of today. This interpretation of paleoclimate was made based on the fauna, flora and water levels that previously existed in this region.

Excavations at the Florisbad fossil site in 1952 yielded several pieces of wood from one of the spring mounds. One of the wood pieces has now been identified as a non-local wood, *Zanthoxylum chalybeum* (Engl.), the kundanyoka knobwood (Rutaceae), which today occurs naturally in Zimbabwe and farther north. As the wooden fragment was associated with Middle Stone Age (MSA) artefacts, it could be as young as 125,000 years or as old as the approximately 259,000-year old cranium. The presence of this plant today so far south implies that there was a southern shift of the vegetation zones (Bamford and Henderson, 2003).

According to Bamford and Henderson (2003) if a plant, or flora, changes its distribution, there needs to be an outside force to bring that change. Bamford and Henderson, (2003) noted that the most common change is climate.

In case Bamford and Henderson (2003) concluded that if the southern shift in the vegetation implies the same shift in the climate where there would have been less frost and slightly higher rainfall. The Pleistocene climate at Florisbad has undergone several fluctuations with a quasi-periodicity of 100,000 years corresponding to the glacial–interglacial couplets (Bamford and Henderson, 2003).

Turning to present-day conditions, most researchers have noted that is seems as if there had been a constant change in rainfall pattern since the 1960s in southern Africa. Lamb (1966) investigated changes in World wind circulations, by looking at prevailing temperatures, rainfall pattern and the levels of African lakes. While investigating the above mentioned phenomenon's he reported on some of the gross features of the world climate behavior since 1960, and declassed an abrupt return to conditions as they were before the well known climates in the twentieth century. And it appeared as if there is a reversal of the change of behavior of large circulation that took place about 1895.

By looking at lake levels he concluded that such lake levels must have responded to the integrated rainfall over the years. Studies that specifically looked at fluctuation of lake level in Florisbad have been done, and will be discussed in more details in the next Chapter.

2.4.2 Present climate

The climate of southern Africa is strongly influenced by the latitudinal position of the subcontinent in relation to the pressure and wind system of the globe. It is therefore important that a general view of the climate of southern Africa is given before looking specifically into Florisbad. The controls upon climate and climatic variability have been summarized by a number of researchers (Tyson, 1988; Preston Whyte and Tyson, 1988; Thomas and Shaw, 1991; Manson and Jury, 1997; Mason *et al*, 1999).

In brief the current climate of southern Africa is characterized by low levels of rainfall during winter months and high level of rainfall around January. Dry conditions are experienced in winter due to the presence of a dominant anticyclone pressure system over the sub continent (Endfield and Nash, 2002).

The South African climate is largely influenced by the disturbance of the southern hemisphere circulation, which appear as cyclones and anticyclones moving around the coast (Schulze, 1994). Factors such as latitude and solar radiation, altitude and position relative to land and sea, ocean current and temperature also have an influence on climatic conditions.

Louw, 1979; Schulze, 1994 and Kruger, 2002 identified three basic weather systems that cause rainfall in the Free State. The primary cause of rain over the interior of South Africa, including the Free State Province is cut off low pressure cells. The forming of cut off pressure cells over South Africa brings in a broad stream of warm moist equatorial air from the north and north west into the Free State Province.

Secondly the Free State receives rainfall because of frontal systems. Finally the Province experiences orographic rainfall due to the presence of anticyclonic system, that promotes uplifting and convergence of the equatorial air.

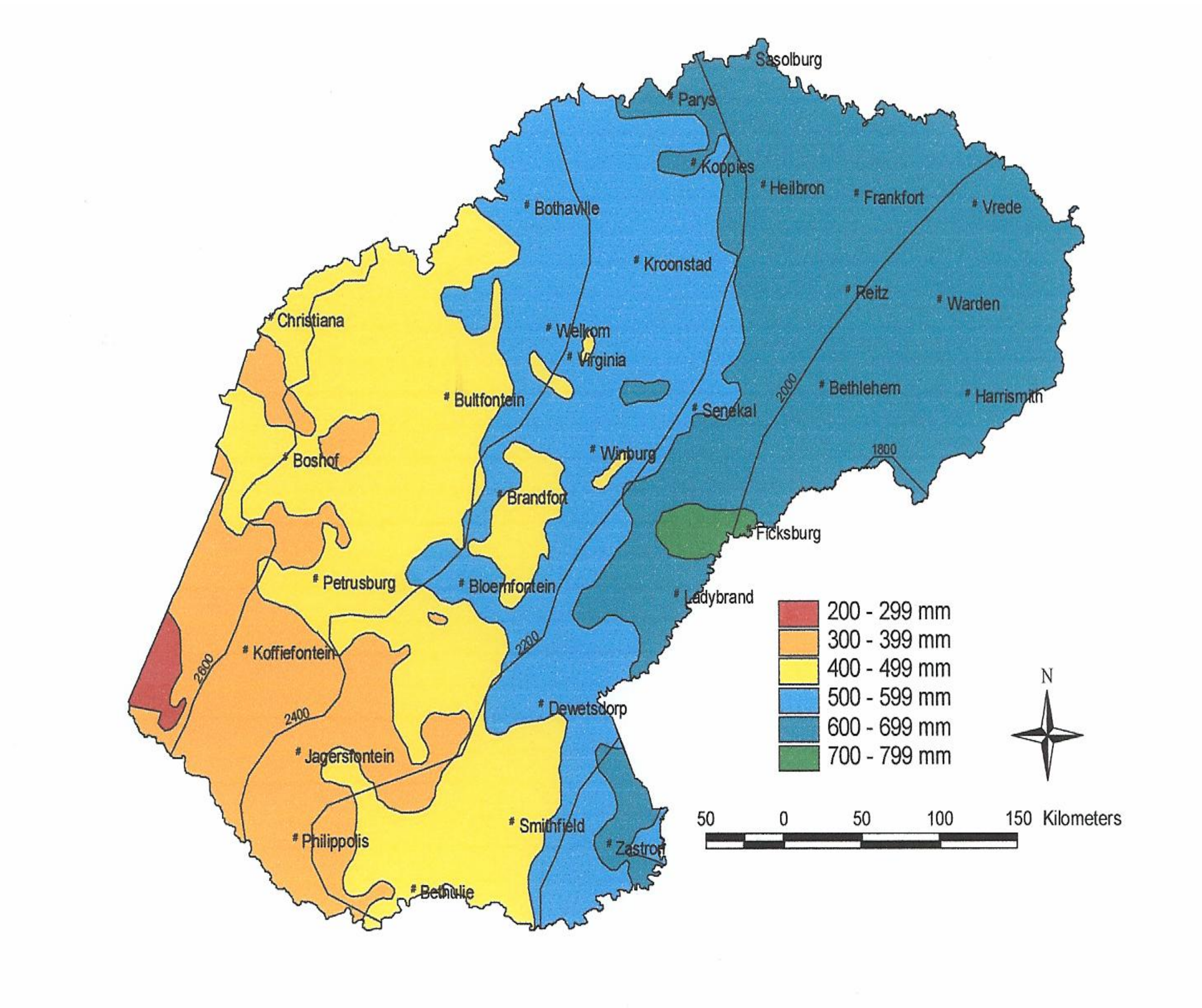

Figure 2.16(a) Mean annual rainfall of the Free State Province (South African Weather Services, 2008).

The Free State experiences warm temperatures in summer (average summer temperature 23º C), when most of the rain falls (between 600 mm and 750 mm in the east to less than 300 mm in the west), but it experiences very low temperature in winter (average winter temperature: 7.7º) , with heavy frost over most of the province (Douglas, 2006b). Snow is often recorded on the eastern mountains and, occasionally, over the rest of the region. These cold conditions are brought about by cold fronts coming from the Atlantic Ocean which, in passing the southern tip of Africa may extend into the Highveld, bringing cold, dense air into the interior.

The 500 mm isohyet passes just to the east of Florisbad. Florisbad receives an annual rainfall of 450-500 mm. However, the annual rainfall of Florisbad is extremely variable with, for example, a maximum of 944 mm in 1988 and a minimum of 271 mm in 1965 (See Table 2.1). Figurer 2.17 provides a 23 year rainfall record of Florisbad showing the considerable annual variation in rainfall.

Table 2.1 Rainfall data from Florisbad (Florisbad weather/research station).

Year	Rainfall (mm)	No of recorded Month
1925		12
1926	474	11
1927	352	12
1928	453	12
1929	541	12
1930	298	12
1931	584	12
1932	280	12
1933	342	11
1934	525	12
1935	507	
1936	476	12
1937	307	12
1938	423	11
1939	648	12
1940	537	12
1941	397	12
1942	594	12
1943	749	12
1944	423	12
1945	328	12
1946	473	12
1947	378	12
1948	413	12
1949	396	12
1950	650	12
1951	428	12
1952	447	12
1953	436	12
1954	458	12
1955	529	12
1956	654	12
1957	526	12
1958	280	10
1959	473	12
1960	599	12
1961	485	12
1962	354	12
1963	709	12
1964	375	12

Year	Rainfall (mm)	No of recorded Month
1965	271	12
1966	409	12
1967	657	12
1968	386	12
1969	334	12
1970	413	12
1971	484	12
1972	517	12
1973	476	12
1974	733	12
1975	557	12
1976	757	12
1977	439	12
1978	401	12
1979	439	12
1980	395	12
1981	669	12
1982	410	12
1983	328	12
1984	298	12
1985	451	12
1986	425	12
1987	472	12
1988	944	12
1989	545	12
1990	418	11
1991	817	12
1992	199	12
1993	446	12
1994	342	8
1995	268	12
1996	474	11

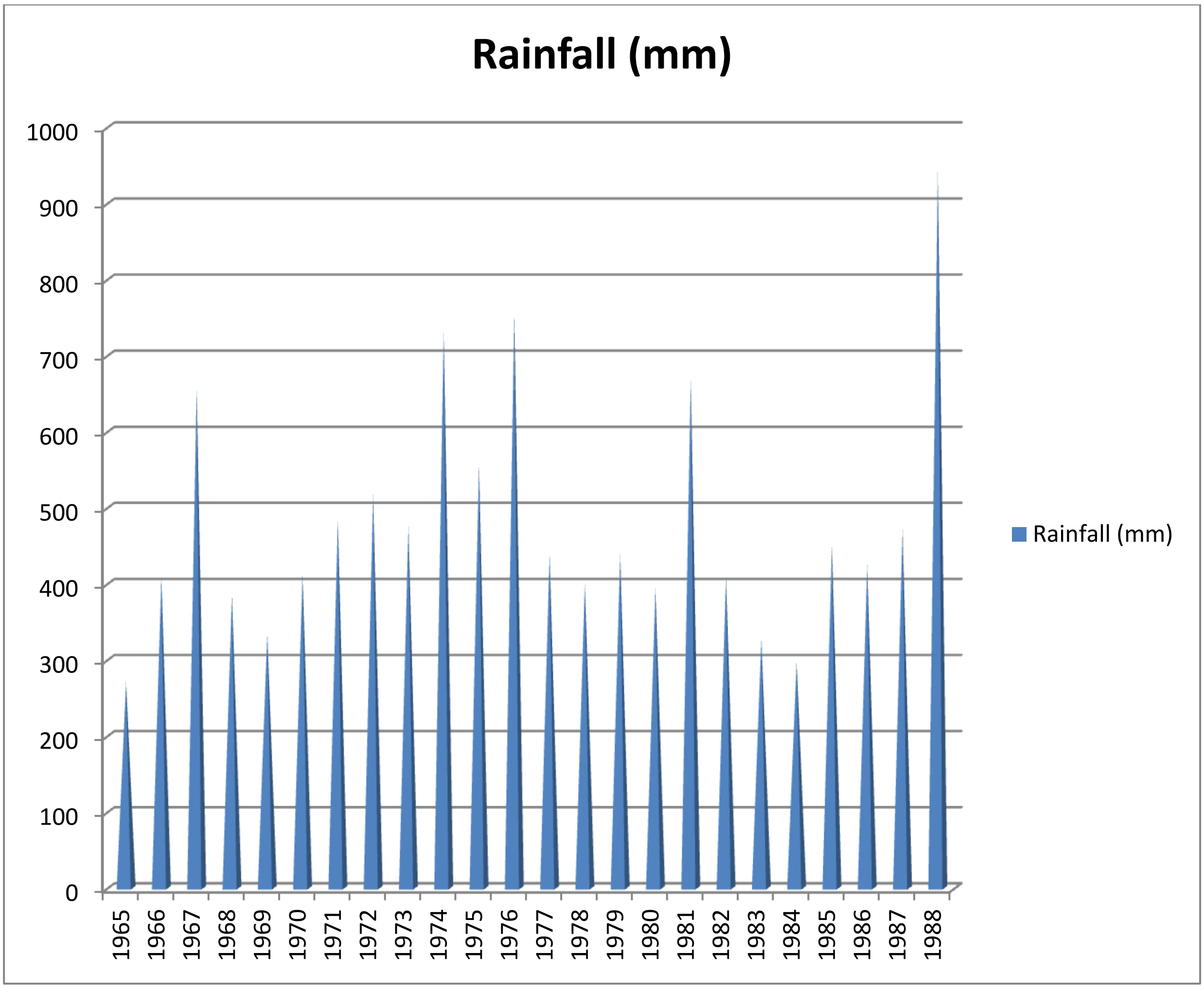

Figure 2.16 (b) Twenty five year annual rain fall at Florisbad showing the variation in annual rainfall between the lowest (1965) and the highest (1988).

Wind plays a vital role in the Florisbad context because it partially determines rainfall. However, more importantly, it has a direct influence on the transportation of aeolian sand, which in turn may lead to (or have lead to in the past) the formation of sand dunes. Although it is evident that previously there had been a prevailing north westerly wind direction, at present it is difficult to assign any prevailing direction for local winds (Loock and Grobler, 1988; Douglas, 2009). Current wind roses show a predominantly north-easterly, through to south westerly and even southerly wind flow throughout the year (Kruger, 2002 and Douglas, 2009).

Despite the difficulty in assigning any prevailing wind direction to local winds, Schulze (1994) has noted that there is predominant north-west wind in January and July. However Douglas (2009) noted that, historically, there must have been extended periods with very dominant prevailing north to north-west wind in order for the south-east dune belt at Florisbad to move.

2.5. VEGETATION COVER

The vegetation of the Free State comprises mainly grass (wetter areas) and Karoo shrubs (drier western parts). Trees (acacias) are only found along water courses. Four biomes occur within the Free State, namely the grassland (72% of the province), Nama Karoo (22%), savanna (5, 95%) and forest biomes (0, 05) Scott and Vogel (2000).

Diagnostic grasses includes the subspecies; *Eragrostis obtusa*, *Eragrostis Lehmaniana*, and occasional *Acacia Karoo* trees along water channels; *Acacia Caffra* (Common Hook Thorn), *Rhus Lancea* (Karee), and *Tragus Racemosus* (Carrot seed grass) (Roberts, 1973; Low and Rebelo, 1996). Portions of the land are cultivated for crops such as wheat and maize.

Florisbad is situated within the *Eragrostis obtusa-Eragrostis lehmaniana* grasslands (O'Connor and Bredenkamp, 1997; Scott and Nyakale, 2001). The area is covered by the grassland biome; this vegetation type covers a broad range of plant species stretching from the west to include the central and the eastern parts of the province. The species require moisture in summer and spring, during the growing season, and are mainly of the C4 type (Vogel *et al*, 1978; Scott and Nyakale, 2001). Regular frosts have prevented the development of woody species in the wider region of Florisbad, except along watercourses and on the dolerite hills where there are woody species such as *Acacia karroo* and *Rhus* spp., *Olea africana*, *Buddleia saligna*.

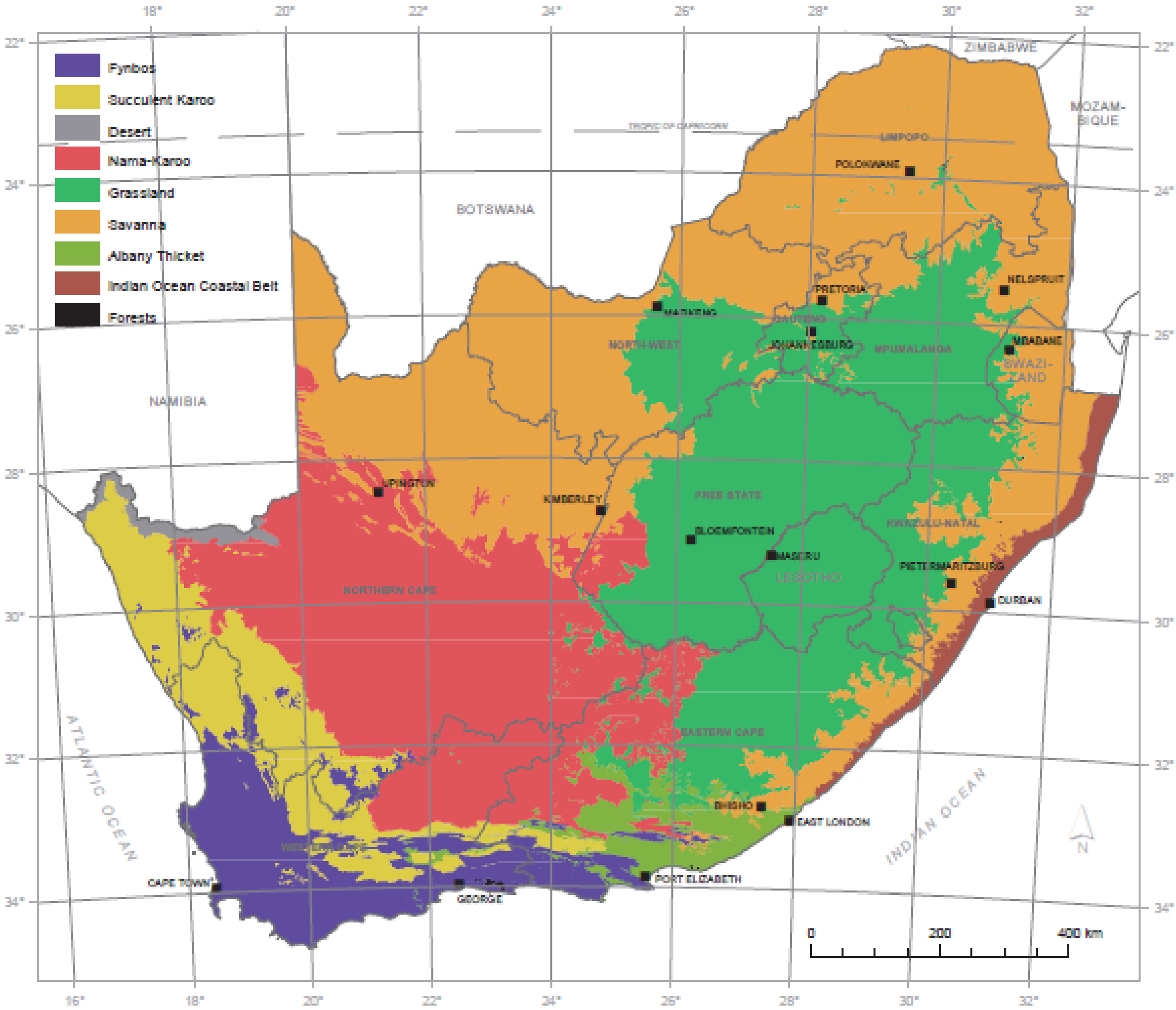

Figure 2.17: Vegetation cover (biomes) of South Africa (Department of Environment Affairs and Tourism, 1998).

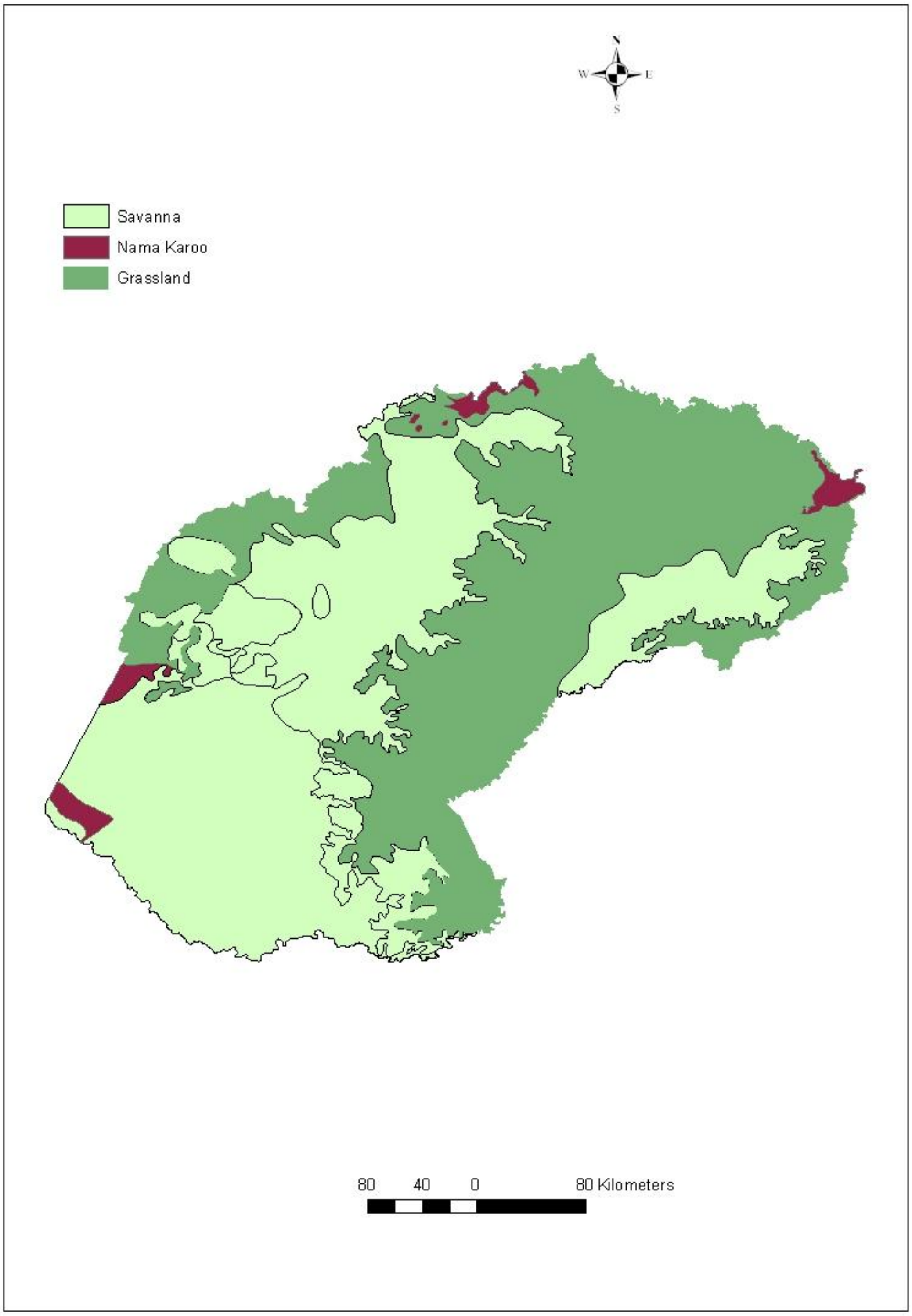

Figure 2.18: Vegetation cover (biomes) of the Free State Province, South Africa (Department of Environment Affairs and Tourism, 1998).

