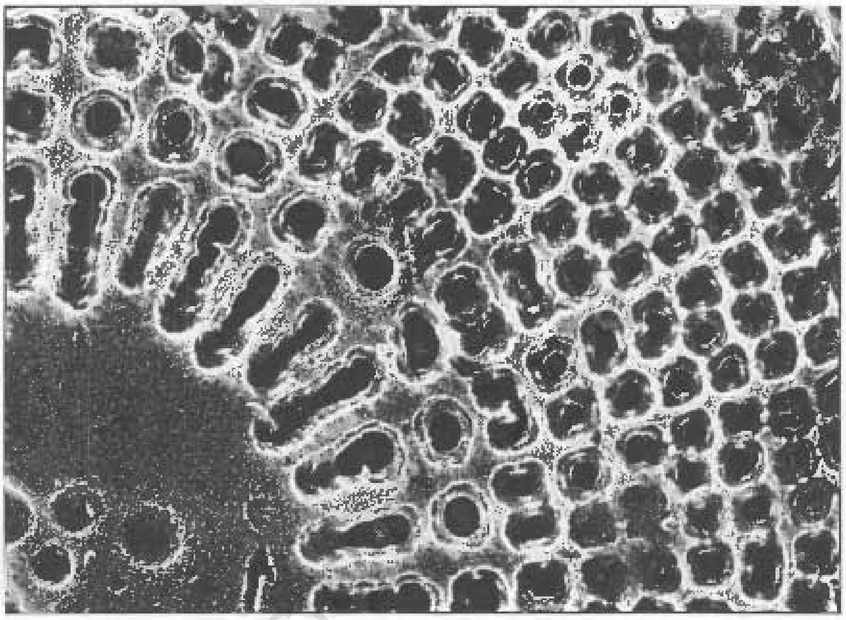
GEOLOGY OF AEOLIAN AND MARINE DEPOSITS IN THE SALDANHA BAY REGION - WESTERN CAPE, SOUTH AFRICA



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Per Martina Cucchi, Franco Medioli e la mia
Nonna che in maniera diversa, ma
significativa, hanno influito nella mia
crescita.

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ABSTRACT

The west coast of South Africa has been exploited for diamonds for most of the last century. Although some literature has accumulated over this period, the evolution of the coastal plain since the Cainozoic remains poorly understood. The aim of this thesis is to offer a multidisciplinary study of the evolution of coastal deposits in the Saldanha Bay area, along the southern part of the west coast. The environments investigated comprise lagoons, coastal dunes and shorelines. The ages of the deposits were obtained with radiocarbon dating, strontium isotope stratigraphy and biostratigraphy.

In the Langebaan Lagoon salt marshes the foraminiferal distribution in relationship to vegetation cover and salinities was recorded. In the transect studied three foraminiferal assemblages were identified. The information concerning the distribution of modern micro and macro benthos in the Langebaan Lagoon was then used to reconstruct palaeoenvironments in a fossilised marsh deposit at Monwabisi, on the False Bay coast.

Coastal dunes were investigated in the Sixteen Mile Beach complex which is also located in the Langebaan Lagoon area. The complex is composed of three distinct units: Sixteen Mile Beach, a 26 km long log-spiral beach of varying width; coast-parallel dunes and, in the southern part, a 24 km long dune plume with mobile and immobile dunes. The Holocene evolution of the complex was elaborated with grain-size analyses and 41 radiocarbon dates sample of both whole shells and sand-sized shell fragments. Human utilization of the area was studied dating *Patella* shells from middens.

The understanding of the Holocene evolution of coastal dunes adds useful information that can be used as a comparison to elucidate older dune deposits. Fossil dune deposits are exposed at Tabakbaai Quarry, just north of the town of Saldanha. A latest Miocene-Pliocene age for this deposit is proposed on the basis of strontium isotope stratigraphy. The close correspondence between the morphology and alignment of the active dune plume of the Sixteen Mile Beach complex and the fossil dune plume exposed at Tabakbaai Quarry suggest that conditions controlling the wind-blown sedimentation in the Saldanha Bay area have not changed much since the latest Miocene. In order to verify the consistency of a latest Miocene-Early Pliocene highstand, other Tertiary deposits in the area were studied. The study of phosphate deposits from the Bomgat Cave and the Langebaanweg Quarry has confirmed highstands during the Late Miocene and during the Early Pleistocene.

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Chapter 1 - Introduction

1.1 OVERVIEW

Scattered Late Cainozoic deposits have been preserved along the west coast of South Africa. The importance of these deposits and their evolution through time is of great interest to geologists because they contain marine and alluvial economic diamond deposits. Diamondiferous gravel has been actively mined since the beginning of last century, but the stratigraphic context, ages and depositional environments of these diamond-rich deposits remains poorly understood (Pether, 1986). The economic value of these diamond-rich deposits is responsible for the little published work as a result of the confidentiality clauses of the mining houses operating along the west coast.