2.6. CONCLUDING REMARKS

In this Chapter the physical environment of Florisbad and its surroundings have been described. Important geomorphological features that might have played a role in the morphology and sedimentation in this area have also been mentioned. The two lunette dunes in this study have similar morphologies. All dunes comprises of unconsolidated and poorly sorted red sediments at the top. In all three dunes changes in colour were detected, and the stratigraphic units were defined mostly in terms of colour changes.

In this Chapter the details of the dunes in the vicinity of Florisbad were outlined and discussed on the basis of the observations which were made in the field. The geomorphological importance of these features will be discussed in more detailed in the next Chapter. In Chapter 3, a detailed literature review of Florisbad is presented. This includes an overview of the scientific literature which forms the basis of this research.

CHAPTER 3: LITERATURE REVIEW

3.1. INTRODUCTION

A description of the characteristics of the physical environment of Florisbad was provided in the previous Chapter. This Chapter presents a detailed literature review of the scientific studies that have been conducted at and around Florisbad. The Chapter focuses primarily on the typical macrogeomorphological features found in the western Free State Panfield, as this provides a context for Florisbad itself. It then looks at the Florisbad site and in particular the Florisbad dune or spring mound. The discussion includes previous work undertaken on the geomorphology and geology at and around Florisbad, as well as related studies from other areas. The Chapter starts by looking at the history of Florisbad, as this will help to give a clearer picture as to why this area is considered an important site, especially in the context of Quaternary studies.

3.2. HISTORICAL OVERVIEW OF THE FLORISBAD SITE

Archaeological sites and other sites of palaeoenvironmental interest are abundant in the Free State (Malan, 1942; Visser, and Van Riet Lowe, 1955; Kuman and Clarke, 1986; Scott, 1989; Wadley et *al,* 1992; Marker, 1994; Ouzman and Wadley, 1997; Henderson, 2001a; Henderson, 2001b; Scholtz, 2001; Kent and Scholtz, 2003). Florisbad, an important archaeozoological site, is situated on the eastern boundary of the Western Free State Panfield (Holmes and Barker, 2006). The topography of the area is slightly undulating with occasional sheet wash from infrequent runoff.

The following, unless otherwise indicated, is based on Kuman *et al* (1999).
Recorded purchase of land for farming in this area go back to as early as 1860 when a trekker farmer by the name of Hendirk Venter bought a farm which included the spring now known as Florisbad (Nyame, 1995).

The mineral water from the spring was believed to have ‘healing powers’ and this made the spring popular. Florisbad spring water was reported to be effective in the treatment of sciatic, muscular and articular rheumatism.

The Florisbad spring had been included in papers and articles on medical springs of South Africa (Kent, 1948 and 1981), but there have never been scientific studies carried out on the possible medicinal properties of the Florisbad spring water (Douglas, 2009). In 1912 a small house was built over the spring eye for protection and privacy of the people who wanted to bath in the spring water. In the same year an earthquake occured about 125km south west of Florisbad with its epicenter near Koffiefontein (Douglas, 2001). This earthquake resulted in a new spring eye erupting in the excavation due to the build-up of gases, throwing up many fossils and artifact (Grobler and Loock, 1988; Douglas, 2009).

The materials were later described as proof of the unequivocal association of extinct mammals with humans (Broom, 1913). “The excavations have also located and uncovered a rich Middle Stone Age horizon, dating to around 121 000 ± 6 000 years ago.” (Brink,1987: 163). Sporadic excavation where conducted for two decades, until the discovery of part of a human cranium, on the 25th of July 1932, in the spring eye by Professor T.F. Dreyer.

In 1952 another series of excavations were started. Material from those excavations underlines the importance of Florisbad, since the material that was found was described as part of the Florisian Land Mammal Age established at greater than 130, 000 to about 10, 000 B.P. (Klein, 1984).

Until 1980 Florisbad was run as a mineral water spa. The spa was closed to the public when the property became a research station, and the buildings now house the offices, laboratories, and collections of the Florisbad Quaternary Research Department. The site is now a declared National Monument, and it has a small educational centre.

Figure 3.1 The Florisbad research station. Arrow indicates the main pit, where most of the excavations were undertaken.

Scientists at the Florisbad Quaternary Research Station have carried out further excavations. From these excavations it was possible to establish the stratigraphy of the spring mound and the depositional circumstances of the skull fragment and related fossils. “In a dating project with members of the Quaternary Dating Research Centre, Australian National University, Canberra, both the sequence and the skull fragment have been dated by the ESR and OSL methods, the skull fragment to 259 000 ± 35 000 years old”. (Nyame, 1995: 54).

The recent studies at Florisbad can be considered in three phases. The first phase, which took place after the 1980s, was aimed at gaining a better understanding of the nature and stratigraphy of the site.

The second phase focused mainly on exploring the extent of the archaeological deposits by means of a series of test pits. The final stage, which began in the early 90s and extended to the present, has mainly involved dating projects, as well as geological and hydrological investigations (Nyame, 1995). The following subsections are devoted to the literature that focused on the landscape of Florisbad, and the above-mentioned studies will also be incorporated in these discussions.

3.3 THE WESTERN FREE STATE PANFIELD

This subsection is going to review literature on pans, with specific focus on the western Free State Panfield for the following two reasons. Firstly because the primary focus of this research is the lunette dunes situated on the eastern boundary of the Panfield, and Holmes *et al* (2008) have noted that due to the close association between pans and lunette dunes, it is important that researchers look at both pans and lunette dunes. Secondly because Douglas (2006) believes the development of the western Free State Panfield was a key factor in the formation of the Florisbad site (Chapter 1).

Eight areas of pan concentration have been identified in southern Africa and six of those are either in or immediately adjacent to South Africa (Figure 3.2). Significant concentrations (within South Africa) occur in the Northern Cape, which forms part of the Kalahari Desert, the Free State, Mpumalanga and the North West Province (Lawson and Thomas, 2002). Marker and Holmes (1995) have also reported on isolated pans found in parts of the Karoo. Pans generally consist of endoreic, flat, periodically inundated, un-vegetated basins (Holmes et al, 2008) that are relatively small, ranging from few meters to 10 × 40 km^2 at Great Vloer (Shaw, 1988; Lawson and Thomas, 2002). Pans in South Africa either hold water seasonally or following years of exceptional rains.

Figure 3.2 (a) The world distribution of pans, original figure from Goudie and Wells, 1995.

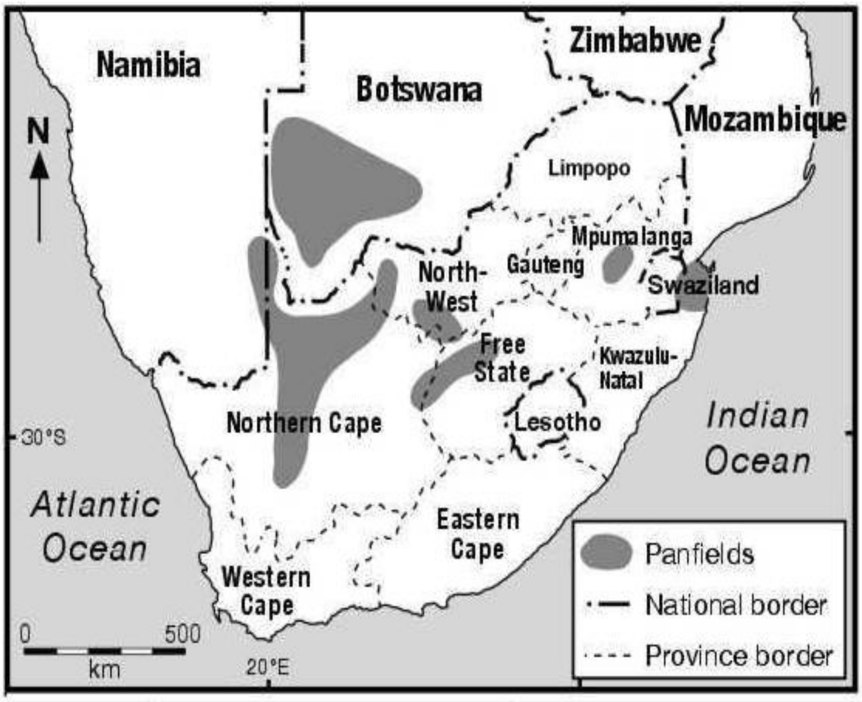

Figure 3.2 (b) The concentration of pans in South Africa, after Lawson and Thomas, (2002).

Seaman *et al* (1995) noted that most of the pans in South Africa lie in a region characterized by less than 600 mm of rainfall per annum, with precipitation predominant between summer and very late summer, and with evaporation greater than 1800 mm. The western Free State Panfield has the greatest pan concentration in South Africa, with densities of up to 16 ha/km^2 (Holmes and Barker, 2006). Florisbad is located on the eastern boundary of the western Free State Panfield.

The origin and development of the western Free State Panfield has been documented by many researchers (Van Zinderen Bakker, 1989; Marshall and Harmse, 1992; Grobler et al, 1998), and the spatial distribution of pans in this area was first documented by Le Roux (1978). Holmes and Barker (2006) recorded 16 803 pans occurring within the western Free State Panfield. They then used GIS, to superimpose pan distribution in the western Free State and the results indicated that shales of the Ecca Group (Karoo Supergroup) are conducive to pan formation, with approximately 10 253 pans occurring on Ecca Group rocks.

Derangements of drainage pattern, wind erosion and removal of dissolved salts by animal have been suggested by Wellington (1945) and Geyser (1947) as a possible cause of pan formation. However Le Roux (1978) disagreed with this hypothesis, stating that the only factors that can account for the wide distribution of pans is climatic derangement in the form of wind.

Although a range of geomorphological processes may be responsible for the developments of these features, Holmes *et al* (2008) noted that in some southern African regions, pan depressions have developed along presently disturbed paleo-drainage lines. Pans are often associated with fringing aeolian sediments accumulation, known as lunette dunes and therefore, in the following section, the literature concerning the pan margin lunette at Florisbad is described.

3.4 THE FLORISBAD DUNE AND LUNETTE

This subsection is going to review literature on dunes, with a specific focus on the Florisbad dune and lunette dunes in the western Free State Panfield. However, prior to description of literature on dunes, a brief description of the Florisbad dune (literature based) is given, so that the reader can gain a clear picture of the Florisbad dune. The Florisbad dune, often referred to as spring mound, is a crescent shaped aeolian deposit, which rises 27m above the pan floor.

Previous scientific studies including research that has been conducted recently, concentrated on this dune. Despite the preoccupation with the term spring mound, it appears as if no research has been carried out to determine the true status of the Florisbad dune (Brink, 1987), and in this dissertation it will be referred to as the Florisbad dune. The springs in Florisbad occur mainly where underground water is forced to the surface, at a point where dolerite intrudes the Ecca shale bedrock (Nyame, 1995). It is believed that the sediments comprising the Florisbad dune were deposited as a results of spring discharge and probably also through wind action (Joubert and Visser, 1991).

Many scientists have tried to explain the origin and developments of the Florisbad dune (Butzer, 1984; Kuman and Clarke, 1986; Brink 1987; Joubert, 1990; Visser and Joubert, 1990; Douglas, 2006). Brink (1987) believed that the sediments where brought to the surface by spring vents, with vegetation growing around margins of the spring pool. According to Brink (1987) the size of the mound eventually grew due to factors such as deposition of windblown sediments, choking vegetation and a diminishing supply of ground water. This hypothesis of sediments coming to the surface due to fissures formed by dolorite intrusion in the Permian shale bedrock was supported by other researchers such as Kuman and Clarke (1986), and Grobler and Loock (1988)

Douglas (2006b) proposed that the development of the western Free State Panfield was also considered crucial in the formation of the original Florisbad site, because faults and fissures would have developed during periods of tectonic activity resulting in the establishment of the Florisbad aquifer and spring. The tectonic disturbances produced a landscape conducive for further modification, by wind, into a pan.

Douglas (2006b, Douglas *et al,* 2010) hypothesized that the spring aquifer and springs originated prior to the development of the Panfield during the time of the tectonic disturbances, although it was assumed that the spring pan would have probably developed during this period, Douglas (2006b) suggested that the spring pan would have been covered by the migrating sand dunes, referred to as the south-east dune belt, resulting in the fossil pan being buried under the sand dunes. As time progressed the dune belt migrated in a south-easterly direction, and allowing the spring to become active on the surface.

Douglas (2006b) proposed five developmental stages for the formation of the Florisbad site. Figure 3.3 represents the plan of the five developmental stages, and the cross sections are shown in Figure 3.4.

Figure 3.5 is the legend for the interpretation of the five developmental stages. In the initial stage it is suggested that the inter-dune ephemeral drainage would have contributed water to the pan during wet periods. Simultaneously a sand dune started to develop along the south eastern bank of Soutpan, mostly because of deflation of Soutpan floor and aeolian deposition from surrounding area.

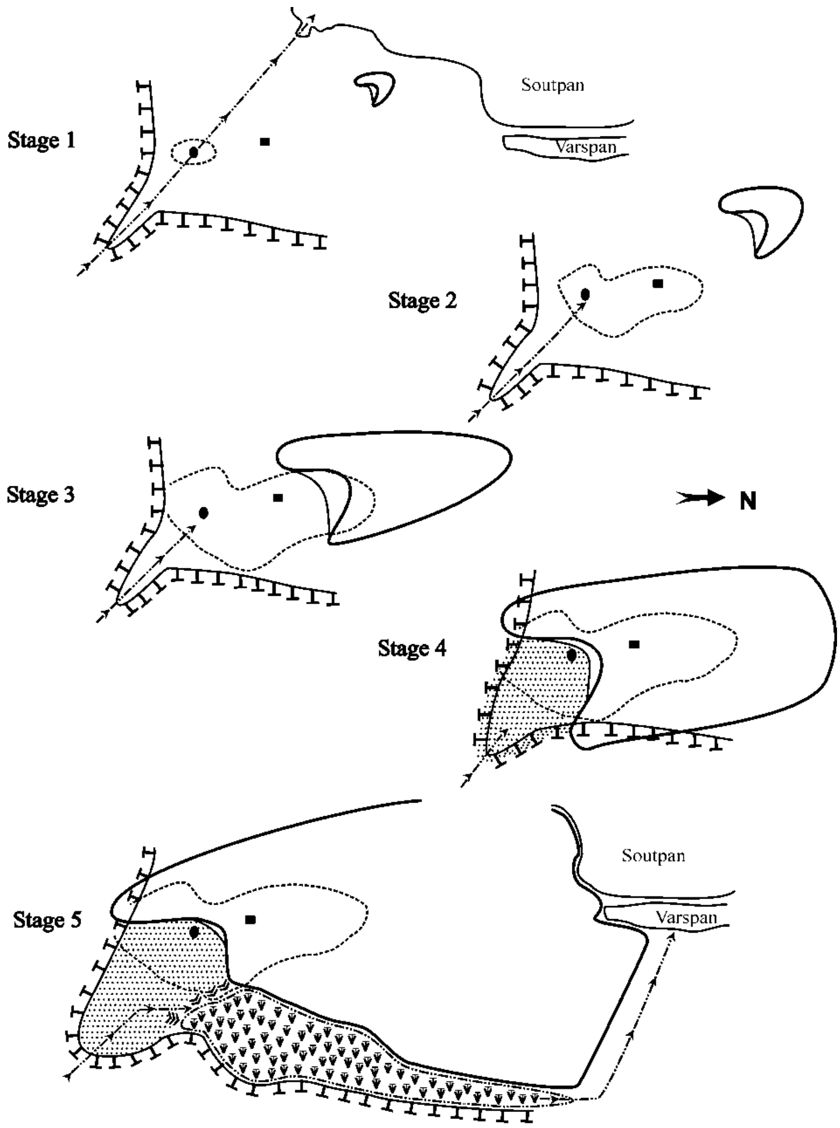

Figure 3.3: A schematic map of the five developmental stages (original figure from Douglas, 2006b).

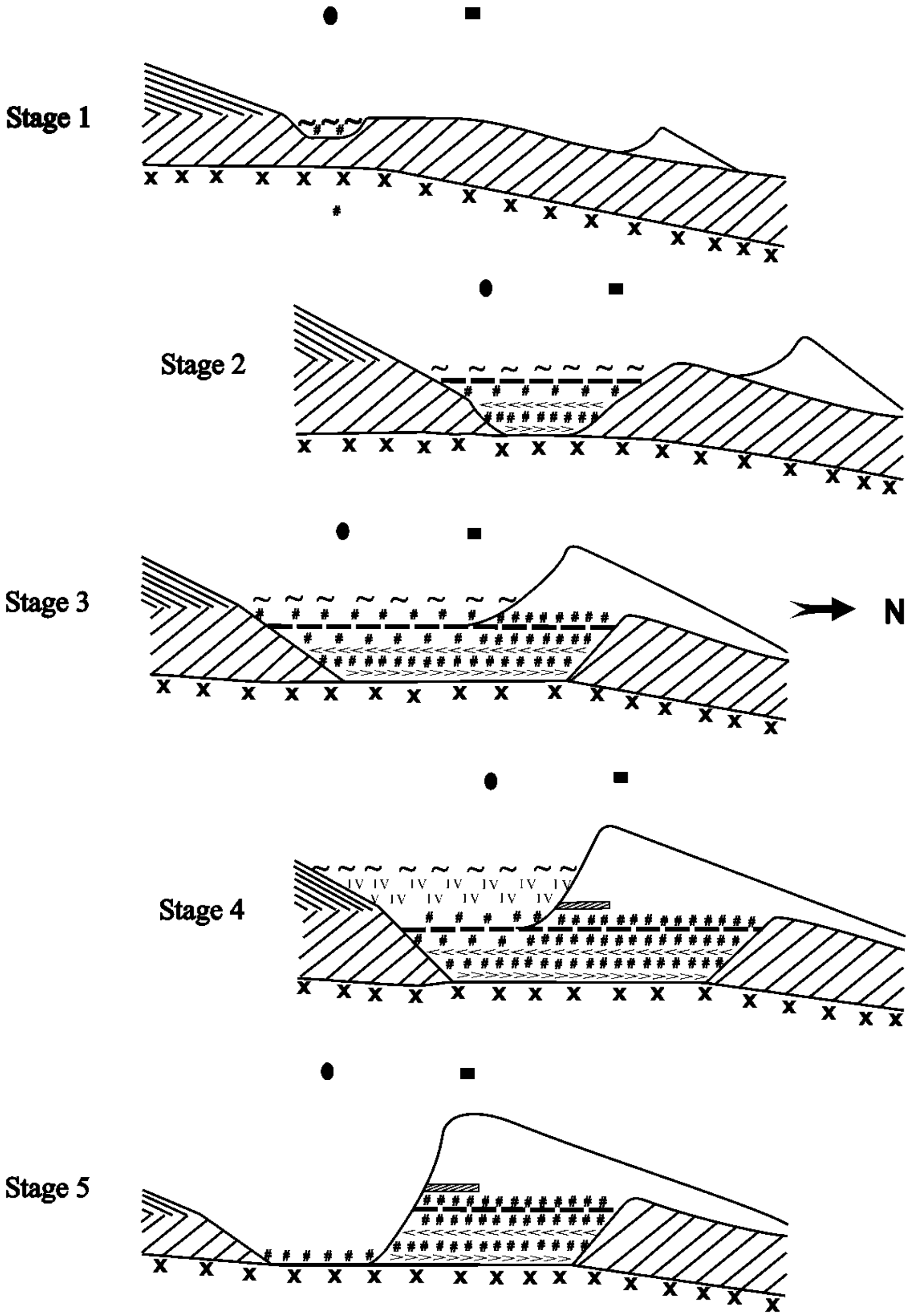

Figure 3.4: A schematic profile of the five developmental stages (original figure from Douglas, 2006b).

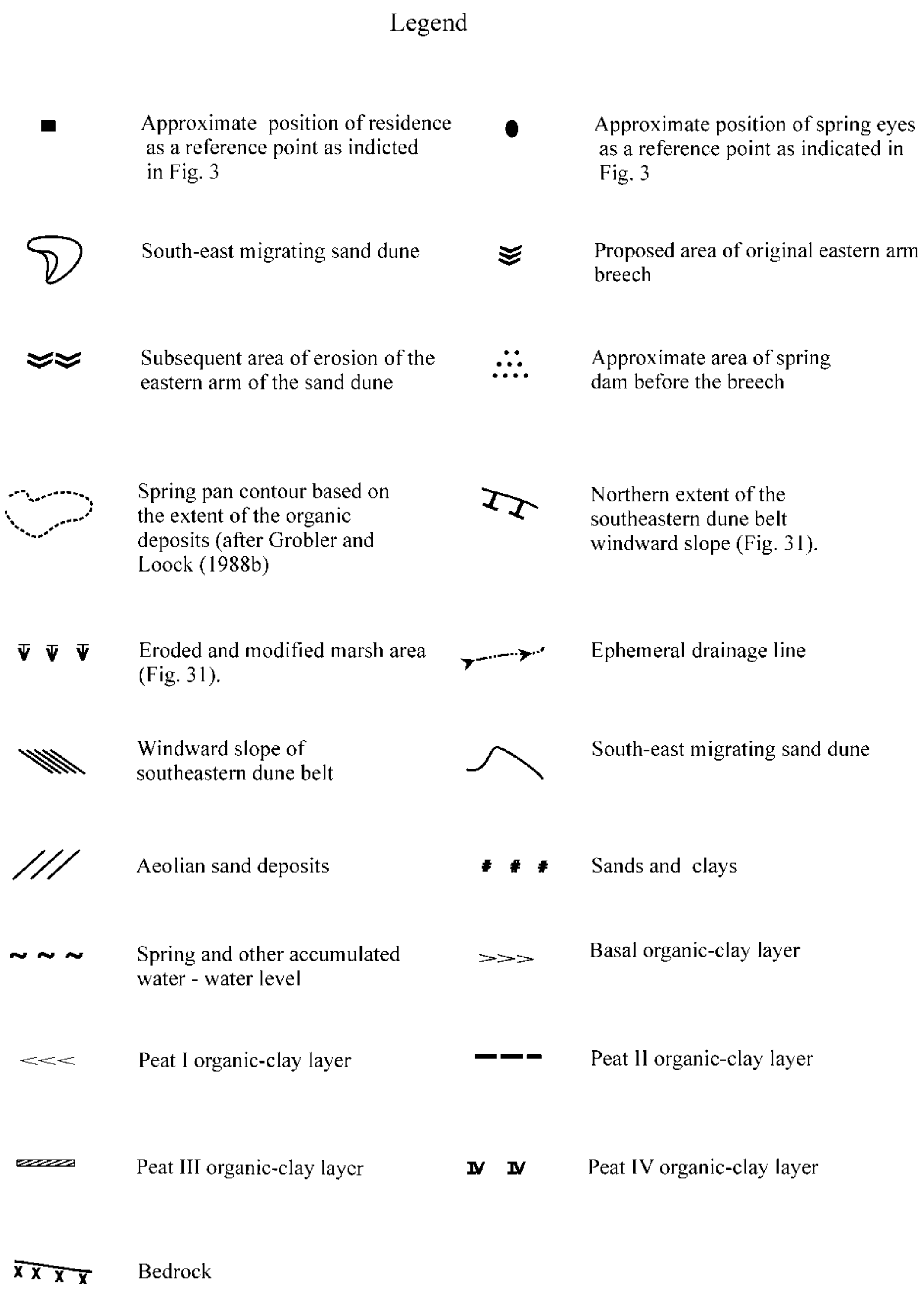

Figure 3.5: Legend for Fig 3.3 and 3.4

In the second stage the spring pan grew to a considerable size, because of the continuous deflation of Soutpan. At the same time the Florisbad dune grew in size and started to migrate in a south easterly direction, towards the spring site. The ephemeral drainage continued to supply water in to the pan during the second and third stage. However in the third stage the Florisbad dune started to migrate across the spring pan, and hindering any further expansion of the pan towards the north. This meant that the pan's growth was limited to areas east, west and south of the advancing sand dune.

During the last two stages of the development of the Florisbad site, the arms of the sand dune met with the south eastern dune belt, blocking and possible outlet to the spring water. As a result the spring pan was transformed into a dam, completely enclosed by sand dunes. The level of water in the dam started to increase due spring flow and ephemeral drainage. At the same time pressure on the arms of the dune was increasing because of the increase in sediments and height of the water. The pressure continued to build on the dune, till the eastern arm of the sand dune was breached.

Although Douglas' (2006b) alternative hypothesis for the formation of the Florisbad spring and fossil site seriously questions previous theories, it does not sufficiently address the complexity of the stratigraphy surrounding the site. Butzer (1984), Kuman and Clarke (1986), Joubert (1990), Visser and Joubert (1990) conducted studies on the stratigraphy and sedimentology of the Florisbad dune. However it is important to note that all the studies discussed below have focused on the small part (the area of spring activity) of the Florisbad sand dune, and therefore the deposits at the Florisbad spring site are poorly understood and controversial (Douglas, 2006).

Butzer (1984) described the mound as spring beds interbedded with organic intrusions and partially covered by aeolian deposits.

He understood that the site developed through spring flow, which resulted from a deep-seated regional aquifer with sand (quartz grains) originating from the underlying Ecca shale and surface dolerite through which the spring water has passed.

The organic horizons were believed to have developed during periods of low discharge, when the spring was less active, due to the fact that the vegetation would have encroached and the vegetation would later submerge when the spring was more active, with spring deposits burying the vegetation.

Visser and Joubert (1990) compared the sediments from the spring mound with those of the shoreline leading from the mound to the palaeolake complex (Van Zinderen Bakker, 1995).

Visser and Joubert (1990) proposed that a close relationship existed between the spring sediments and the lake sequence leading to the palaeolake, and therefore deposition at Florisbad was directly related to the palaeolake levels, which reflected climatic condition during deposition.

This would have involved cyclic sedimentation with soil horizons forming during dry periods, when the palaeolake levels were low. The deposition of the palaeolake bottom silt would have occurred during wet period, when the spring area was flooded by the palaeolake (Douglas, 2006a).

Through these cyclic transgression and regression sequences of the palaeolake shoreline, four low water level phases and three high water level phases since the Middle Pleistocene were recognised. Although faunal evidence (pollen) also reflect the presence of these high water bodies in the past (Van Zinderen Bakker, 1989; Visser and Joubert, 1990; Van Zinderen Bakker, 1995), Douglas (2006) still questions if this has a direct relationship with water levels in the palaeopan. It was also concluded that the organic-rich horizon around the spring vents on the mound developed due to the changes in the palaeolake level (Van Zinderen Bakker, 1989).

Although Van Zinderen Bakker (1998)'s findings have indicated changes in the palaeo lake levels, it is important to also note that not all changes in lake levels will necessary reflect change in climate. According to Hugget (1991) local conditions can cause fluctuations in lake levels which are not directly related to climate change.

For example any sudden change in drainage may cause a drastic drop in lake levels. Sometimes the change may be linked to a decrease in continental ground water as a result of an exceptional episode of rift opening and subsequent volcanism. However, studies have revealed that, in Africa, during the late Pleistocene and Holocene, there have been about six phases of climatic and environmental change (Brink, 1987; Swezey, et al. 1999; Holmgren and Shaw, 1997).

Though not all changes in lake levels reflect climate change, fluctuations of lake levels are still a good indicator of palaeoclimate variability. For example water level fluctuations in Lake Tanganyika over the last 26 000 years are in good accord with the global sea level and ice volume. "The ice level was intermediate between 26 000 and 12 000 years ago, low from 21 000 to 13 000 years ago with a minimum 18 000 years ago and a high from 13 000 years ago to present." (Hugget, 1991: 63). These lake fluctuations were in agreement with the fluctuation of African lakes north of the equator. Lake Tanganyika reflects hydrological changes in the oceans resulting from the glacial and deglacial processes and the availability of global atmospheric moisture during warmer global climatic phases.

Kuman *et al*, (1999) and Van Zinderen Bakker (1989) looked at sand grain shapes and surface features and noted that the spring sediments appear to have been derived predominantly from an aeolian source. However the sands in the lower level showed signs of water transportation, but they also appear to be originally of an aeolian nature.

Douglas (2009) noted that although in some areas the base of the dune rests on spring deposits, it does not seem possible for such large quantities of spring sand to have been available to produce a sand dune this size. Douglas (2006) proposed an alternative hypothesis for the formation of the Florisbad spring and fossil site, were he assumed that there was a division in the fluvial deposits as a result of tectonic disturbance.

"The effect of tectonic disturbances can be illustrated by an earthquake, which occurred at Fauresmith, 130 km west of Florisbad in 1912, when it was reported that the Florisbad spring discharge increased fourfold after the quake" Douglas (2005: 706). Douglas (2006b) further stated that additional wind activity would have been the key player in shifting the dune belt towards the south east.

Although the Florisbad sand dune has been previously referred to as a lunette (Brink, 1987; Loock and Grobler, 1991), no research has been carried out in order to determine the dune's actual status. Douglas (2009) noted that the Florisbad sand dune is closely related to barchanoid dunes, because it is composed of aeolian sand deposits that are originally from outside the Florisbad area. Due to a lack of information on the sedimentation, composition and structure, the dune's actual status is still undetermined, and no attempt will be made in this research to try and classify this dune.

Holmes *et al* (2008) noted that fringing lunettes in most pans, including those in the Free State Panfield are very distinct, well defined and they clearly merge with the pan margins. However Soutpan's lunettes are less common and obvious and they don't clearly merge with the pan margins. The orientation of the Soutpan lunettes was discussed in more detail in Chapter 2 (Section 2.3).

3.5. DUNE MIGRATION

This section is going to review studies that have focused on dune migration, specifically looking at the environmental and climatic factors that allow dunes to migrate. Most studies on dune migration have focused on barchans, because of their simple morphology and preserved form (Bristow and Lancaster, 2004; Yao *et al*, 2005), but in this research more attention will be given to studies that were conducted on parabolic dunes, because they are closely related to lunette dunes (Forman *et al*, 2008), which are the primary focus of this research. Tsoar *et al* (2004) have classified active dunes it three distinct groups, namely migrating, elongating and accumulating dunes.

Migrating dunes are those dunes in which the whole dune body advances with little or no change in shape and dimension. These dune types are best represented by transverse and barchan dunes. Elongating dunes are those dunes that extend in length with time; they are influenced by processes that are quite different from those affecting migrating dunes. The best representation of these dune types are linear dunes. Sand dunes with little or no net advance or elongation are classified as accumulating dunes. Star dunes are best representative of this dune type.

The difference among these dunes is determined by the index of directional variability (Tsoar *et al*, 2004). This means dunes that are formed under a bi-directional wind regime, where two main direction are about 90° apart, will only elongate with no lateral advance, lateral migrations takes place when the angle of incidence of two main directions are oblique and perpendicular respectively. Sand dunes that are affected by a wind regime that falls between that of migrating and elongating dunes can elongate with lateral advance. Several dunes that can achieve both migration and elongation simultaneously have been reported on, by Carson and Maclean, 1986; Bristew *et al*, 2000 and Tsoar *et al*, 2004.

Different studies have indicated that the type of vegetation, strength of wind, availability of sand supply and climate, are the most important factors in dune mobility, although the level of significance of each factor may vary, from one study to the next (Tsoar, 1985; Forman *et al*, 2003; Marin *et al*, 2005 and Forman *et al*, 2008).

Forman *et al* (2009) conducted a study investigating aeolian activity in the late Holocene on the southern high plains in north west Texas. One of the findings in this study was that dune systems, including lunettes in this area, show repeated reactivation within the past 4000 years with the latest dune movements sometime between ca. 1000 and 400 years ago and in the 19th century. The reactivation of these dune systems was associated with severe droughts experienced at the time.

As part of their study Forman *et al* (2009) presented new stratigraphic, pedologic and chronologic data to assess the sensitivity of aeolian systems in North America to Holocene climate variability. Optical dating of two aeolian sequences indicated similar ages for dune reaction but different ages for dune stabilization. Despite the difference in ages, there was a clear indication that sand dunes stabilize during wet periods.

Forman *et al* (2009) also concluded that the difference in timing in dune stabilization may be a reflection of different vegetation associated with each site. Since the sand dunes were covered with different vegetation, other sites were vegetated with grass while others had oaks, which are shallow rooted and readily disturbed by vegetation. Although it is highly improbable that oaks or trees would be found on lunettes, it is important to note that the vegetation of the Free State comprises Karoo shrubs (drier western parts) with trees (acacias) along water courses (Chapter 2). In other words the area around the Florisbad dune is covered with Karoo shrubs while the Florisbad dune is vegetated with trees, due to the presence of the spring.

As highlighted by Forman *et al* (2009), the difference in vegetation cover may have had an influence in stabilization and mobilization of dunes in the vicinity of Florisbad since some vegetation types can tolerate drought better than others.

Yao *et al* (2005) conducted a study on dune migration rates on the Alxa Plateau of Inner Mongolia, using remote sensing (Landsat images). The calculated dune migration rates in the Northern Alxa Plateau from 1973 to 2000 ranged from 4.0 to 7.4 m/yr. After comparing their findings with other studies that were conducted in the Taklanakan Desert a few years earlier, Yao *et al* (2005) concluded that differences in wind strength, wind direction, dune morphology and regional landforms had significant effects on the rate of dune migration.

The findings of Yao *et al* (2005) were similar to the findings of Marin *et al* (2005) and Forman *et al* (2008). Marin et al (2005) in their study concluded that larger dunes tend to migrate faster because “coalescence forms have ample sand supply for wind entertainment and less vegetation to impend saltation” (Marin *et al*, 2005; 180), and less near-surface obstruction reduces turbulence favoring laminar flow and efficient downwind transport of sand and sustained grain flow near the dune crest, enhancing migration. Forman *et al* (2008) used remote sensing and Geographic Information Systems (GIS) techniques to monitor land surface changes and to quantify dune migration at Cape Cod National Sea Shore, over the past 65 years. In that study it was noted that dunes with limited source of sand had lower total net migration as compared to others dunes with ample apparent sediments supply and no heavily vegetated surface (i.e. wetland or forest).

Marin *et al* (2005) and Forman *et al* (2009) had conclusive findings in their studies; both studies indicated that dune drift rates increase during drought and decrease with ensuing wetter intervals, indicating predominance of vegetation cover change on controlling migration.

Aerial photographic analysis of migration of eleven parabolic dunes indicated that during drier periods dune migration rates accelerated to 7m/yr, and decreased to ≤ 2m/yr during wetter interval (Forman *et al*, 2008). Although both studies had similar findings, both studies had different conclusions in terms of the primary controlling factors in dune mobility.

Marin *et al* (2005) concluded that the two primary factors in dune mobility are the interaction of vegetation cover and wind velocity, i.e. most dunes will be mobile when wind velocity increases and there is a reduction in vegetation cover. Marin *et al*'s (2005) study indicated that rates of parabolic dune migration have varied with drought state over the past ca 70 years. There was a recorded three- to six-fold increase in dune drift during pronounced drought in the 1930s, 1950s and 1990s compared to intervening wet years.

Forman *et al* (2009) provided insight into potential minimum climatic threshold for dune reactivation. According to Forman *et al* (2009)'s findings, a severe and prolonged drought of at least two years leads to a significant drop in grassland above and below ground primary productivity, leading to reduction in vegetation cover that binds the subjacent aeolian sand.

However Holmes *et al* (2008) raised an important issue that relates to lunette sedimentation in the Free State Panfield during the last few centuries. According to Holmes *et al* (2008) the recent, reactivation of lunette dune in the Free State Panfield coincides with the period of colonization of Africa by Europeans, and the introduction of farming. Holmes *et al* 2008 asked if human activities would have lead in a period of landscape instability, and inhanced aeolian activites.

3.6. CONCLUDING REMARKS

In this Chapter, an overview of the scientific literature which forms the basis of this research has been given.

Previous paleoenvironmental studies conducted in the study area have focused on a small part of the Florisbad dune (the Spring Mound), and therefore the deposits at the Florisbad spring site remain poorly understood. It is the aim of this research to contribute information about the area around Florisbad, in order to gain a better understanding of the geomorphologic landscape of Florisbad. In the following Chapter a description of the research methodology used to help achieve this aim will be presented.

CHAPTER 4: RESEARCH METHODOLOGY

4.1 INTRODUCTION

In Chapter 3 the literature around Florisbad, which is the area were this research is focused, was reviewed. This Chapter discusses the research methods that were employed in the Florisbad environment. A description of research procedure, which includes method and problems of using aerial photos to identify lunette dunes, and the detailed research methodology, will be presented. In the research methodology, the field, laboratory and statistical analysis utilised to achieve the stated aims for this dissertation are reviewed.

4.2 INITIAL IDENTIFICATION OF LUNETTE DUNES

A 1:50 000 topographic map (Sheet 2825 DB) of the region (Free State Province) and aerial photographs were used to determine the location and distribution of potential lunette dunes which might serve as part of this investigation. According to Verstappen (1977) the use of aerial photography in identification of landforms is advantageous, because it requires less deduction compared to other techniques, and due to the direct nature of interpretation (i.e. the actual landform may be seen). Verstappen (1977) also noted that this method of identifying landforms can be problematic, since one can only see the surface layer of the earth, and there is usually distortion of land forms in the photographs. In this study three dunes were selected; an outer lunette dune on the south west side of the Florisbad salt pan (28°45′ 45,5" S 26°03′12,9″E) approximately one hundred meters from the pan perimeter was chosen as the main study site. Three other locations (28°45′ 51,5" S 26°03′30,5″E; 28°46′ 00,8" S 26°03′58,9″E and 28°46′ 21,0" S 26°04′30,3″E) were chosen along the length of this south westerly lunette (Figure 4.1).

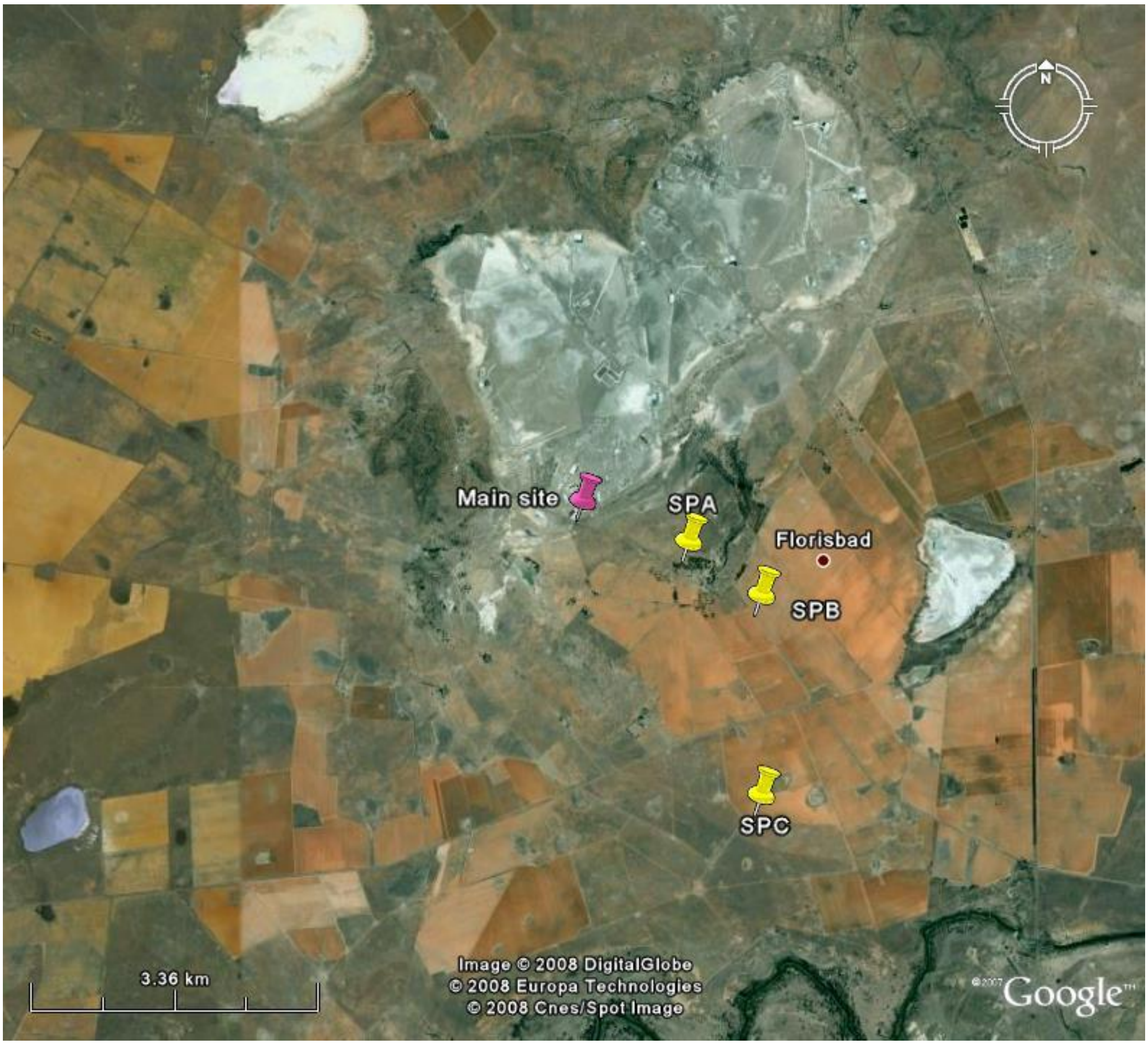

Figure 4.1 Main study site (The south western lunette) and other locations, SPA SPB, SPC, along the length of the south western lunette (source Google earth).

Two other sites included in this research are the Florisbad sand dune (28°45′ 59,0'' S 26°04′08,0″E) and another outer lunette dune that runs on the eastern side of the pan (28°45′ 50,0'' S 26°04′25,0″E). A clear description of these sites will be provided in the following Chapter.

The sites were chosen on the basis that they offered clear exposure of the sand dunes to allow adequate sampling and analysis of the sediments. However the extent of the south westerly lunette was difficult to trace due to the fact that the western side is covered or masked by young aeolian red sand.

After identifying suitable lunette dunes in the study area, ground truthing of the lunette dunes which had been identified using aerial photographs and topographical maps was undertaken. When the identification and ground truthing process was completed, detailed fieldwork was initiated. Sites were logged in the field, and sediment samples and GPS readings taken at all locations. Photographs were taken for orientation and explanation. Samples were collected from each of the three sites mentioned above. In the next section methods that were used in the field are reviewed, followed by a description of the laboratory and statistical methods that were used to analyse the collected samples.

4.3 FIELD METHODS

Before samples were taken, GPS (Global Position System) readings were recorded in order to determine the exact geographical location of each site. The outer face of an exposure in the dune was cleaned by scrapping off the exposed face. The exposed face was then photographed, and its depth was determined using a tape measure, and the colour of the sand was defined according to the Munsell Colour System (1994).

At the main study site, samples were taken every 30 centimetre (cm) down the cleaned profile, in addition three grab samples from the crest of the lunette (higher elevation relative to the pan) where taken. The two OSL samples were taken at the top and bottom of the lunette profile as indicated in Figure 2.7 (Chapter 2).

At the Florisbad sand dune, samples were taken every metre down the profile. At the eastern lunette dune, samples were taken systematically at 50, 80, 120, 140 and 160 centimetres, down the cleaned profile. The structures of these dunes have been discussed in more details in Chapter 2.

Samples were placed in zip-lock sample bags and were given unique field codes. Samples for optically-stimulated luminescence dating were also taken at the top and base of the south western lunette. For collection of OSL dating samples, the face of the lunette was cleaned and then 20 cm PVC pipes were hammered in to the exposed face of the lunette. The ends of the pipes were sealed off and shipped for laboratory analysis at the University of Sheffield, United Kingdom.

4.4 LABORATORY METHODS

In the laboratory, the zip-lock sample bags were re-numbered with simple ordered codes for ease of working. The samples were weighed to 100 g in glass beakers and dried in an oven for over 24 hours at a temperature of 70^0 C to remove water in the sediment and ensure that the analysis was carried out on a known mass of sediment (Smith and Atkinson, 1975). Preparations for particle size analysis using the sieving method, and geochemical analysis using X-ray fluorescence spectrometry (XRF) followed. A small portion of the sediments from each sample (except samples from the eastern lunette) were sent to the University of Leicester, United Kingdom, for particle size analysis using a laser particle size analyzer, because samples were presumed to be generally too clay-silty for the settling column technique (Holmes, pers. comm.). The samples from the eastern lunette dune were not sent to the United Kingdom, because they were collected at a later stage, after all the other samples had been analyzed.

At the University of Leicester, the samples were soaked in Calgon and then run through a Coulter laser sizer using ultra-sonic disaggregation both prior to and during measurement. Although a number of samples took a significant application of ultrasound before disaggregating and producing a stable peak, averaged runs from multiple sub-samples were consistent.

4.4.1 PARTICLE SIZE ANALYSIS

Particle size analysis is a very important feature in the description of sediment transformation and deposition and depositional landforms. Pitty (1997) states reasons why geomorphologists may find a knowledge of the physical properties of soils and sediments useful. Those reasons include the following:

- Sediments may develop properties characterizing their depositional environment, for example the size of sediments that are carried by wind may give an indication of the speed of that wind.
- Both soil and sediments profiles provide researchers with records of phases of erosion and stability and paleoenviromental conditions over thousands of years.

The most common method of analysing sand is to weigh 100 or 200 grams, and put it into a nest of sieves of decreasing size aperture. An automatic shaking instrument is used to obtain uniformity of treatment of each sample, which normally takes 15 to 20 minutes to sieve. This procedure helps to define the distribution of sand in terms of coarse, medium and fine sand. Particle size distribution of finer material such as silt and clay may be assessed by using the hydrometer method (King, 1966).

Soil particle size analysis is a standard procedure used to determine or distinguish various amount in size distribution of mineral particles in soil samples. Performing the procedure, three techniques were used in this research namely; the sieving method, sedimentation and laser particles size analyzer.

4.4.2 SEDIMENTATION

The sedimentation technique is based on an application of Stokes' law to a soil/water suspension and periodic measurement of the density of the suspension (http://www.dlwc.nsw.gov.au/care/soil/soil_pubs/soil_tests/pdfs/psa.pdf). The procedure has been especially useful in distinguishing between clay and sand particles. Using the hydrometer, the proportion of sand, silt and clay can be determined from the soil or sediment samples. In this research this procedure was used to determine the proportion of fines (clay and silt) versus sand.

50g from each sample was put in a glass beaker and placed in an oven overnight to dry at a temperature of 70^0 C. A 10ml calgon (sodium hexamethaphosphate) solution, prepared by mixing 50g of calgon powder and 1 liter of distilled water in a glass flask, was added to each glass beaker to disperse the sediments and ensure that grains remain detached from one another (Black *et al*, 1965).

The glass beakers were then placed in a shaker for 12 hours, and then the fines (silt and clay) were washed away using running water in a 3 Ø sieve and dried again in an oven. The washed sand was used to determining the distribution in size of the sand particles in more details.

4.4.3 THE SIEVING METHOD

In this process the remaining portion comprises washed sand. The samples were re-weighted in order to calculate the total percentage of silt and clay that had been washed out. Sediment samples were then emptied into the stack of sieves and shaken using a mechanical shaker.

The three sieves sized 2Ø for coarse sand; 1Ø for medium grained sand and a collecting pan for fine sand were used to separate particles of different sizes. Sediments collected at each sieve were weighed and the proportion of particles in sediments determined. Measurements were recorded according to the guidelines of soil classification (http://www.geog.ucl.ac.uk/lab/partsize.htm).

4.4.4 pH Readings

Soil pHs have an extreme range of 2 to 11, but most soils pH's range from 5 to 9 (Birkerland, 1999). Soil pH is dependent on the ionic H^+ content and concentration in both the soil solution and the exchangeable cation complex adsorbed to the surface colloids.

The measurement of pH is useful in weathering and in vegetation studies, since it forms one of the most comprehensive single summaries of the chemical condition of soils. For example "change of pH in relation to time of exposure of depositional land forms are particularly note-worthy (Pitty, 1997: 12)."

pH or hydrogen activity measures the concentration of H^+ and OH^- ions in an aqueous solution. This is significant as it can serve to indicate the overall condition of the soil as a function of soil climate. It can also indicate potential leaching between the soils (Smith and Atkinson, 1975), and thus provide an indication of processes which might have occurred since the time of deposition. In this case approximately 10 g of each sediment sample was poured into separate glass beakers and mixed with distilled water. An automated electronic multimeter, designed to read directly the pH units, was calibrated using a buffer solution of 0.01 mol $CaCl_2$ to the pH of 7 which is the balanced level of H^+ and OH^- in a neutral solution (Smith and Atkinson, 1975).

A rod with the sensor on its end was submerged in the sample suspensions and readings were recorded. A separate glass beaker with distilled water was continuously used for cleaning and stabilization of the measuring glass rod during use.

4.4.5 Conductivity Readings

From the same sample used to determine the pH readings, electrical resistance readings were determined. This was done to measure the presence of soluble salts (conductivity) in the soil samples in order to provide an indicator of the concentration of salts (King, 1966). Obtained readings were then recorded for analysis and interpretation. Utilizing the multi meter adjusted for conductivity measuring, a 0.02mol $AgNO_3$ buffer solution was used to calibrate the instrument for the procedure.

Readings were calculated with the sensor in the instrument rod and noted for each sample. Similar to pH readings, the instrument was continuously submerged in distilled water in order to keep the sensor clean and operable.

4.4.6 Geochemical Analysis

Geochemical analysis was done to determine major elements through X-ray fluorescence (XRF) spectrometry, on briquettes of powdered whole sample. XRF is a non-destructive, rapid, quantitative multi-element technique used to identify and determine the concentrations of elements present in solid, powdered and liquid samples.

To prepare samples for XRF analysis, dry sieving was undertaken and the ≤0.212 mm portions of sediments were retained. The retained portion of the sample was then ground to an ultra-fine powder using a milling instrument.

The major elements determination fusion discs were prepared by mixing 0.02g of sodium nitrate, 1.5g spectro flux and 0.28g of powder sample before introducing the sample into the XRF machine. The machine then presents the results as percentages.

Figure 4.2 XRF Spectrometer used to analyze samples

4.4.7 OPTICALLY STIMULATED LUMINESCENCE DATING

Optically stimulated luminescence (OLS) is a method of dating quartz and feldspar sediments found in depositional environments, such as the region in this study. Luminescence dating is a Quaternary dating method used to determine the age of a sample. This method was introduced in the 1960s for dating pottery.

It was only in 1979 that this method was introduced and applied to dating geological sediments (McKeever, 1985). This method can produce ages from a few hundred years up to almost a million years. However it is important that there was adequate exposure of minerals grains to sunlight before they were buried (Lian and Huntley, 2002; Lang and Glade 2007).

This method is based upon the fact that naturally occurring minerals such as quartz and feldspars can acts as dosimeters, recording the amount of radiation that they are exposed to. The resulting radiation damage within these minerals remains as structurally unstable electron traps within the mineral grains. Exposure to light or heat resets the luminescence signal, which allows for calculation of the time period since the sediment was last exposed to sunlight (burial). For a more detailed description of the application of OSL dating techniques in southern Africa, the reader is referred to Lowe and Walker, 1984; Botha *et al*, 1994; and Bateman *et al*, 2003 who all conducted studies in southern Africa using this method. A brief summary of procedures that were employed when analysing samples for ages is provided in Appendix A (Quartz Optical Dating Report).

4.5 Multivariate Statistical Analyses

Multivariate statistics is a form of statistics encompassing the simultaneous observation and analysis of more than one statistical variable. Two different multivariate statistical analyses were conducted in order to classify the data from Florisbad south western outer lunette (9 samples), 8 samples from Florisbad spring mound and 5 samples from the eastern lunette dune.

The methods were employed to ascertain how different variables within dune environment relate to each other. The statistical analyses were conducted using the computer package STATISTICA, and two main techniques were employed, namely principal component analysis (PCA) and cluster analysis.

4.6 Concluding Remarks

The research procedure and methods that were used in this investigation have been reviewed in this Chapter. The identification of lunette dunes using topographical maps and aerial photographs was discussed, as well as methods that were used to collect sediments so as to generate and analyze the required data. In the following Chapter, the analytical results of the field, laboratory and statistical components of this research will be presented.

Chapter 5: Results

5.1 Introduction

The research methods that were employed in the Florisbad environment to achieve the stated aims for this dissertation were discussed in Chapter 4. The site description, indicating *inter alia* where sediments were collected, was given in Chapter 2. In this Chapter the results that were obtained following the laboratory analysis of sediments samples are presented. The results include the following; results of particle size analysis, the results from the chemical analysis (i.e. pH, conductivity and chemical composition analysis) and the results of the optically stimulated luminescence dating (OSL) procedure are presented. Finally, the statistical results obtained from multivariate analysis of the data will be presented.

5.2 Particle Size

Since two different methods for particle size analysis were used in this research, two sets of results are presented in the Tables, Table 5.1 and 5.2. Table 5.1 presents the results obtained using a laser particle size analyzer. The results from the laser analyzer show that all the samples from both the lunette dunes and the Florisbad dune comprise mainly silt (more than 75%), with the exception of two grab samples (SPB and SPC) which were taken along the length of the south western lunette, which consisted mainly of sand.

However the sedimentological results (Table 5.2 and Figure 5.2a) from the wet and dry sieving procedure indicates that all samples consist primarily of sand (more than 60%) with an exception of one sample from the Florisbad dune (FB10) and two samples from the eastern lunette dune (EL4 and EL5).

Figure 5.2 shows that 90% of the sand from all samples is fine sand.
The significance of these findings, together with an explanation as to why different methods of particle size analysis gave different results, will be presented in the next Chapter.

The entire range of sediment samples from all three sites is poorly sorted. The samples from the Florisbad sand dune are negatively skewed, while the samples from the lunette dunes are very negatively skewed. The negative values of skewness indicate that the distribution of sediments in both dunes has a more pronounced tail of coarse particles or deficiency of finer sediments in relation to the mean particle size. With exception of one sample from the Florisbad sand dune (FB 10), which is mesokurtic all other sample's kurtosis is platykurtic (Table 5.1).

Figure 5.1 Location of all three study sites.

Table 5.1 Particle size and graphic statistics for sediments fraction (refer to Appendix B for key site names)

				Moments				
Sample Code	**% Sand**	**% Silt**	**% Clay**	**Mean**	**Median**	**Sorting**	**Skew**	**Kurtosis**
SP1	0.0	86.5	13.5	5.96	5.52	poorly sorted	very negatively skewed	platykurtic
SP2	1.5	85.3	13.1	5.97	5.66	poorly sorted	very negatively skewed	platykurtic
SP3	3.0	77.2	19.8	6.39	6.22	poorly sorted	negatively skewed	platykurtic
SP4	6.2	80.7	13.1	5.96	5.67	poorly sorted	very negatively skewed	platykurtic
SP5	1.1	82.2	16.7	6.23	5.99	poorly sorted	negatively skewed	platykurtic
SP6	0.0	87.1	12.9	6.00	5.62	poorly sorted	very negatively skewed	platykurtic
SPA	5.6	77.0	17.4	6.22	6.05	poorly sorted	negatively skewed	platykurtic
SPB	78.5	17.8	3.7	3.45	3.05	poorly sorted	very negatively skewed	very leptokurtic
SPC	74.3	20.6	5.2	3.82	3.19	poorly sorted	very negatively skewed	very leptokurtic
FB1	7.6	78.7	13.8	5.99	5.79	poorly sorted	negatively skewed	platykurtic
FB2	8.1	79.1	12.9	5.92	5.69	poorly sorted	negatively skewed	platykurtic
FB3	6.8	79.8	13.4	6.00	5.77	poorly sorted	negatively skewed	platykurtic
FB4	1.6	83.2	15.2	6.09	5.83	poorly sorted	negatively skewed	platykurtic
FB5	8.6	74.4	16.9	6.14	5.96	poorly sorted	negatively skewed	platykurtic
FB6	9.1	75.6	15.4	6.02	5.86	poorly sorted	negatively skewed	platykurtic
FB10	0.0	68.2	31.8	7.04	6.99	poorly sorted	negatively skewed	mesokurtic

Table 5.2 Particle size, sand distribution and colour properties (refer to Appendix B for key site names).

				Sand distribution		
Sample	**% Clay and silt**	**% Sand**	**% Coarse**	**% Medium**	**% Fine**	**Munsell Colour**
SP1	25.78	74.22	0.78	4.26	94.96	5YR 6/3
SP2	33.46	66.54	0.06	2.1	97.86	2.5Y 4/5
SP3	40.86	59.14	0.61	7.14	92.26	5YR 4/1
SP4	36.38	63.62	0.50	5.16	94.34	10YR 4/2
SP5	33.06	66.94	0.47	4.48	95.01	10YR 4/3
SP6	26.36	73.64	0.46	8.31	91.25	5YR 6/2
SPA	47.46	52.54	0.61	5.52	93.72	5YR 5/4
SPB	11.76	88.24	0.57	9.38	90.05	5YR 5/3
SPC	8.26	91.74	0.26	4.95	94.76	2.5YR 4/8
FB1	21.2	78.8	0.32	7.36	92.32	10R 4/3
FB2	22.46	77.54	0.67	7.27	92.06	10R 4/3
FB3	21.04	78.96	0.38	7.52	92.09	10R 4/3
FB4	18.44	81.56	1.42	7.18	92.77	7.5 YR 4/3
FB5	18.28	81.72	0.24	8.49	91.26	7.5YR 4/3
FB6	28.28	71.72	1.06	8.28	90.66	7.5YR 4/3
FB10	42.22	57.78	2.04	0.00	97.96	5 R 4/2
EL1	20.62	79.38	0.60	1.70	97.70	7.5YR 5/4
EL2	24.36	75.64	0.35	1.50	98.15	7 YR 5/2
EL3	52	48	1.95	2.90	95.15	10R 4/3
EL4	54.02	45.98	5.45	3.05	91.50	10R 3/6
EL5	42.52	57.48	1.20	2.05	96.75	5R 4/3

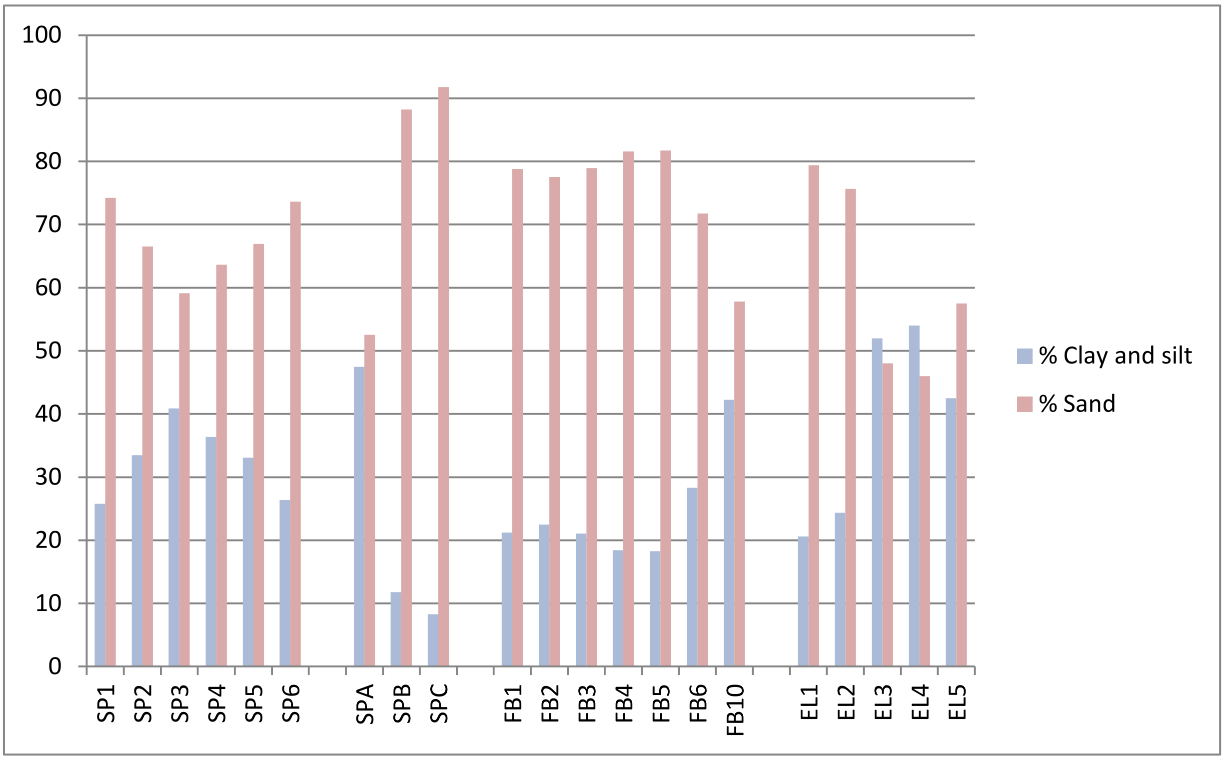

Figure 5.2 (a) Distribution of sediments in terms of fines (clay and silt) and sand (refer to Appendix B for key site names)

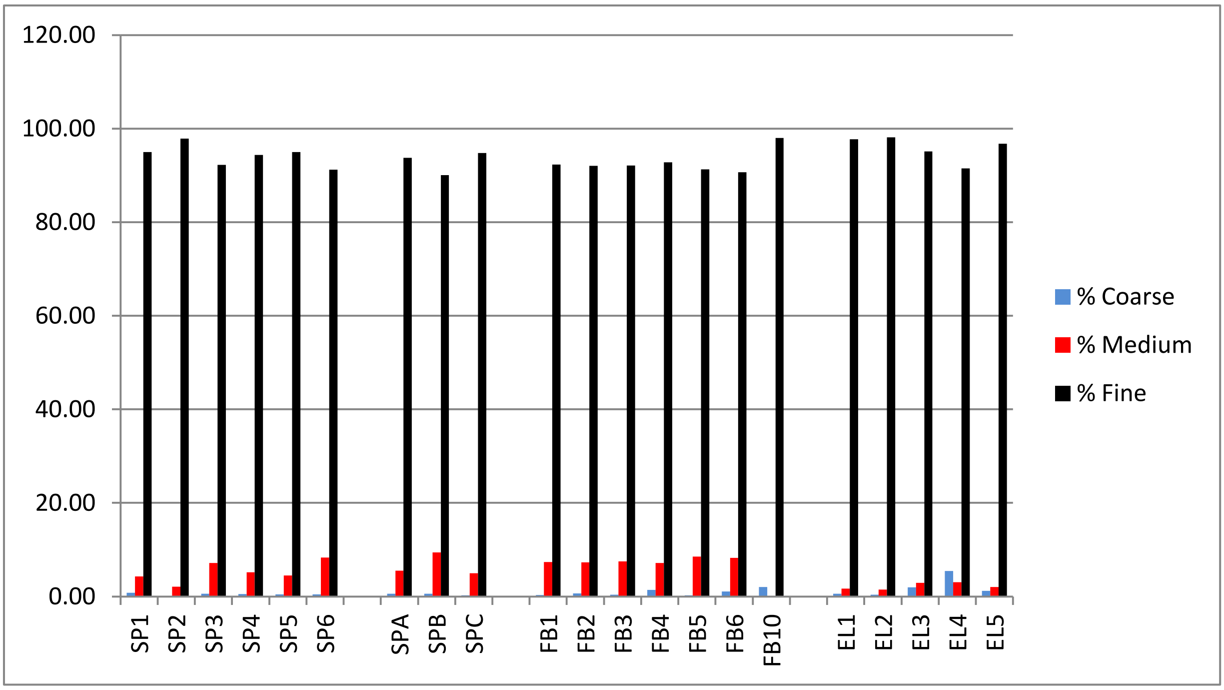

Figure 5.2 (b) Distribution of sand in terms of coarse, medium and fine sand (refer to Appendix B for key site names)

5.3 pH AND CONDUCTIVITY RESULTS

pH ranges between 7-9, meaning the pH level is neutral to alkaline in all the sediments from the lunette dune and the Florisbad sand dune. The conductivity levels for the borehole samples from the Florisbad sand dune range from 50 - 300 µs, with the exception of one sample, (FB10) that has a conductivity value of 1340 µs.

The conductivity values of the samples from the lunette dune are slightly higher, with the exception of one sample from the eastern lunette dune which has an extremely high conductivity value (9000 µs) compared to the others. The grab samples from the lunette dune have the lowest conductivity values ranging from 20 µs to 200 µs. Figure 5.3a- 5.5b show the pH and conductivity values for each site. In all the sites there are no obvious major trends for either pH or conductivity.

Table 5.3 pH and conductivity values (refer to Appendix B for key site names).

Sample	pH Value	Conductivity (µs)
SP1	8.70	70
SP2	9.1	110
SP3	8.60	4780
SP4	9.10	8960
SP5	8.80	4120
SP6	9.10	2850
SPA	9.30	200
SPB	8.60	80
SPC	7.30	30
FB1	7.70	50
FB2	7.80	140
FB3	8.00	90
FB4	8.10	150
FB5	8.10	180
FB6	8.10	300
FB10	7.70	1340
EL1	7.90	3400
EL2	8.00	120
EL3	7.60	9000
EL4	8.40	3760
EL5	8.20	42.20

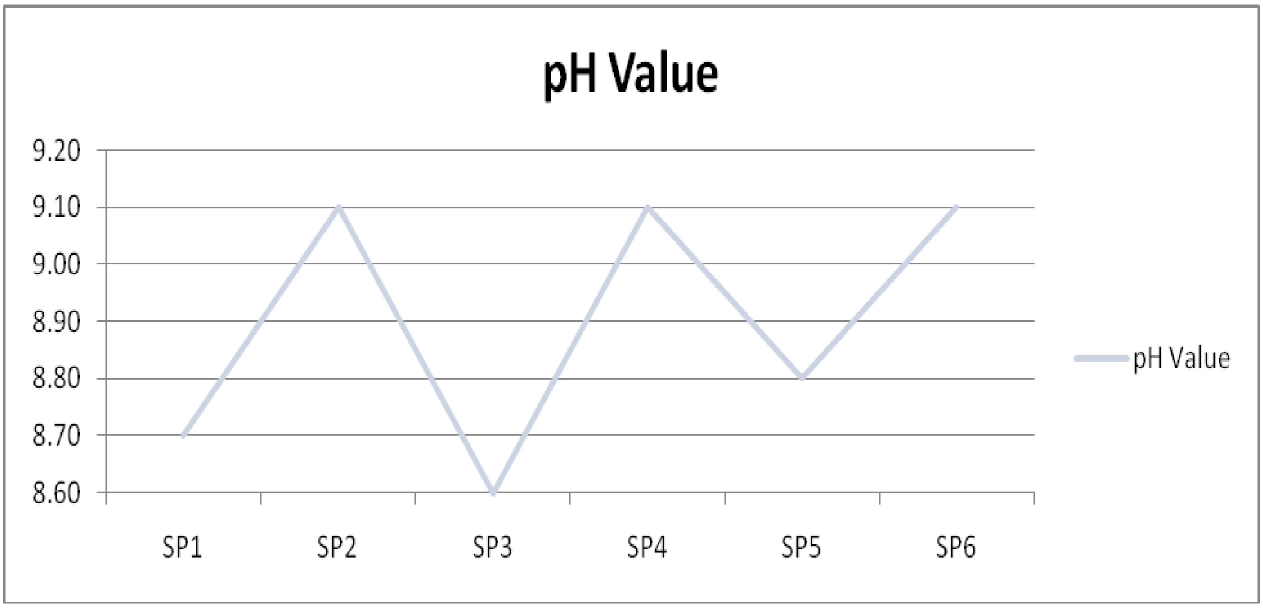

Figure 5.3 (a) pH values for the south western lunette dune

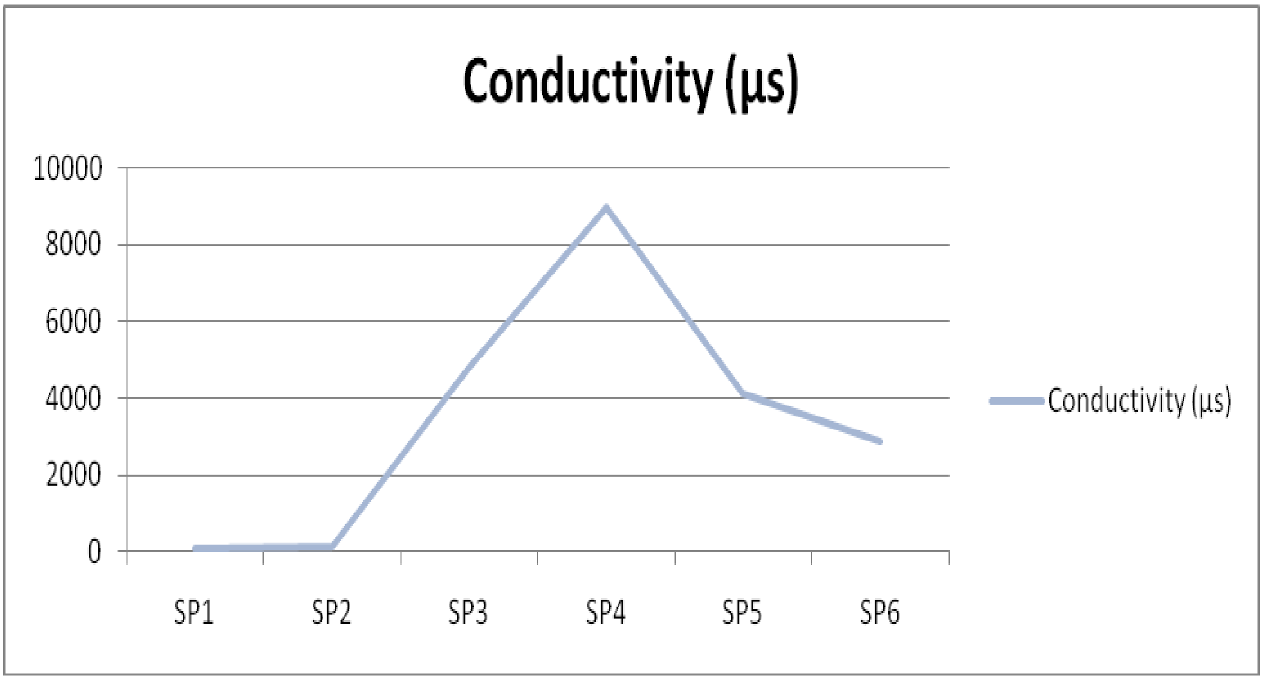

Figure 5.3 (b) Conductivity readings for the south western lunette dune

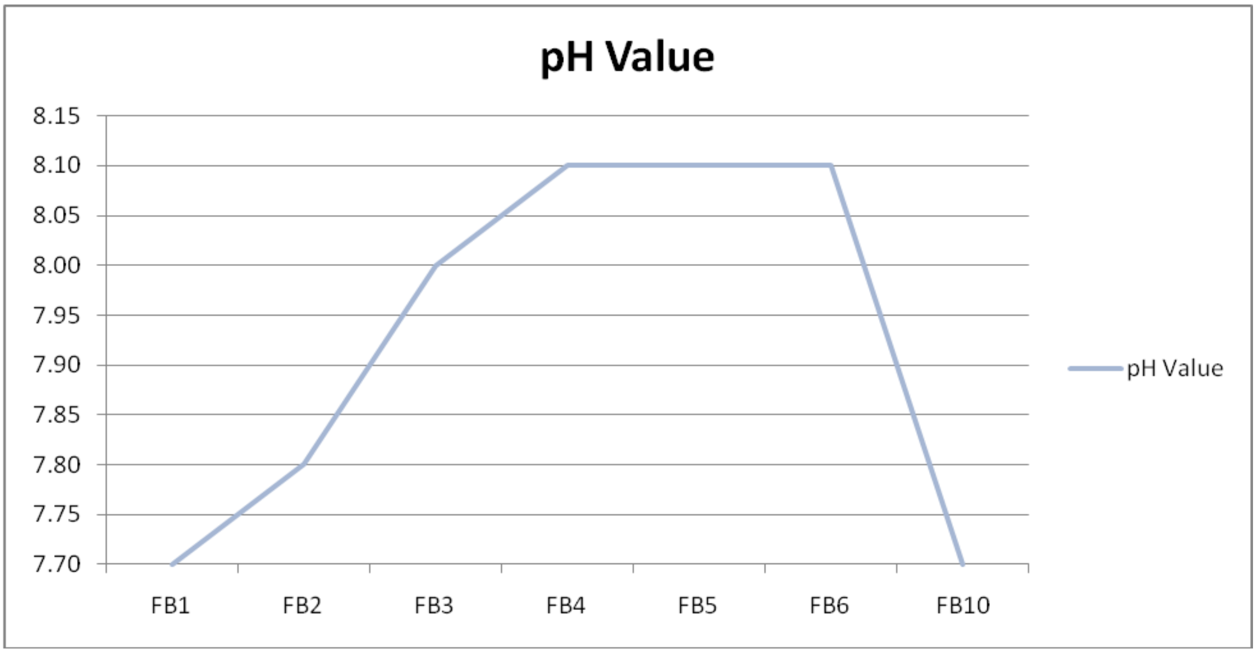

Figure 5.4 (a) pH values for the Florisbad sand dune

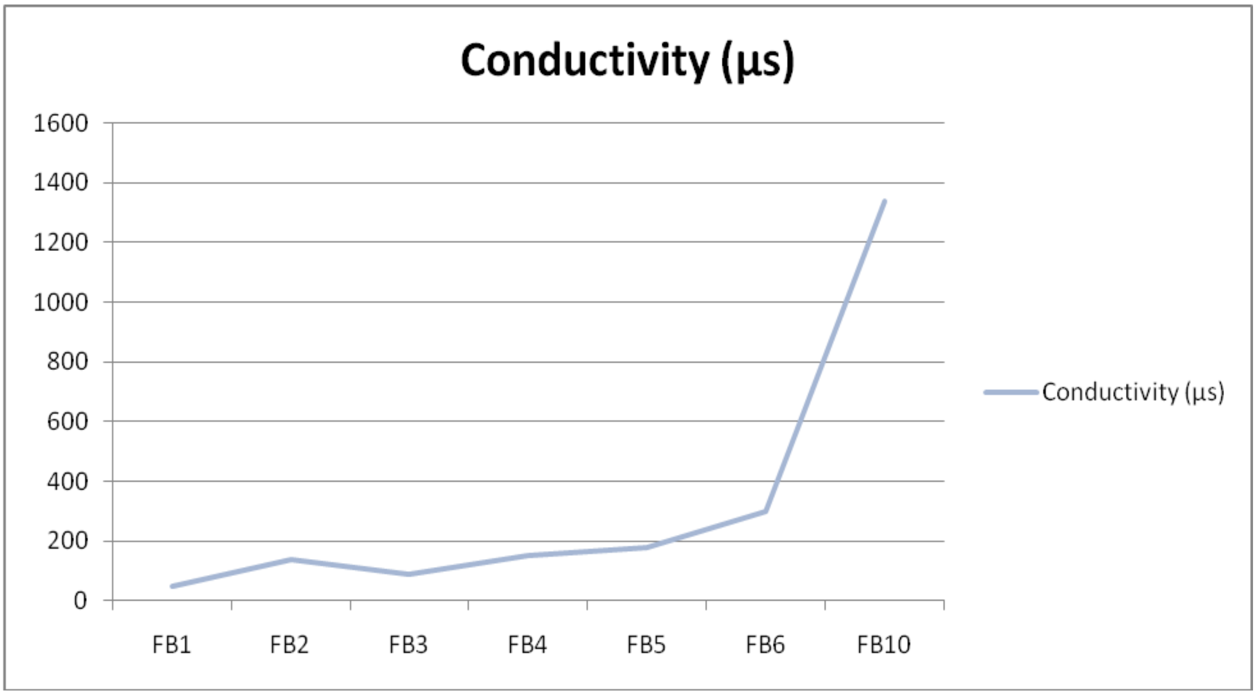

Figure 5.4 (b) Conductivity readings for the Florisbad sand dune

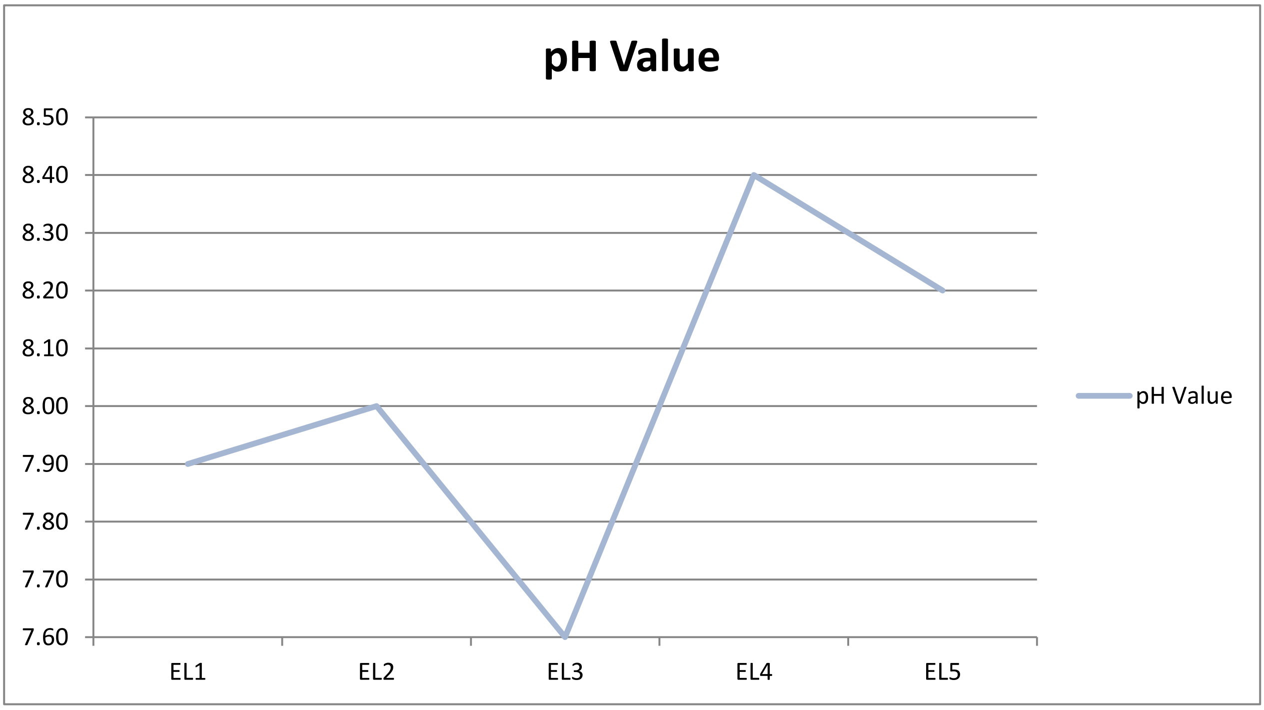

Figure 5.5 (a) pH values for the eastern lunette dune.

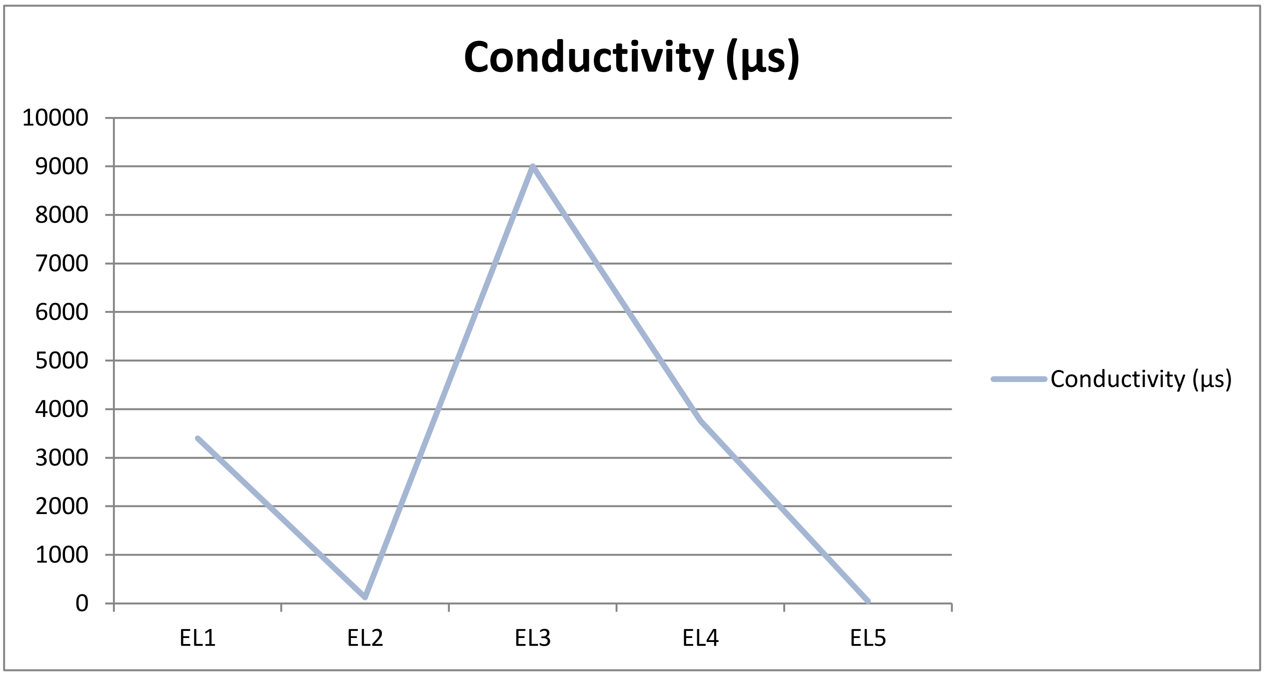

Figure 5.5 (b) Conductivity readings for the eastern lunette dune

5.4 Chemical Composition Analysis

The chemical composition results (Table 5.4) clearly shows that silicon dioxide (SiO_2) is the most abundant mineral comprising all the samples. This implies that all the sediment (from the lunettes and the Florisbad sand dune) are derived from a silica-rich source. Aluminum oxide (Al_2O_3) and iron oxide (Fe_2O_3) are the second-most abundant compounds in all the samples. Figure 5.6 shows that the samples from the lunettes and the Florisbad sand dune are almost identical in terms of their chemical composition. However Figure 5.7 indicates minor differences between the samples from all the sites. In Figure 5.7 it is clear that samples from the lunettes contain slightly more MgO, CaO, K_2O and Na_2O, than the borehole sample from the Florisbad sand dune. The significance of these findings will be discussed in the following Chapter.

Table 5.4 Percentage of the minerals found within the sediments samples.

Sample code	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5
SP1	82.61	5.80	3.28	0.05	1.66	4.07	0.63	1.11	0.71	0.71
SP2	81.84	5.61	3.24	0.06	1.93	4.10	0.34	1.08	0.69	0.06
SP3	76.96	8.04	4.33	0.07	2.34	4.71	1.25	1.57	0.63	0.11
SP4	81.15	6.61	3.49	0.05	1.80	4.26	0.52	1.34	0.71	0.07
SP5	78.40	6.94	4.00	0.06	1.23	5.52	1.28	1.34	0.56	0.08
SP6	78.72	8.01	3.80	0.07	2.09	4.41	0.65	1.63	0.56	0.09
SPA	75.88	10.42	5.22	0.78	1.94	3.19	0.56	1.22	0.84	0.04
SPB	85.93	4.85	3.96	0.05	1.24	1.88	0.40	0.79	0.86	0.04
SPC	90.84	3.61	2.40	0.03	1.28	0.41	-0.01	0.76	0.65	0.02
FB1	87.74	5.28	3.30	0.47	0.91	0.87	0.13	0.99	0.70	0.32
FB2	88.20	5.20	3.35	0.06	0.97	0.89	-0.37	1.00	0.66	0.03
FB3	88.48	5.22	2.98	0.04	0.75	0.84	-0.06	1.00	0.70	0.03
FB4	88.39	4.61	2.89	0.36	0.86	1.57	0.04	0.95	0.62	0.03
FB5	88.41	4.64	2.91	0.04	0.80	1.51	-0.03	0.95	0.65	0.04
FB6	84.71	10.35	3.53	0.05	1.08	1.20	0.64	1.39	0.67	0.06
FB10	79.31	9.76	5.11	0.29	1.23	1.18	0.36	2.32	0.66	0.03
EL1	88.89	4.00	2.25	0.04	0.78	1.43	0.16	0.89	0.91	0.04
EL2	88.22	4.63	2.42	0.05	0.48	0.94	0.15	1.02	0.77	0.03
EL3	77.49	9.97	5.25	0.05	1.59	1.42	1.34	1.97	0.64	0.04
EL4	67.42	8.79	4.45	0.05	2.43	13.50	0.87	1.58	0.59	0.04
EL5	79.62	7.55	4.29	0.05	1.23	3.50	0.84	1.58	0.81	0.04

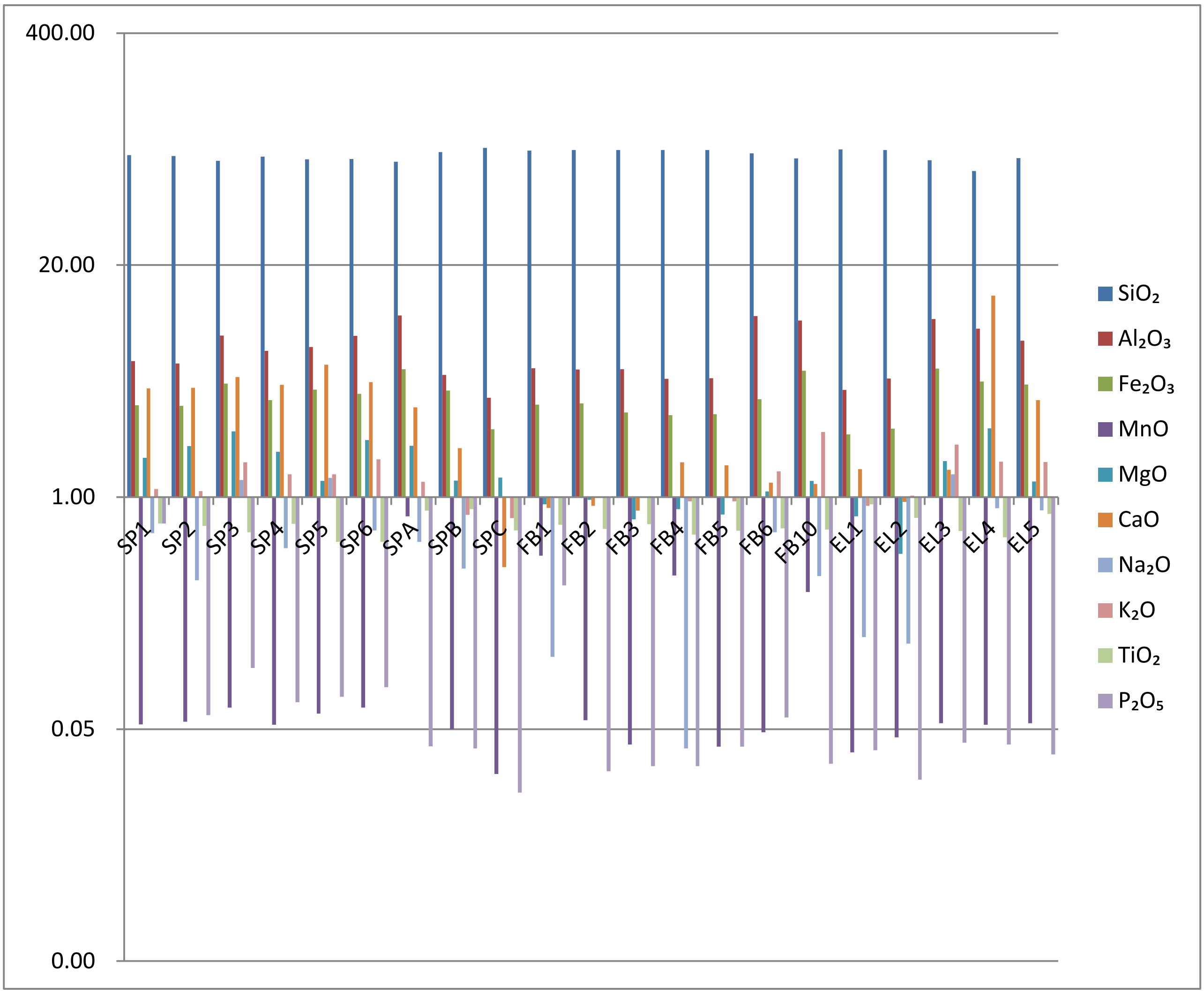

Figure 5.6 Distribution of all the minerals found within the sediments (refer to Appendix B for key site names).

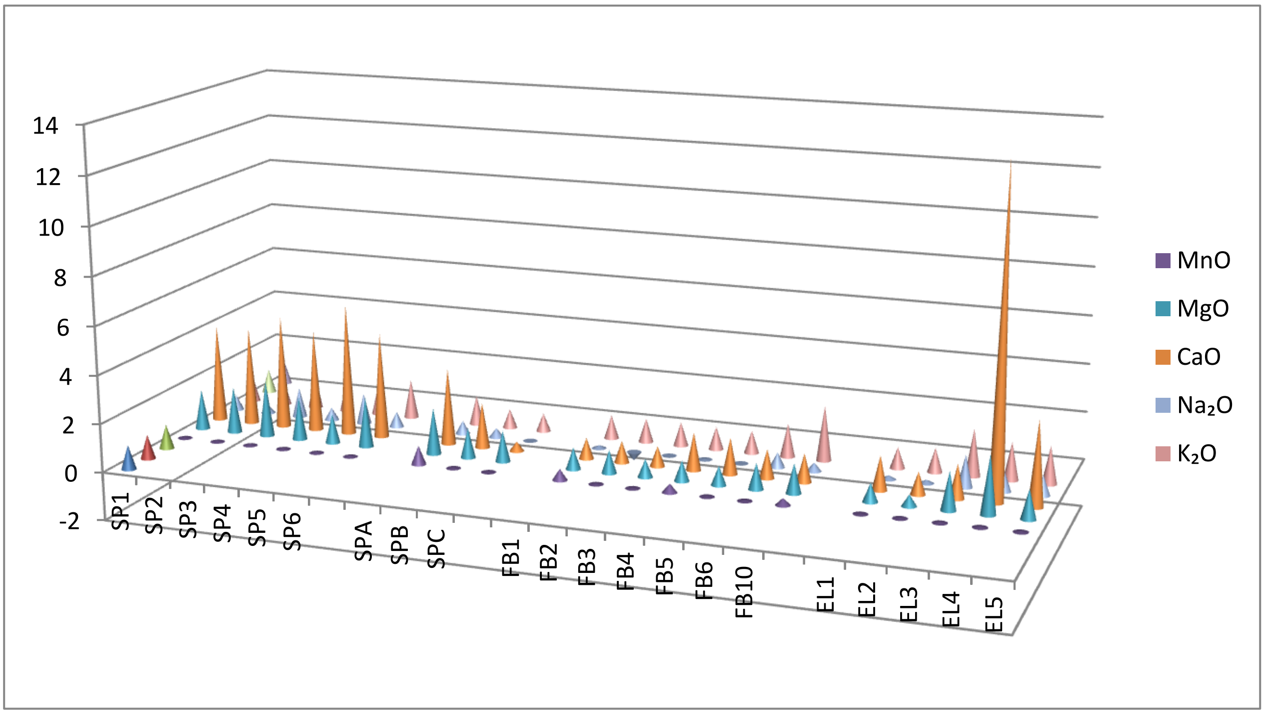

Figure 5.7 (a) Distribution of some of the minerals found within the sediments (refer to Appendix B for key site names).

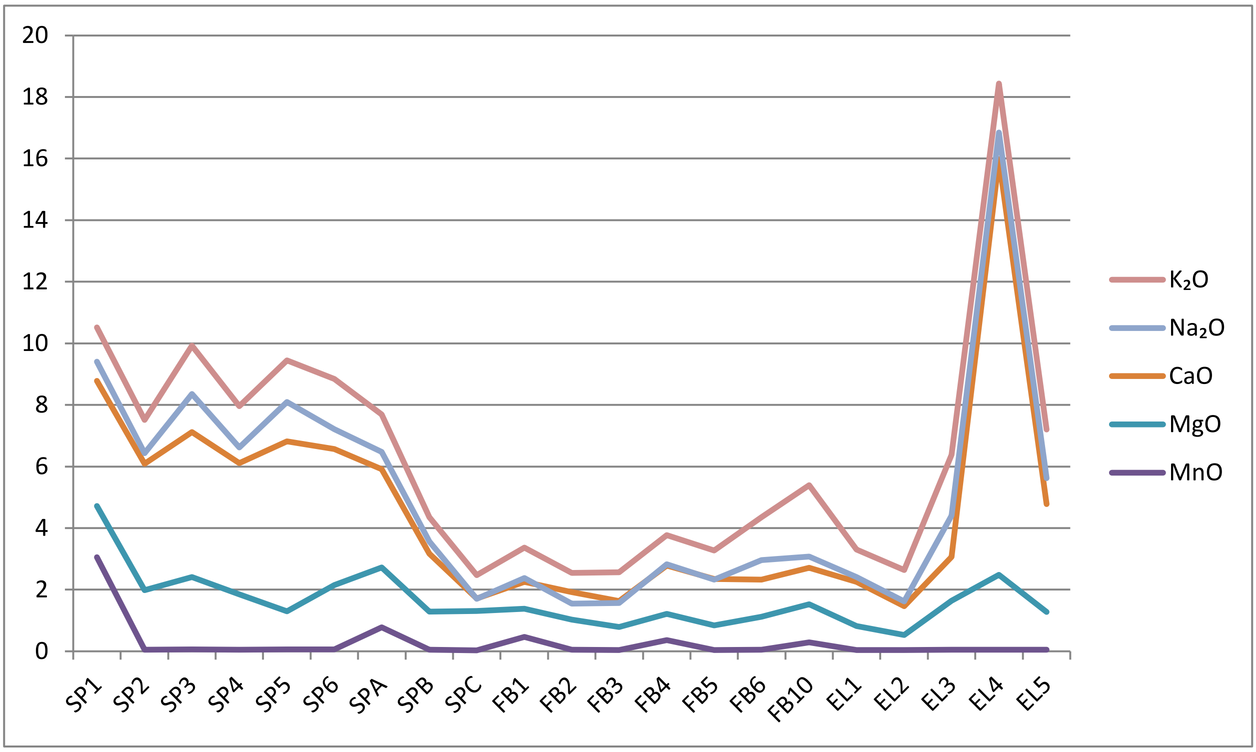

Figure 5.7 (b) Distribution of some of the minerals found within the sediments (refer to Appendix B for key site names).

5.5 Optically Stimulated Luminescence Results

The results for the two samples subjected to optically stimulated luminescence (OSL), dating are given in Table 6.5 below. These samples all responded well to laboratory radiation, they were both bright and sensitive and appeared to behave well when undergoing OSL measurement (Bateman, 2010). Analysis of replicates of sample palaeodoses indicated no appreciable scatter and from this it is concluded that the samples' OSL signals were fully reset prior to burial (Refer to appendix C). The best estimates of the burial ages range from 0.57 ± 0.04 ka to 0.28 ± 0.04 ka. These ages simple imply that the lunette dunes near Florisbad were probably active aeolian features during the recent 500 to 200 hundred years.

Table 5.5 optically stimulated luminescence dating results for the south western lunette dune

Lab Code	Field Ref	Depth (cm)	De (Gy)	Dose rate (μGy/a⁻¹)	Age
Shfd10078	SP2	50	148.7±3.7	1582±71	0.28±0.04
Shfd10079	SP6	180	139.4±4.4	2159±107	0.57±0.04

5.6 Statistical Results

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

5.6.1 Principal Component Analysis

Table 5.5 shows the results of the first PCA test that was run on samples from the south western lunette and the Florisbad dune. The results show that most of the variance is explained by three factors, factor 1, at 54% explains most of this proportional variance.

Table 5.6 indicates that the components mean, median, kurtosis, fine, clay and silt, all display loadings >0.7. The PCA therefore shows that the variance in factor 1 is explained by parameters which are mostly related to grain size, thus indicating that grain size is an important determining variable when attempting to distinguish samples, in an aeolian environment. Factor 3 has no loading with scores >0.7, while in the case of factor 2, pH has a component loading of 0.82. pH is an indicator of possible leaching within a soil or sediments profile, and therefore may be regarded as significant when investigating processes in sem-arid areas.

When the unrotated PCA (Table 5.6) is compared to the rotated PCA (Table 5.7) there is very little difference between the two sets of results, and therefore all the other statistical tests were conducted on the unrotated PCA results only.

Table 5.8 shows the second PCA test that was run on all the samples from the study area. It shows that most variance is explained by three factors and that factor 1 at 50% represent most of this proportional variance. The highlighted minerals (Table 5.8) display component loadings of >0.7. The PCA shows that the above highlighted components appear to be significant for distinguishing between samples, in this semi-arid area. There was also little difference between the unrotated and rotated PCA, and therefore the rotated results loadings are not presented.

Table 5.6 PCA unrotated factors loadings for the south western lunette and the Florisbad dune.

	Factor	Factor	Factor
	1	**2**	**3**
Mean	**-0.916135**	0.255408	-0.190297
Median	**-0.921867**	0.281005	-0.187440
Sorting	-0.528274	0.671326	0.215821
Skew	**-0.821743**	0.378805	-0.312172
Kurtosis	**0.803281**	-0.177687	0.476452
Clay and silt	**-0.922617**	-0.279488	0.207691
Sand	**0.922617**	0.279488	-0.207691
Coarse	-0.164959	0.530471	0.468282
Medium	0.637640	0.157855	-0.568418
Fine	**0.915743**	0.275254	-0.126766
pH value	-0.371673	**-0.827968**	-0.189245
Conductivity	-0.393270	-0.541688	0.009384
Expl.Var	6.556365	2.287208	1.123012
Prp.Totl	0.546364	0.190601	0.093584

Table 5.7 PCA rotated factors loadings for the south western lunette and the Florisbad dune.

	Factor	Factor	Factor
	1	**2**	**3**
Mean	**0.966005**	0.087030	0.003040
Median	**0.975453**	0.111200	0.007813
Sorting	0.577108	0.657207	-0.106561
Skew	**0.925862**	0.161371	0.181511
Kurtosis	**-0.909496**	0.085203	-0.263431
Clay and silt	**0.784625**	-0.252452	-0.541389
Sand	**-0.784625**	0.252452	0.541389
Coarse	0.146380	0.654324	-0.279880
Medium	-0.451429	-0.021265	**0.741863**
Fine	**-0.797329**	0.279096	0.465609
pH value	0.249437	**-0.864441**	-0.223628
Conductivity	0.276310	-0.526607	-0.307431
Expl.Var	6.132920	2.143684	1.689982
Prp.Totl	0.511077	0.178640	0.140832

Table 5.8 PCA unrotated factors loadings for all dunes in the study area.

	Factor 1	Factor 2	Factor 3
SiO_2	**-0.965609**	0.077075	0.092058
Al_20_3	**0.860850**	0.364712	0.101561
Fe_2O_3	**0.864232**	0.404560	0.012285
MnO	0.128837	**0.739041**	-0.432627
MgO	0**.799151**	-0.268453	-0.253399
CaO	0.676788	-0.507156	-0.191871
Na_2O	**0.823644**	-0.134292	-0.009801
K_2O	**0.810983**	0.186522	0.317289
TiO_2	-0.363570	0.458255	-0.361950
P_2O_5	0.002448	-0.272418	**-0.773285**
Expl.Var	5.001914	1.515114	1.136878
Prp.Totl	0.500191	0.151511	0.113688

6.6.2 CLUSTER ANALYSIS: SINGLE LINKAGE

Two types of cluster analyses were undertaken, namely single linkage and Ward's clustering. In the single linkage cluster analyses, two main clusters were evident in all Euclidian distance tree diagrams. In Figure 5.8 EL4 and FB6 have been identified as outliers and FB6 is also identified as an outlier in Figure 5.9. In Figure 5.9 SP4, SP6 and FB10 are outliers. The strongest clustering is evident in Figure 5.8.

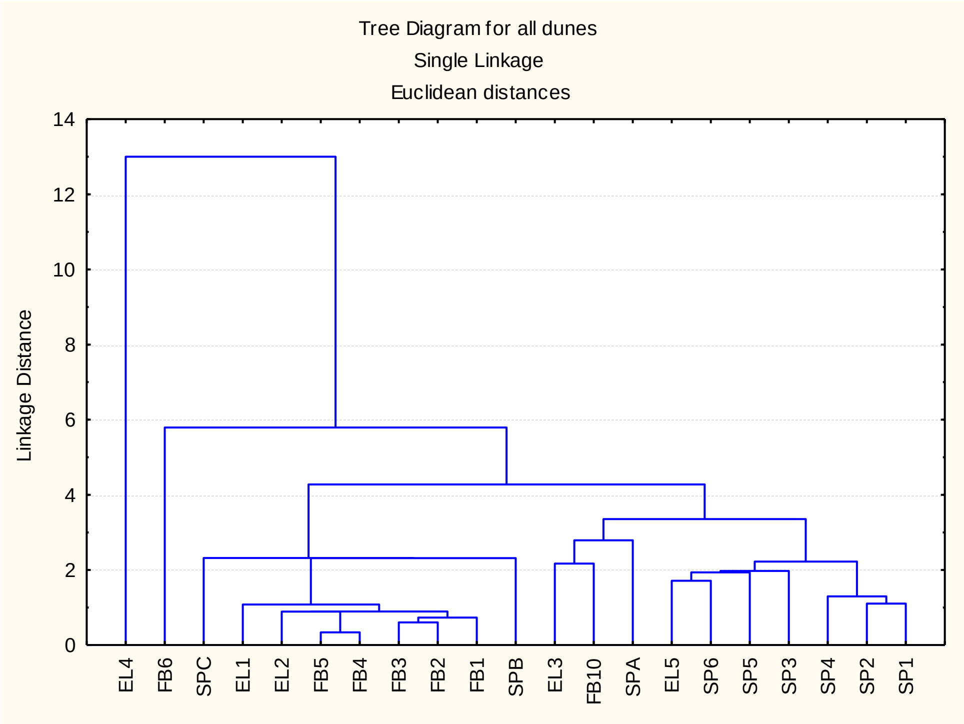

Figure 5.8 Clustering of the diagram for the samples from all the dunes in the study area.

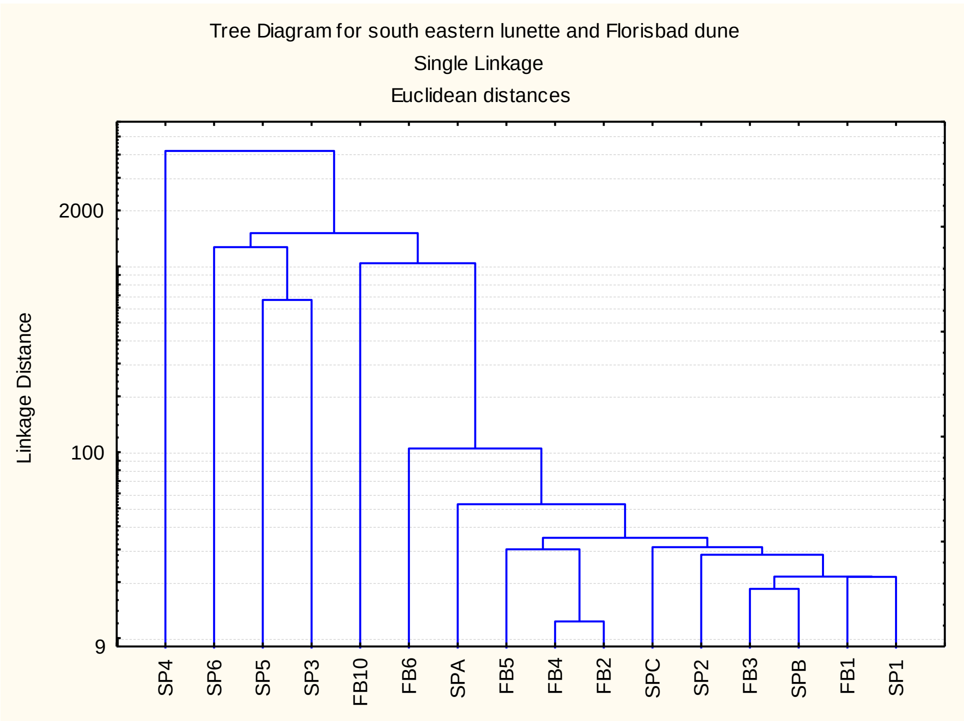

Figure 5.9 Clustering of the diagram for the samples from the south eastern lunette and the Florisbad dune.

6.6.3 CLUSTER ANALYSIS: WARD'S METHOD

A Ward's method cluster analysis was run on two PCA test in order to identify groups rather than outliers. It is evident from Figure 5.10 and Figure 5.11 that the Ward's method has identified two main groups within the data set. In general, one group represents the lunettes dunes and the other group represents the Florisbad dune. The exception being sample FB 10, from the Florisbad dune, which is grouped with samples from the lunette dunes, and sample EL1 and EL2 from the eastern lunette dune are also grouped with sediment samples from the Florisbad dune.

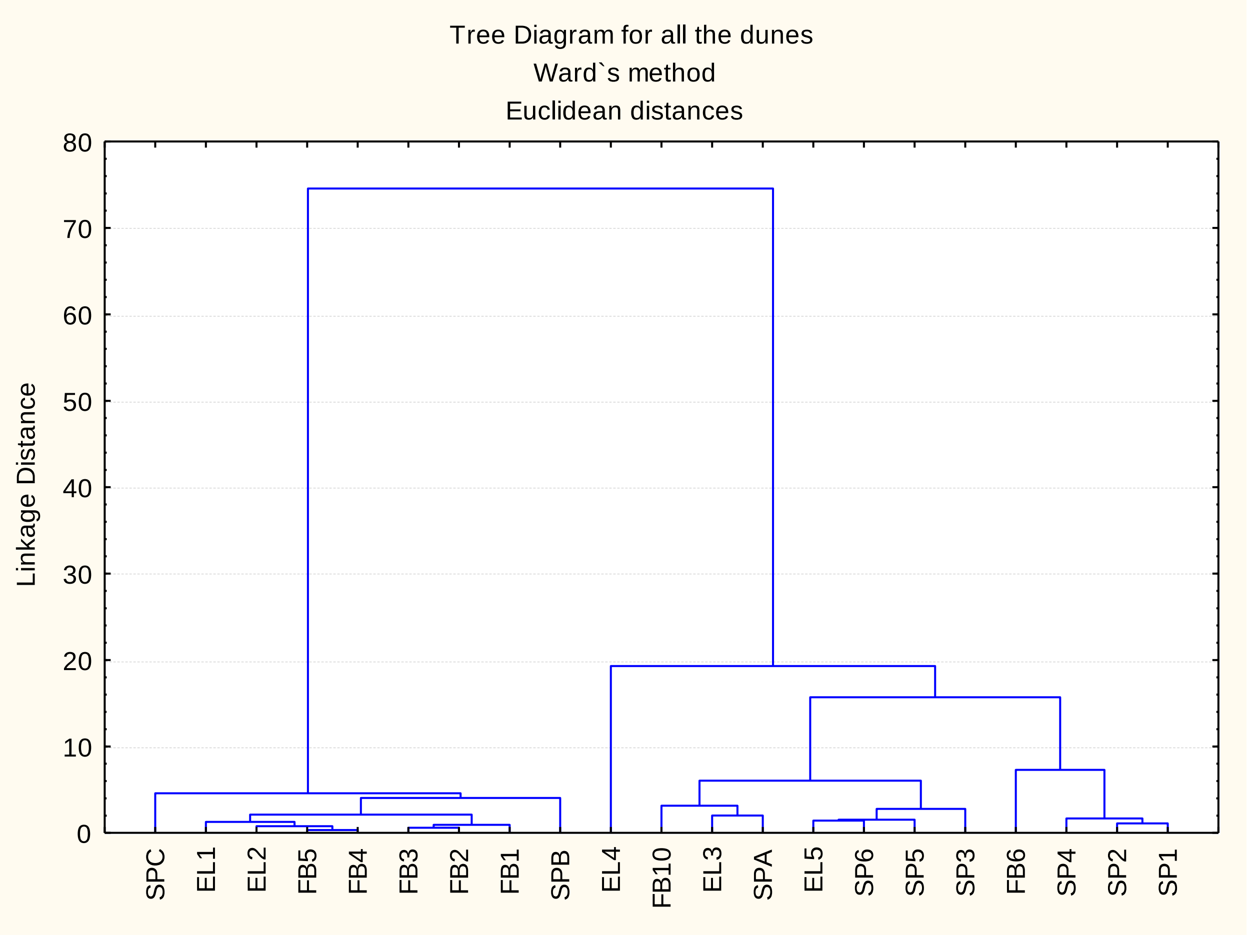

Figure 5.10 Ward Clustering of the samples from all the dunes in the study area.

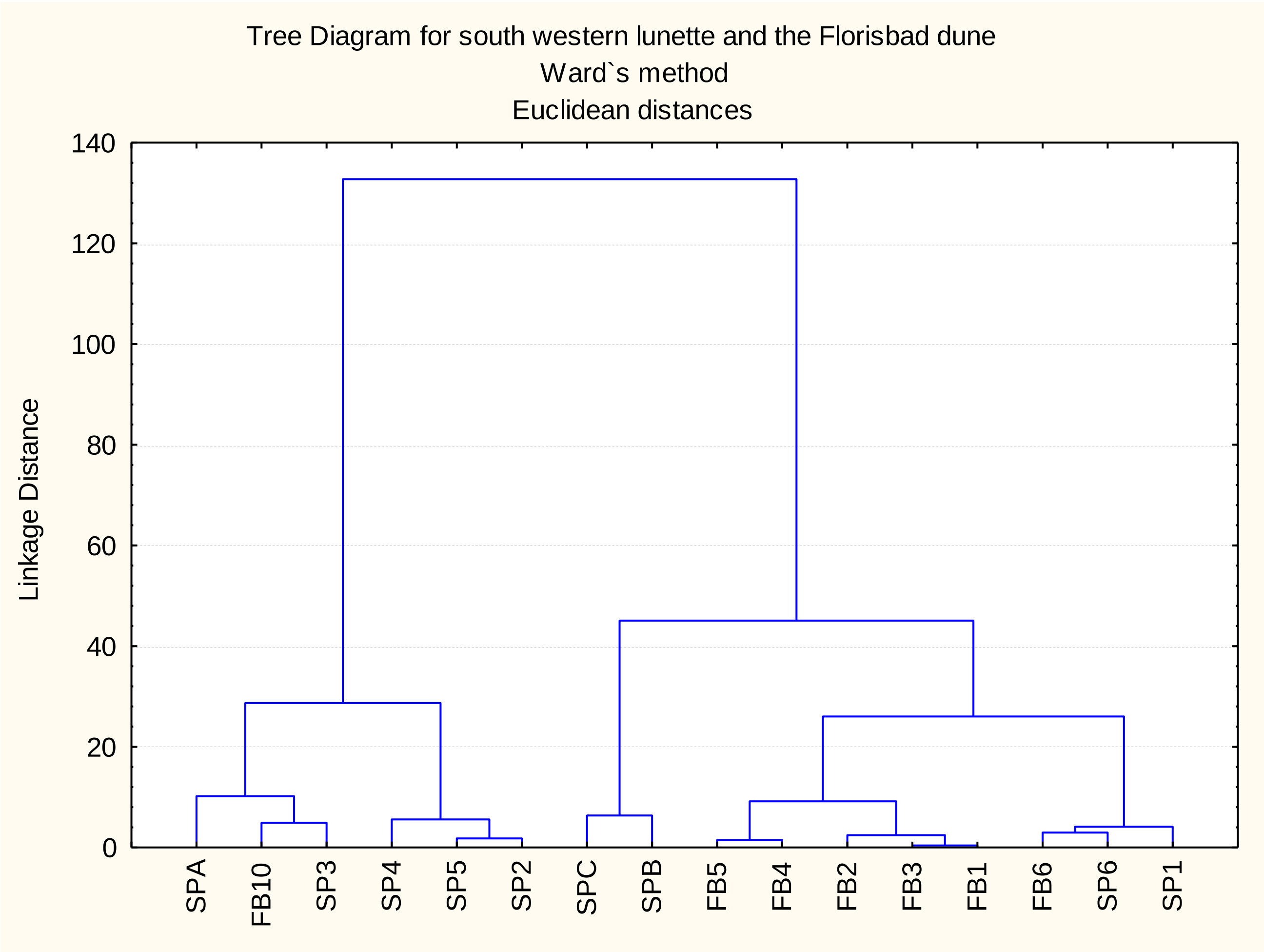

Figure 5.11 Ward Clustering of the samples from the south eastern lunette and the Florisbad dune.

Even though the sediments from the lunettes and the Florisbad dune appear similar on inspection, the cluster analyses have assisted in distinguishing between the Florisbad dune sediments and the lunette sediments and confirm subtle differences in sedimentological and geochemical composition of the respective geomorphological features.

5.7 CONCLUDING REMARKS

In this Chapter, the analytical results of the field, laboratory and statistical components of this research were presented. In the following Chapter the results will be further discussed and compared with results from lunette dunes in the literature. They will then be discussed in terms of their significance towards shedding more light into understanding the complex depositional environment of Florisbad. The information will then be used to determine the usefulness of lunette dunes in South Africa, as indicators of environmental change. In addition the results are compared with other scenarios of Quaternary environmental change in South Africa.

CHAPTER 6: DISCUSSION

6.1 INTRODUCTION

In the previous Chapter the analytical results of field and laboratory procedures were presented, showing that the samples (and therefore the lunette dunes and the Florisbad dune) are relatively uniform with respect to sediment particle size, pH, and chemical composition. However it was also noted that there were minor differences when it comes to dune structures, electrical conductivity and chemical composition. In this Chapter the question of whether there is a relationship between the Florisbad dune and the lunette dunes in the study area is addressed. Another important component of this Chapter is the environmental reconstruction of the lunette dune that was sampled for dating. Subsequently, the paleoenvironmental significance of these dunes, with regard to both the local and international contexts, is discussed.

6.2 THE RELATIONSHIP BETWEEN STRATIGRAPHY AND TEXTUAL COMPOSITION OF THE OUTER LUNETTE AND THE SPRING SITE DEPOSITS

In this section the question of whether there is a relationship between the stratigraphy and textual composition of the outer lunettes and the spring site deposits (Florisbad dune) is examined. However before looking at the relationship between these dunes, there is a need to explain why different methods used to analyze particle size distribution in the sampled sediments, gave diverse results, as well as to indicate which results are going to be referred to in this Chapter.

In the previous Chapter, the particle size results from the laser particle size analyzer showed that the sediments from the Florisbad dune comprise mainly silt (Table 5.1), whereas the particle size results from the sedimentation procedure indicated that the sediments from the same study area consist mainly of fine sand (Figure 5.2).

Since both procedures were duplicated, taking due care, reproducible (accurate) results were obtained. The sediments (unwashed and washed) were viewed under a microscope, and the washed sand-sized sediments were seen to be comprised of separate grains. Furthermore, they behaved like sand grains when water was added to the slide. Since both results were considered to be true, and accurate, literature was consulted in order to help ascertain whether the sediments are more likely to be silt or fine sand. The first step was to look at the accuracy of both methods used to analyze the sediments, and then to look at the characteristics of sediments from other dunes in the region and elsewhere.

Bale (1996) noted that sediment particle size analysis through laser diffraction has some limitation and some of those limitations include the following;

- When increasing settling velocities, there is a continual concern regarding the breakup of fragile flocks in the process of drawing off samples from the water column.
- Some flocks may not consist of solid materials and if flocks have small pores, light may be diffracted through these pores which will contribute to the diffraction pattern in a similar way as smaller particles would.

The sedimentation procedure has no limitation that could result in sand sized sediments being represented as silts or vice-versa. Based on Bale’s (1996) conclusions about limitations of particle size analysis through laser diffraction, it is quite possible that the sediments under question here are sand sized silt/clay aggregates.

Due to the fact that the sediments in this study behaved like sand grains when water was added to the slide, literature was consulted to confirm if it is possible for sand sized silt/clay aggregates to behave like sand grains.

Like any other arid and semi-arid country, Australia, is dominated by widespread aeolian deposits. However what is interesting about these deposits is that in some regions where there are widespread aeolian deposits, the deposits are not composed of sand and silt, but are composed of sand/silt sized, clay aggregates. A number of researchers have studied the behavior of these aggregates. Petticrew *et al* (2007) noted that fines (<63 microsimens) in natural water are mostly bonded with particulate organics into composite particulate termed flocks or aggregates, and these aggregates behave like sand-sized particles. Wakeling and Webb (2007) also noted that most silts and clays that are bonded into sand and silt-sized aggregates, behave like sand during transportation.

Dare-Edwards (1984) stated that once the clay aggregates are fused together they lose their individual character and tend to behave like sand or silt depending on their size. Dare-Edwards (1984) discussed three possible mechanisms for formation of clay pellets. The three possible mechanisms are: deflation of saline florescence from lake floors, erosion of pre-existing soil surfaces, and stripping of alluvial outwash.

The above-mentioned mechanisms are not going to be discussed in detail because it is beyond the scope of this dissertation to look at how these aggregates were formed. However it is important to recognize that all dunes in the study area appear to be composed mainly of sand sized silt and clay aggregates that behave like sand.

All the sediments from the sample site mainly consisted of sand-sized silt aggregates, with the exception of two samples, one from the Florisbad dune and the other from the eastern lunette dune, which contained more clay (Figure 5.2a).

90% of the sand-sized sediments were classified as fine to very fine sand (Figure 5.2b). This size of sediments is within the size range for aeolian sediments. The equal size distributions and degree of kurtosis (Table 5.1 and Figure 5.2a) also support an aeolian source.

The presence of clay-sized sediments in the Florisbad dune and the eastern lunette is not necessarily an indication of fluvial deposits as previously reported. Lunettes with high clay content have been previously reported by Twidale (1971). Twidale (1971), noted that in the Simpson desert, central Australia, some of the sediments from the lunette dunes have relatively high clay contents. It was concluded that the high clay content was presumably caused by eluviation of particles trapped by and with saltating sand grains.

Butzer (1988) previously argued that the morphology of the sediments from the Florisbad dune indicates they are unlikely to be of aeolian origin, because the grains are sub-rounded. Although Grobler and Loock (1998) and Van Zinderen Bakker both concluded that the sediments from the Florisbad dunes are predominantly derived from an aeolian source, analysis of sediments from the surrounding dunes was necessary to confirm this.

Although sub-rounded to rounded grains are mostly associated with fluvial transportation (Zaghlou *et al*, 2009) this study has revealed that sediments from the surrounding lunette dunes are sub-rounded. Since the sediments from the lunette dunes may be of aeolian origin (Table 5.1 and Figure 5.2a), and have the same morphology as those from the Florisbad dune, there exists the probability that the sediments comprising both dunes are of the same origin. Sub-rounded aeolian sand grains also exit in many areas such as the dune cores in the Simpson Desert, central Australia and the Libyan Desert (Twidale, 1971).

Despite the lack of stratigraphic units on the south western lunette, it is apparent that the Florisbad dune has similar structural units (in terms of colour changes), as the eastern lunette dune.

Both these dunes are overlain by red sediments on the crest, followed by a reddish brownish layer, and then the green clay layer (Figure 2.7 and Figure 2.8). The only difference between these two dunes is that the Florisbad dune has thicker layers.

It is possible that the sediments in these two dunes were deposited during the same period, under the same environmental conditions. The reason why the south eastern lunette dune does not show similar structural units is probably because sampling was undertaken on reworked sediments. This will be discussed in more details in the next section. A possible explanation for greater amounts of sediment accumulating in thicker layers at the Florisbad dune is the vegetation which was growing at the spring, and which helped to trap sediments and to stabilize the dune.

The Florisbad dune was probably stabilized by vegetation which had established itself and survived partly because it was closer to the spring and near surface ground water. The plausible scenario for Florisbad is one in which vegetation growing at the spring helped to trap more aeolian sediments than on the surrounding lunette dunes.

The south western lunette dune at Florisbad lies in a zone which is out of reach of soil moisture at most times, which therefore makes the area unfavorable for plant growth. Wind and blowing sand could also have a negative effect on vegetation, because plants may be easily buried by sand or even blown away by strong winds. Hence the south western lunette structure varies from the Florisbad sand dune and the eastern lunette dune.

As mentioned in the previous Chapter (Section 5.4), the chemical composition results clearly showed silicon dioxide (SiO_2) as the most abundant mineral in all the samples. Therefore the results of the chemical composition analysis indicate that the sediments (from the lunettes and the Florisbad sand dune) were derived from a quartz-rich parent material.

Although the sediments appeared to be identical, there were minor differences between samples from the lunettes and the Florisbad dune when it comes to soluble and mobile elements such as Na_2, MgO and CaO (Figure 5.7).

The sediments from the lunette dunes have slightly higher concentration of these soluble and mobile elements. The noted difference in the concentration of certain elements is important because characteristics of major geochemical elements in terrestrial sediments generally serve as effective proxies to demonstrate the intensity of chemical weathering and to reflect environmental change in terms of variation in precipitation or the amount of moisture in the soil (Sun *et al*, 2009).

According to Sun *et al* (2009) climate plays the most important role in affecting chemical weathering processes, since water from rainfall is commonly thought of as the first order, controlling factors that initiates chemical weathering and determines the intensity of chemical weathering processes.

Highly weathered elements in sediments as a result of enhanced chemical reactions are generally produced during warm and humid period. This basically means the rates of chemical weathering are higher during warm and humid environments than under cold, dry conditions.

High concentration of soluble and mobile elements such as Na_2, MgO and CaO in sediments from the lunette dunes suggests relatively enhanced chemical weathering under warm-humid climatic conditions. The reason why the sediments from the Florisbad dune have less soluble and mobile elements, as compared to those from the lunette is possibly because chemical weathering was more pronounced at the Florisbad dune site. Pronounced chemical weathering in solution, results in a greater loss of the more soluble and mobile elements such as Na_2, MgO and CaO in sediments (Sun *et al*, 2009).

The variation in distribution of soluble and mobile elements can also be used to explain why the lunette dunes appear to be excessively eroded, as compared to the Florisbad dune. In other words the lunette dunes are probably older than the Florisbad dune. Radiocarbon dating has revealed that the top reddish sandy layer (Figure 2.12 and Figure 2.13) is about 11 700 years old while the brownish sandy layer has a ^{14}C date of greater than 43 700 and the grey clay layer is outside the ^{14}C dating range (Butzer, 1988).

Erosion and gully development are enhanced by high levels of silt and clay, and high levels of exchangeable sodium within sediment increases the susceptibility of gulling in lunette dunes (Lawson and Thomas, 2002). Although all the dunes in the study area contain almost the same amounts of clay and silt, the lunette dunes are, likely, more vulnerable to erosion and gulling than the Florisbad dune due to the higher concentration of exchangeable sodium within their sediments (Table 5.4).

The conductivity values of the samples from the lunette dune are slightly higher than the values of the samples from the Florisbad dune, with the exception of one sample from the eastern lunette dune which has an extremely high conductivity value (9000 µs) compared to the others. The reason for this high conductivity in the lunette dune samples is because they have higher concentration of Na_2O thus supporting that the sediments from the lunette had undergone previous weathering cycles that the sediments from the dune have not undergone.

6.3 AGE OF THE FLORISBAD OUTER LUNETTE

One of the objectives of this study is environmental reconstruction of the outer lunette dunes. In order to achieve this objective, two samples for OSL dating were taken from the south western lunette dune.

The ages of the two samples are going to be discussed below, and since no samples were taken to determine the ages of the eastern lunette dune and the Florisbad dune, the ages that will be discuss below are only applicable to the area immediate to the south of the Florisbad proper. The south western lunette ages will also be compared to the ages of other lunette dunes in the Free State, and the ages from the Florisbad sand dune.

The best estimates of the burial ages for the south western lunette range from 0.57 ± 0.04 ka to 0.28 ± 0.04 ka. As mentioned before the results of geochemical analysis has indicated that the sediments from the lunette are older than the sediments from the Florisbad dune. Two scenarios are suggested which could explain the young OSL ages obtained from the lunette sediments. Firstly, these ages may imply that the lunette dunes in Florisbad were active aeolian features during the past 500 to 200 hundred years. Secondly, fluvial reworking of sediments down the slope could have caused older material to be displaced or contaminated by younger aeolian sediments. Thomas and Shaw (1991) have noted that it is quite difficult to determine the true age of the original emplacement of Kalahari sands in some dunes because of extensive reworking of sand.

Although sediment accumulations during this period have been recorded from other lunettes in the western Free State (Holmes *et al*, 2008), it is important to note that in that study, the oldest dated sediments were from Morgenzon pan dated at ~ 18ka, which is in good accordance with the sediments from lunette dunes in the western Kalahari, South Africa, (Lawson and Thomas, 2002).

Holmes *et al's* (2008) assessment of six pan fringing lunette dunes revealed that in the western Free State, sediment has accumulated on all the lunette dunes in the western Free State that were investigated, during the last 0.5 ka, with the highest accumulation rates occurring during the period 0.07-0.3 ka.

A second reason for a lack of older ages in sediments from the south western lunette dune is perhaps because this research was looking at reworked sediments, which had been re-worked downslope, either by water or by wind. There was evidence in the field of colluvial action, for example long, angular sandstone and well rounded dolerite clasts which were present at the base of the lunette.

The dolerite boulders at the base of the profile probably came from a dolerite dyke, which is situated about 3km upslope. It is possible that the dolerite clasts had reworked themselves down slope over the years, probably indicating past wetter periods and sheet wash to move the clasts.

It is quite evident that the lunette sediments are older than 500 years. Although it is not possible to give the precise ages of the lunettes in the study area, Based on the sedimentological and structural similarities of the lunettes with the Florisbad dune, it is highly possible that the ages of the lunettes are just slightly older than the ages of the Florisbad dune. However this can only be confirmed through OSL dating of the eastern lunette dune. The Electron Spin Resonance (ESR) dating of the hominid tooth produced a range from 259 000 ± 35 000 years while the basal deposits which should be closest in age to the origin of the spring have produced a range 279 000 ± 47 000 years for the earliest layer in the Florisbad dune (Grün, *et al*, 1996).

Although geochemical results suggests that the lunettes are older than the Florisbad dune, it is important to note that the dune rests on spring deposits, (Douglas, 2009) and the above mentioned dates were derived from those spring deposits and may be older than the lunette dunes.

The sandy layer underneath the green clay (Figure 2.12) has been dated to 121 000 ± 6 000 years (Grün, *et al*, 1996), and this research suggest the lunette dune may be as old as or even older than that layer.

The ages of the hominid tooth (259 000 ± 35 000) are not considered important in this study, since the layer in which the tooth was found may not be the original layer in which the tooth was emplaced. The tooth may have been reworked by water or even moved by wind when the dunes were active features.

The lunette dunes in the study may even be as old as the lunette dune at Morgenzon pan which was investigated as part of the study by Holmes *et al* (2008), because Scott and Nyakale (2002)'s findings on pollen analysis from the Florisbad dune where in agreement with pollen analysis from the Morgenzon pan. The lunette dune at the Morgenzon pan will be discussed in more detailed in the following section, together with other lunette dunes in the western Free State Panfield and elsewhere.

6.4 The Composition and Morphological Aspects of Florisbad Outer Lunette in Relation to Other Lunette In South Africa

One of the objectives of this research is to compare the composition and morphological aspects of the Florisbad outer lunette dunes with other lunette dunes in southern Africa. According to Moon and Dardis 1988; Lawson and Thomas, 2002; Holmes *et al*, 2008, the high sand content and the orientation of most outer lunette in southern Africa suggest that these features were formed during dry seasons which were dominated by strong winds.

Although it is important to relate this study to other similar studies that have been conducted elsewhere, it is important to note that landforms such as lunette dune don't always demonstrate equal potential for paleoenvironmental reconstruction.

For example, Fitzsimmons and Telfer (2008) concluded that the inter-dune sediments at Witpan offered a shorter record of aeolian deposition because the sediments were reflecting changes in sediment source rather than pedogenesis, but the inter-dune sediments in the southern Kalahari offered potential for reconstruction of long periods of aeolian deposition .

The lunette dunes at Morgenzon pan, just like the lunettes at Florisbad, did not display any obvious sedimentary structures; however there were obvious colour changes within the dune facies. The sediments from Holmes *et al*'s (2008) study are similar to the sediments from the Florisbad sand dunes in terms of sedimentological properties such as particle size, pH and electrical conductivity. All the lunette dunes are composed of very fine sand-sized sediment, with few cases where there is more than 40% clay content.

All the lunettes in this study, just like the six lunette in Holmes *et al* (2008)'s study are notably gullied. Gulling involves a cycling process, where sediments from the lunette dunes are returned to the pan floor, making those sediments available again for wind entrainment (Thomas *et al*, 1993).

Just like the lunettes studied by Holmes *et al* (2008), the Florisbad lunettes have very low rates of accumulation, as compared to the Kalahari lunettes. Kalahari lunettes have higher accumulation rates because of the presence of linear dune fields. The linear dune fields are comprised of extensive aeolian accumulations of reworked Kalahari sand, and they serve as the primary source of material from outside the pans (Lawson and Thomas, 2002).

Pans are the primary source of sediment supply in the study area (Grobler and Loock, 1988). Free State pans are smaller features as compared to other pans in the Kalahari. The pan sizes limit the supply of sediment for lunette dune construction (Telfer and Thomas, 2006), thus the reason for low rates of lunette accumulation.

Most sediment are made available through recycling by gulling, the evidence from Witpan is of more extensive gulling systems when compared to that of the Free State lunettes.

Holmes, *et al*. (2008), noted that the scarcity of sediments older than 1 ka at Witpan may be an indication of extended palaeorecords in Free State dunes. And this may be an indication that the Free State dunes have higher preservation potential.

Although lunette dune development is not necessarily an indication of aridity (refer to Chapter 1, section 1.3) lunette dune accumulation in the western Free State pan field at 10-12 ka corresponds with a period of very dry conditions recorded at the Kathu Pan. Lunette development at 1-2 ka ago corresponds with dry conditions recorded in pollen records from western Free State pans (Scott, 1988). The marked a phase of lunette construction from 3.5-5.0 ka presents an interesting challenge given from spring deposits and peat accumulation on the floor of Deelpan (Holmes *et al,* 2008) at 3.5 and 4.5 ka, BP.

However due to the facts that the above mentioned wet period lies within a generally drier period recorded in Kathu Pan, Holmes *et al* (2008) concluded that the sediments in the Free State lunette dunes were probably accumulated during dry periods in the southern African interior.

Telfer and Thomas (2006) detailed records of lunette accumulations in the Kalahari pans, shows a relative high rate of sediments accumulation during the late-Holocene. A detailed study from Witpan revealed over 5m of sedimentation recorded in one section of the lunette in the last 570 ±40 years and 6m of accumulation in the past 600 ±40 years in another part of the dune (Telfer and Thomas, 2006).

However in the Florisbad area, looking at the chronological record from the south western lunette, it seems as if historical accumulation rates have been lower than those in the Kalahari. They are nonetheless significant, with accumulation rates of sediment in the western Free State lunette ranging from 1.3 to 2 m, during the same period (Holmes *et al*, 2008).

Although there was no evidence of mid-Holocene accumulation in the dated sediments from most of the western Free State lunette dunes, the lunette dune at Morgenzon pan showed considerable rate of accumulations (i.e. 1.3 m), during this period.

It is important to note that even in the Kalahari lunette dunes there were very little preserved sediments from the mid-Holocene (Lawson and Thomas, 2002; Telfer and Thomas 2006). However OSL dating of samples from the lunette dunes in the southern Kalahari have revealed records of discontinuous sedimentation for the past 18 ka (Holmes *et al,* 2008).

Thomas and Lawson (2002) proposed that the sediment supply to lunette dunes in the Kalahari is controlled by both regional (e.g. climate) and local factors such as ground water level. Lower ground water tables and drier conditions combined with greater sand transport potentials are believed to be a pre requisite for lunette dune construction in the Kalahari region (Thomas *et al,* 1998).

Lunette dunes in the south west Kalahari are predominately composed of sand sized sediments with the exception of areas where multiple dunes occur. In such cases the inner dunes tend to contain a higher percentage of fine material derived from clay rich pan floors (Lawson and Thomas, 2002).

The majority of the sites that were investigated by Lawson and Thomas (2002) and the lunettes in the western Free State Panfield that were investigated by Holmes *et al* (2008) indicated that there are significant increases in age with depth, and the same increase can be expected from the lunette dune in the study area. Lawson and Thomas (2002) noted that high level of exchangeable sodium within sediments increases the susceptibility of gulling in lunette dunes, which sometimes makes it difficult to determine the true age of original emplacement of sediments.

Figure 6.1 Cross profile of the study area from southwest to northeast, which includes Soutpan and the Florisbad dune (see Figure 5.1).

The general nature of the dunes in this study and their relationship to Soutpan has being indicated by the maps/schematic drawings in Figure 1.2 and Figure 2.5. The lunette dunes in this study are generally in a form of large outer lunette dunes on the margins of the pan depression, the south western lunette dune with its crest line 1-1.5 km from the pan edge and 15 to 25 m above the depression floor.

The south western lunette dune's crest line is 2-3 km from the pan edge and 20 to 30 m above the depression floor. While the crest line of the Florisbad dune is 1-2 km from the pan edge and 35 to 45 m above the depression floor (Figure 6.1). A shallow depression separates the lunette dunes, in the study area. Both dunes are asymmetric in profile, with their steeper slopes forming a slip face towards Soutpan (Figure 6.2).

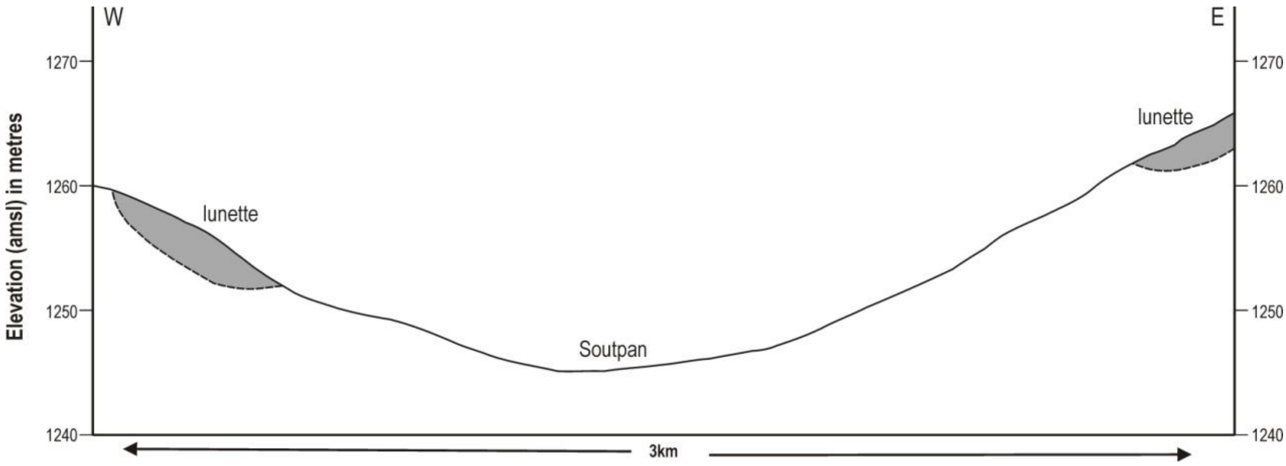

Figure 6.2 Cross profile of the study area from west to east (see Figure 5.1).

6.5 THE RELATIONSHIP BETWEEN TOPOGRAPHY AND DEPOSITIONAL SITES

This section aims to ascertain whether there is any relationship between topography and depositional sites. Looking at the relationship between depositional sites and topography will also assist in determining if a sand dune, which was formed on the southern shore of Soutpan, migrated towards the Florisbad spring site, and then covered the spring (Douglas, 2006b and Douglas *et al,* 2010). Studies of modern dune fields have shown that, when large dunes form, they create a topographically irregular surface and the later occurrence of aeolian activity commonly fills the low-lying areas between the older dunes, resulting in beds that are laterally discontinuous (Langford et al, 2008).

The environmental conditions that are conducive to dune migration have been discussed in Chapter 3 (Section 3.5). Type of vegetation, strength of wind and availability of sand supply and climate were identified as the most important factors in dune mobility, although the level of significance of each factor may vary from one study to the next (Tsoar, 1985; Forman *et al*, 2003; Marin et al, 2005 and Forman *et al*, 2008).

Douglas (2009) noted that although in some areas the base of the Florisbad dune rests on spring deposits, it does not seem possible for such large quantities of spring sand to have been available to produce a sand dune this size. Although it is difficult to assign any prevailing wind direction at Florisbad, Schulze (1994) has noted that there is a predominant north-westerly wind in January and July and Douglas (2009) noted that, historically, there must have been extended periods with very dominant prevailing north to north-westerly winds in order for the south-east dune belt at Florisbad to have moved.

However if there had been migration of the south-east dune belt towards the spring site, the dune would have created a topographically irregular surface, since the latter aeolian activity would have filled the low lying areas between the older dunes, which would have resulted in beds that are laterally discontinuous. It is quite possible that the dune was formed as a result of aeolian deposition and that the Florisbad dune owes its large size, in part at least, to the vegetation which was growing at the spring and which helped to stabilize the dune.

The topography of the area suggested a possibility of the existence of a third outer lunette dune (Figure 6.1), to the further south, were the area has been blanketed by young aeolian sand (Figure 2.15). Although three grab samples were taken (Figure 4.1), Table 6.2 has indicated that unlike other samples from the lunette dunes in this area, that mostly consist of sand sized silt and clay aggregates, two of those samples (SPB and SPC) consist of sand grains, in addition the Munsell colour of samples from those site is similar to those of fence line dunes found in the western Free State. In other words the analysis which was conducted on the three grab samples did not give a clear indication of whether there is a third dune or not. Coring needs to be done in order to positively conclude if indeed there is a third dune in the vicinity of Florisbad.

6.6 CONCLUDING REMARKS

In this Chapter the relationship between the Florisbad dune and the lunette dunes in the study area has been examined. It has been established that the Florisbad dune has the same structure as the eastern lunette dune. The sediments from all the dunes in the study area have similar sedimentological characteristics.

The only difference between the Florisbad sand dune and the lunette dunes is that the lunette dunes appear to be excessively eroded. This may be explained by the fact that the sediments in the lunette contain high level of sodium, which renders the lunettes more susceptible to erosion than the Florisbad dune. The research also noted that the OSL ages from the south western lunette were determined from the lunette sediments which have likely been reworked down the slope over a number of years. This suggests that the original sediments may have been older. It was also noted that the dunes in the Florisbad vicinity have a similar composition and morphological characteristics to other dunes in the region.

CHAPTER 7: CONCLUSION

7.1 OVERVIEW AND SUMMARY

This study has elaborated on the geomorphic context of the area immediately surrounding the Florisbad spring site. The primary aim of this research was to reconstruct the palaeoenvironmental conditions which prevailed around Florisbad, to gain a better understanding of the geomorphologic landscape around Florisbad, and to try to explain some of the landforms (which, in this case, are primarily dunes) in terms of the geomorphological processes that shaped them.

The Florisbad dune and two outer lunette dunes located to the south west and east of the Florisbad salt pan where investigated. The study has contributed to an understanding of the sedimentology and geochemistry of aeolian deposits in the vicinity of Florisbad, as well as shedding light on the palaeoenvirometal histories of these dunes. A further objective of the study was to ascertain whether or not the palaeoenviromental conditions around Florisbad would have been conducive for migration of sand dunes as speculated by Douglas (2009).

Although there have been previous studies on the geomorphology and geology of the spring and its deposits, which included aspects of its sedimentology as well as its palaeoenvironmental history (refer to the literature review in Chapter 3), no research that specifically looks at the surrounding geomorphology and aeolian deposits has, as far as can be ascertained, been published. This study has therefore been pioneering in its attempt to understand the geomorphology and aeolian deposits in this region. This study has also attempted to establish if there is any relationship between the lunette dunes and the Florisbad dune.

Aerial photographs and topographical maps were used to identify lunette dunes in the study region. The identified lunette dunes were then ground-truthed and sampled for laboratory analysis and optically stimulated luminescence (OSL) dating. In the field Munsell colours of the dunes was recorded and site sketches were drawn. In the laboratory particle size analysis, pH, conductivity and X-ray fluorescence (XRF) spectrometry was used to analyze the chemical composition of the sediment samples which were taken. 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 sediments samples (and therefore the lunette dunes and the Florisbad dune) are uniform with respect to particle size and pH, and minor differences were noticed with respect to the structures and chemical composition. All the dunes in the study area are comprised of very fine to fine sand sized quartz sediments that are poorly sorted.

The best estimates for the burial ages range from 0.57 ± 0.04 ka to 0.28 ± 0.04 ka for the two samples from the south western lunette dune which were subjected to OSL dating. Although no OSL dating of the sediment from the Florisbad dune has been done, as far as previously published work is concerned, Grun, *et al*, (1996) has indicated that the sediments in the Florisbad dune may be as old as 121 000 ± 6 000 years.

The geochemical results in the study have indicated that the lunette dune sediments are, in all probability, older than the Florisbad dune sediments. Two possible scenarios were given to explain the young OSL ages obtained in the study. Firstly it was suggested that possibly the lunette dune were active aeolian feature within the last 200 to 500 year, or the young ages were because sampling was undertaken on reworked sediments. The lunette dunes in the study were compared to lunette dunes in the western Free State Panfield (Holmes *et al*, 2008), as well as other studies (Tsoar, 1985; Thomas *et al*, 1993; Lawson and Thomas, 2002; Forman *et al*, 2003; Marin *et al*, 2005 Telfer and Thomas, 2006; Forman *et al*, 2008).

The final aspect of this study was to ascertain whether there is any relationship between topography and depositional sites. Looking at the relationship between depositional sites and topography also assisted in determining if a sand dune, which was formed on the southern shore of Soutpan, migrated towards the Florisbad spring site, and then covered the spring. It was suggested that if there had been migration of the south-east dune belt towards the spring site, the dune would have created a topographically irregular surface and the latter aeolian activity would have filled the low lying areas between the older dunes, which would have resulted in beds that are laterally discontinuous.

It was proposed that that the dune was formed as a result of aeolian deposition and that the Florisbad dune owes its large size to the vegetation which was growing at the spring, and which helped to trap sediments and stabilize the dune.

7.3 CONSTRAINTS AND LIMITATION

There are number of limitation associated with the present study which should be taken into account when assessing the results. Perhaps the most obvious constraint is the financial limitation which limited the study to analyzing only two samples for OSL ages. In addition the difficulty experienced when tracing the lunette dune as explained in Chapter 4, resulted in a delay in taking samples from the eastern lunette dunes, hence those samples were not sent to the University of Leicester, United Kingdom, for particle size analysis using a laser particle size analyzer.

7.3 RECOMMENDATIONS

The research has concluded that aeolian deposits in Florisbad provide a basis for Quaternary correlations within the landscape of the west-central Free State, and suggest that further research on aeolian deposits that would include OSL dating of the eastern lunette dune and the Florisbad dune is required so that Florisbad issue could be put into a tighter temporal context.

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Appendix A

Sediment classification

Particle size	Class name	
2mm	Gravel (not normally included in analysis of aeolian material)	
1.0 - 2.0mm	Very Coarse Sand	-0.5 - 0.0 Ø
0.5 - 1.0mm	Coarse Sand	0.25 - 1.0 Ø
0.25 - 0.5mm	Medium Sand	1.25 - 1.75 Ø
0.125 - 0.25mm	Fine Sand	2.0 – 2.75 Ø
0.05 - 0.125mm	Very Fine Sand	3.0 – 3.75 Ø
0.02 - 0.05mm	Coarse Silt	4.0 – 4.75 Ø
0.002 - 0.02mm	Medium and Fine Silt	5.0 – 8.0 Ø
0.002mm	Clay	9.0 – 14.0 Ø

(Source: http://www.geog.ucl.ac.uk/lab/partsize.htm)

Appendix B

Study sites and abbreviations

Study site	Abbreviation
Florisbad dune	FB
Eastern Lunette dune	EL
South western lunette dune	SP

Appendix C: Quartz Optical Dating Report

Sheffield Centre for International Drylands Research

Quartz Optical Dating Report

10th September, 2010

Florisbad, South Africa

Abstract: Optical luminescence dating at the single aliquot level was applied to coarse quartz grains extracted from two samples taken from Florisbad, South Africa. These samples were bright and sensitive to laboratory radiation and appeared to behave well when undergoing OSL measurement. Analysis of replicates of sample palaeodoses indicated no appreciable scatter and from this it is concluded that the samples' OSL signals were fully reset prior to burial. The best estimates of the burial ages range from 0.57 ± 0.04 ka to 0.28 ± 0.04 ka.

1. Introduction: Two samples in tubing from Florisbad, South Africa were submitted for luminescence dating by Prof. Peter Holmes. All luminescence work was carried out at the Sheffield Centre for International Drylands Research (SCIDR) luminescence laboratory. The samples were assumed not to have been exposed to sunlight during sampling or transportation to the laboratory. Upon arrival, the samples were allocated Sheffield lab numbers (Table 1). This report provides a brief summary of the procedures employed and results obtained for the samples.

Table 1. Sample descriptive data.

Lab No.	**Field Reference**	**Latitude** (° N)	**Longitude** (°E)	**Altitude** (m)	**Sampling Depth** (cm below surface)
Shfd10078	SP2	28° 45'	26° 03'	500	50
Shfd10079	SP6	28° 45'	26° 03'	500	180

In order to derive an optically stimulated luminescence (OSL) age both the palaeodose (De - the amount of absorbed dose since the sample was buried) and the dose rate (the estimated radiation flux for the sedimentary bodies) have to be determined. Aitken (1998) gives a detailed explanation of both these parameters. To calculate an age, the palaeodose (expressed in Grays) is divided by the annual dose rate (Grays/yr). An inherent assumption in these age calculations is that the sediment was fully reset or 'bleached' by exposure to sunlight during the last transport event or whilst *in situ* prior to burial and that no post-depositional sediment disturbance has occurred. As part of this investigation, efforts have been taken to establish if the sediments sampled have been bleached or disturbed by, for example, bioturbation.

Table 2. *Summary of results – Dosimetry related data.*

Lab Code	U (PPM)	Th (PPM)	**Rb** (PPM)	K (%)	D_{cosmic} + ($\mu Gy/a^{-1}$)	**Moisture** (%)	**Dose rate**† ($\mu Gy/a^{-1}$)
Shfd10078	1.29	4.8	38.5	0.8	226 ± 11	8.2 ± 5	1582 ± 71
Shfd10079	1.71	5.8	65.9	1.3	178 ± 9	8.0 ± 5	2158 ± 107

+ Cosmic dose is calculated as a linear decay curve at depths below 50 cm. Above this depth, errors in calculation may lead to an under-estimation of the cosmic dose contribution.

† Total Dose is attenuated for grain size, density and moisture.

2. Dose Rate Analysis: Naturally occurring potassium (K), thorium (Th), rubidium (Rb) and uranium (U) are the main contributors of dose to sedimentary quartz. The concentrations of these elements were determined by inductively coupled plasma mass spectrometry (ICP) at SGS laboratories Ontario Canada (Table 2). Elemental concentrations were converted to annual dose rates using data from Adamiec and Aitken (1998), Marsh et al. (2002), and Aitken (1988). This took into account attenuation factors relating to sediment grain sizes used, density and palaeomoisture. It has been assumed that each sample formed part of a thick homogeneous unit with no gamma contribution (other than from cosmogenic sources) being received by the sample from other unsampled sedimentary units. This assumption may not be valid if the units samples were less than 50 cm thick. Attenuation of dose by moisture used present-day moisture values with a ± 5% error to incorporate seasonal and longer-term fluctuations in moisture which the sample may have endured since burial (Table 2). The contribution to dose rates from cosmic sources were calculated using the expression published in Prescott and Hutton (1994; Table 2).

The dose rates calculated are based on analyses of the sediment sampled at the present day. This assumption is only valid if no movement and/or reprecipitation of the four key elements has taken place since sediment burial and the adjacent sediments to that sampled had similar dose rates. Further analysis would have to be undertaken to establish whether radioactive disequilibrium is present and to try and establish whether movement of elements has occurred during sediment burial.

3. Palaeodose Determination: Samples were prepared under subdued red lighting following the procedure to extract and clean quartz outlined in Bateman and Catt (1996). Prepared aliquots samples were taken from within a maximum size range of 90-250 µm to ensure sufficient material for measurements. The samples then underwent measurement at the single aliquot level using an upgraded Risø TL DA-12 luminescence reader with radiation doses administered using a calibrated ^{90}strontium beta source. For measurement purposes, quartz grains were mounted as a 5mm diameter monolayer on 9.6mm diameter aluminium discs using silkospray. A 150w filtered halogen lamp provided the stimulation and luminescence detection was through a Hoya U-340 filter. Samples were analysed using the single aliquot regenerative (SAR) approach (Murray and Wintle 2000), in which an interpolative growth curve is constructed using data derived from repeated measurements of a single grain which has been given various laboratory irradiations (Figure 1). Checks using infrared stimulated luminescence found no evidence of feldspar contamination. The last irradiation dose within the SAR protocol replicated the first to check if sensitivity changes cause by repeated measurement of the same grain had been correctly monitored and corrected for (known as the recycling ratio). All aliquots where the ratio of first and last dose point exceeded ±10% of unity were excluded from further analysis. The most appropriate preheat temperature for each sample was selected using a dose recovery preheat plateau test

(Fig.2). Results of this resulted in selection of preheat temperatures of 220 °C for 10 seconds, which were applied to each sample prior to OSL measurement to remove unstable signal generated by laboratory irradiation.

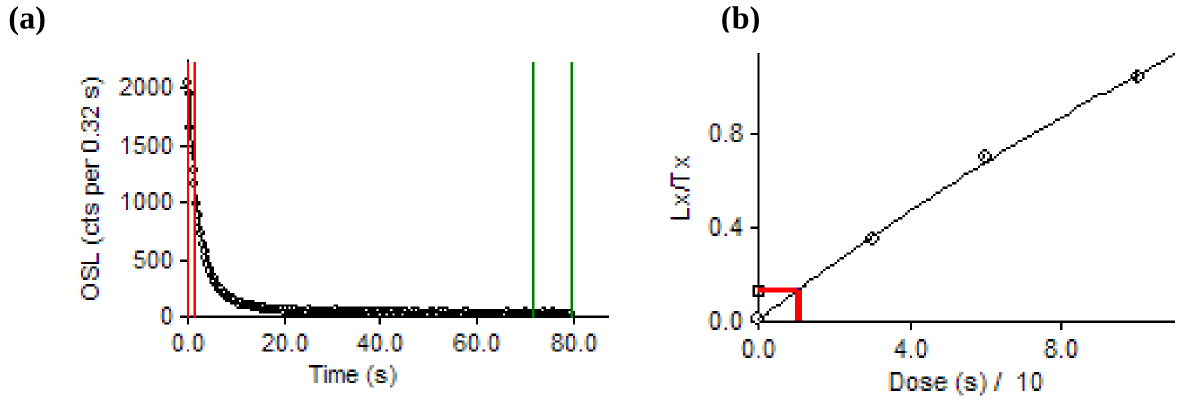

Figure 1: Examples of single aliquot OSL data for (a) Sample Shfd10078 OSL decay of naturally acquired signal; (b) Sample Shfd10078 SAR growth curve growing with laboratory dose with an interpolated naturally acquired dose from which a Palaedose (De) can be determined.

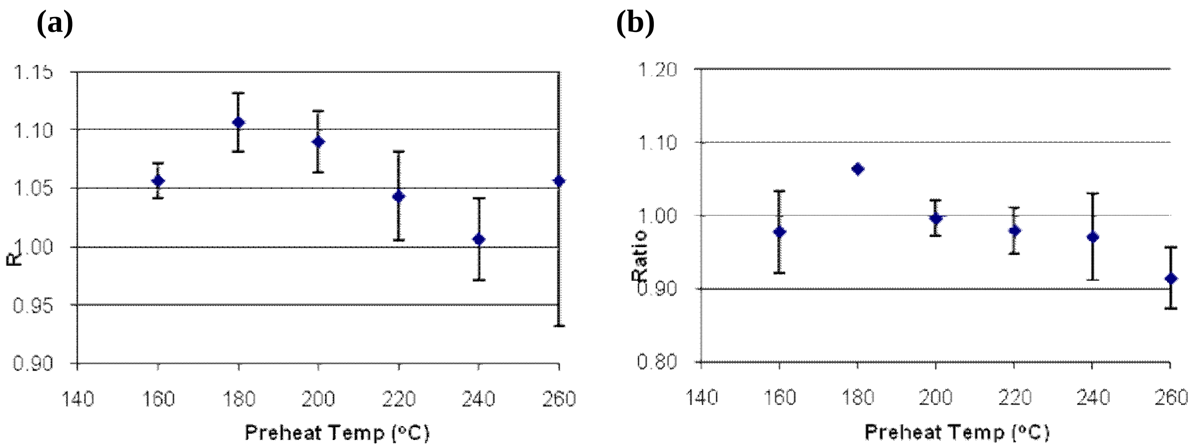

Figure 2. Results of Dose recovery test on Shfd10079 used to determine appropriate preheat for SAR protocol. (a) recycling ratio of different preheats; (b) results of different preheat temperatures in recovering a 18 Gy beta radiation dose

All samples showed good luminescence characteristics (Fig. 1a), with recycling ratios mostly within 10% of unity and a marked increase in OSL signal with laboratory dose (Fig 1b). 24 replicate palaeodoses per sample were attained to give an indication of the reproducibility of the palaeodose measurements, and to attempt to assess sample bleaching behaviour (see section 5; appendix 1).

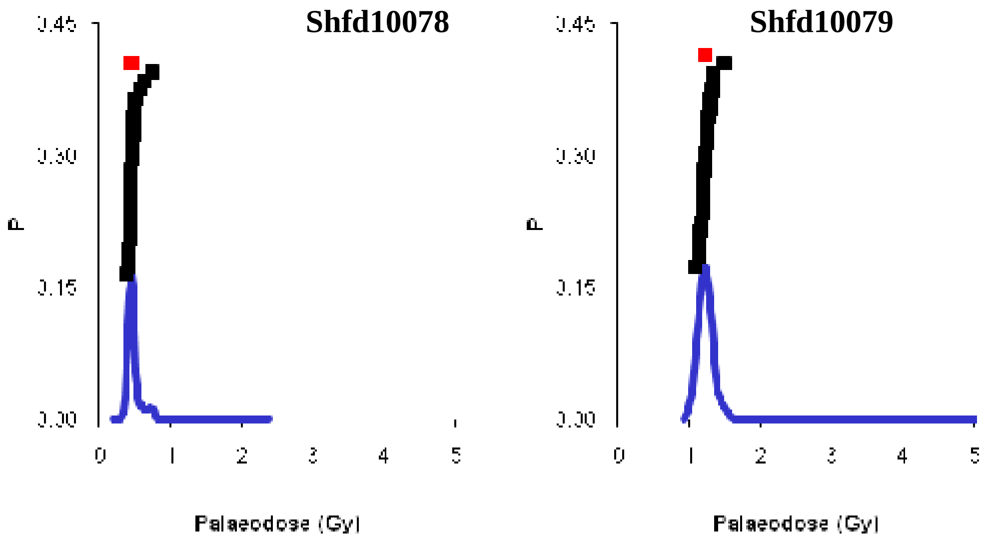

Figure 3: A combined probability density function of De values from single aliquot measurements showing degree of inter-aliquot variability. Also plotted are individual aliquot De values (black) and the unweighted mean De (red).

4. Sedimentary bleaching behaviour: The effects of incomplete bleaching of the sediment during the last period of transport or exposure *in situ* can be profound. Typically, poorly bleached sediments retain a significant level of residual signal from previous phases of sedimentary cycling, leading to inherent inaccuracies in the calculation of a palaeodose value. By plotting the replicate data for the sample as a probability density function some assessment of whether older or younger material has been included in the sample measurements can be made (Figure 3). In principle a well bleached unpost-depositionally disturbed sample should have replicate palaeodose (De) data which is normally distributed and highly reproducible (See Bateman *et al.* 2003, Fig 3; Bateman et al 2007a). Where post-depositional disturbance or incomplete bleaching prior to sample burial has occurred skewing of this distribution may occur and/or replicate reproducibility may be lower (Bateman et al 2007a; Bateman *et al.* 2007b). In the case of poorly bleached material skewing should be evident with a high De tail (e.g. Olley *et al.* 2004). It should be pointed out that by making OSL measurement of samples on a 5 mm diameter aliquot with approx. 1000-1500 grains any heterogeneity in De that individual grains have may be masked. This could be overcome by analysis at a smaller aliquot size or at the single grain level or measurement of smaller aliquots.

Table 3. *Summary of OSL results*

Lab Code	Field Ref.	Depth (cm)	De (Gy)	Dose rate (μGy/a^{-1})	Age (ka)
Shfd10078	SP2	50	148.7 ± 3.7	1582 ± 71	**0.28** ± **0.04**
Shfd10079	SP6	180	139.4 ± 4.4	2158 ± 107	**0.57** ± **0.04**

As Figure 3 and Table 3 (see also appendix) show, the single aliquot De data distribution for the samples are normally distributed with low levels of scatter. As a result the OSL signal of the samples are considered to have been fully reset prior to burial. For age calculation purposes the De was calculated using a mean based on the central age model (Galbraith and Green 1990) excluding outliers (those aliquots outside 2 standard deviations of the mean).

5. Age Calculation and Conclusions: Ages are quoted in years from the present day (2010) and are presented with one sigma confidence intervals which incorporate systematic uncertainties with the dosimetry data, uncertainties with the palaeomoisture content and errors associated with the De determination. Table 3 shows the final single aliquot OSL age estimates. Aliquot-specific data for the sample is included in appendix 1. The data presented shows that the samples appear to be reproducible and (based on the data) to have been reset prior to burial thus providing measured dose rates have not changed through time these samples should provide true burial ages. Best estimate of ages for these samples range from 0.57 ± 0.04 to 0.28 ± 0.04 ka.

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Appendix 1

Single aliquot data and plots for Florisbad, South Africa

Sample specific data including:-

- list of De's derived from individual grains
- calculated statics for De distribution (Skewness, kurtosis and sorting)
- calculated means based on a range of statistical models including Finite Mixture Modelling (FMM)
- histogram plot of distribution of De within a sample
- probability density plot (curve) with ranked De data (black points) and probability mean (uppermost red point).

Field Code:	**SP2 TOP**	**Site:**	**Florisbad**
Lab Code:	**Shfd10078**		Freestate, RSA
Aliquot Size:	**Small**		

Aliquot	**Palaeodose (Gy)**	**error**
1	0.472	0.037
2	0.432	0.027
3	0.425	0.020
4	0.445	0.023
5	0.641	0.040
6	0.445	0.027
7	0.439	0.044
8	0.425	0.020
9	0.405	0.017
10	0.459	0.023
11	0.385	0.013
12	0.405	0.023
13	0.506	0.013
14	0.735	0.024
15	0.472	0.013
16	0.466	0.013
17	0.499	0.027
18	0.472	0.013
19	0.573	0.017
20	0.445	0.020
21	0.459	0.013
22	0.439	0.037
23	0.412	0.047
24	0.439	0.020

De Distribution	**All Data**	**Minus Outliers**
Skewness	2.44	-0.14
Kurtosis	5.40	-0.10
Median	0.45	0.45
Sorting	0.12	0.06

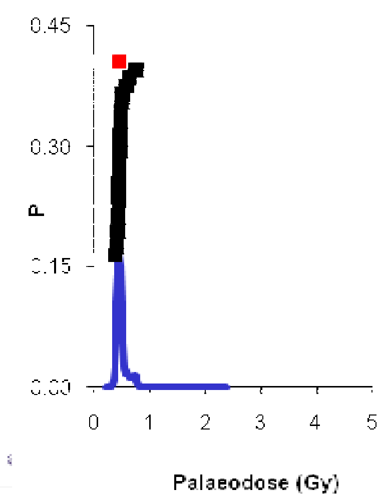
	De (Gy)	**error**
Minimum	0.38	0.01
Maximum	0.74	0.02
N	24	

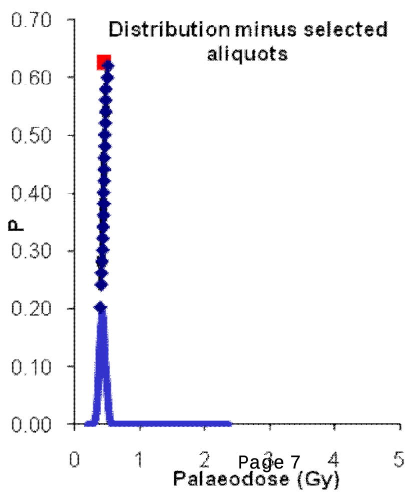
Unweighted	All Data	Minus Outliers
Mean (Gy)	0.47	0.44
SD	0.08	0.03
SE	0.02	0.01
N	24	21

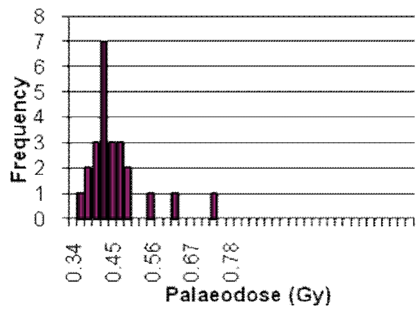
Weighted	All Data	Minus Outliers
Mean (Gy)	0.47	0.45
SD	0.09	0.07
SE	0.01	0.01
N	24	21

Probability	All Data	Minus Outliers
Mean (Gy)	0.45	0.45
SD	0.07	0.07
SE	0.01	0.01
N	24	21

Central Age Model	All Data	Minus Outliers
Mean (Gy)	0.47	0.45
SD	0.06	0.06
OD (all data)	13.92%	5.89%
N	24	21







Field Code:	**SP6 BOTTOM**	**Site:**	**Florisbad**
Lab Code:	**Shfd10079**		Freestate, RSA
Aliquot Size:	**Small**		

Aliquot	Palaeodose (Gy)	error
1	1.282	0.034
2	1.262	0.034
3	1.187	0.081
4	1.127	0.064
5	1.255	0.064
6	1.187	0.054
7	1.322	0.067
8	1.127	0.064
9	1.295	0.044
10	1.208	0.061
11	1.201	0.050
12	1.221	0.050
13	1.322	0.064
14	1.147	0.037
15	1.167	0.040
16	1.248	0.037
17	1.181	0.040
18	1.154	0.051
19	1.316	0.044
20	1.086	0.044
21	1.214	0.034
22	1.235	0.030
23	1.181	0.031
24	1.478	0.037

De Distribution	All Data	Minus Outliers
Skewness	1.50	-0.14
Kurtosis	2.19	-0.71
Median	1.21	1.21
Sorting	0.05	0.05

	De (Gy)	error
Minimum	1.09	0.04
Maximum	1.48	0.04
N	24	

Unweighted	All Data	Minus Outliers
Mean (Gy)	1.23	1.21
SD	0.08	0.07
SE	0.02	0.01
N	24	23

Weighted	All Data	Minus Outliers
Mean (Gy)	1.23	1.22
SD	0.10	0.08
SE	0.02	0.01
N	24	23

Probability	All Data	Minus Outliers
Mean (Gy)	1.22	1.21
SD	0.09	0.09
SE	0.02	0.02
N	24	23

Central Age Model	All Data	Minus Outliers
Mean (Gy)	1.23	1.22
SD	0.06	0.06
OD (all data)	5.68%	3.30%
N	24	23