The Saldanha Bay area (Western Cape Province) located in the southernmost part of the west coast, is the central focus of this thesis (Figs. 1.1 and 1.2). Even though the Saldanha area is of relatively low economic and mining interest, it has aroused international attention because of the discovery of several deposits rich in archaeological and palaeontological remains. The Mio-Pliocene fauna found at the Langebaanweg phosphate quarry (Hendey, 1973, 1981a, b), the discovery of a Middle Pleistocene cranium of *Homo sapiens* at Saldanha (Singer and Wymer, 1968) and the Late Pleistocene fossil human footprints found in the western flank of Langebaan Lagoon (Roberts and Berger, 1997), have highlighted the importance of these deposits.

Late Cainozoic sediment deposition in the Saldanha Bay area was controlled by changes in sea level, driven by polar ice advance and

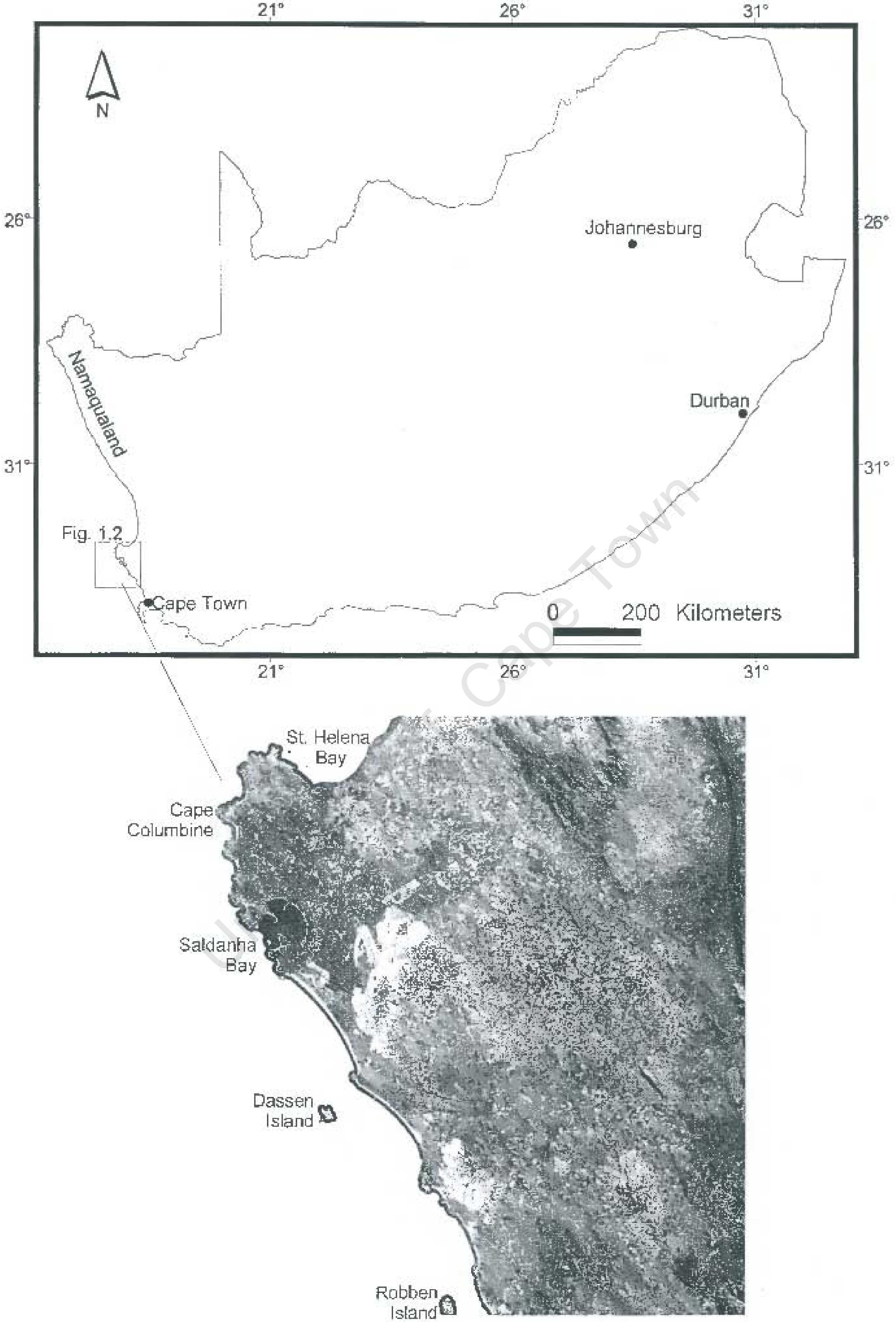


Fig. 1.1 Location of the Saldanha bay area and Landsat image of the southern part of the west coast (from St. Helena to Cape Town).

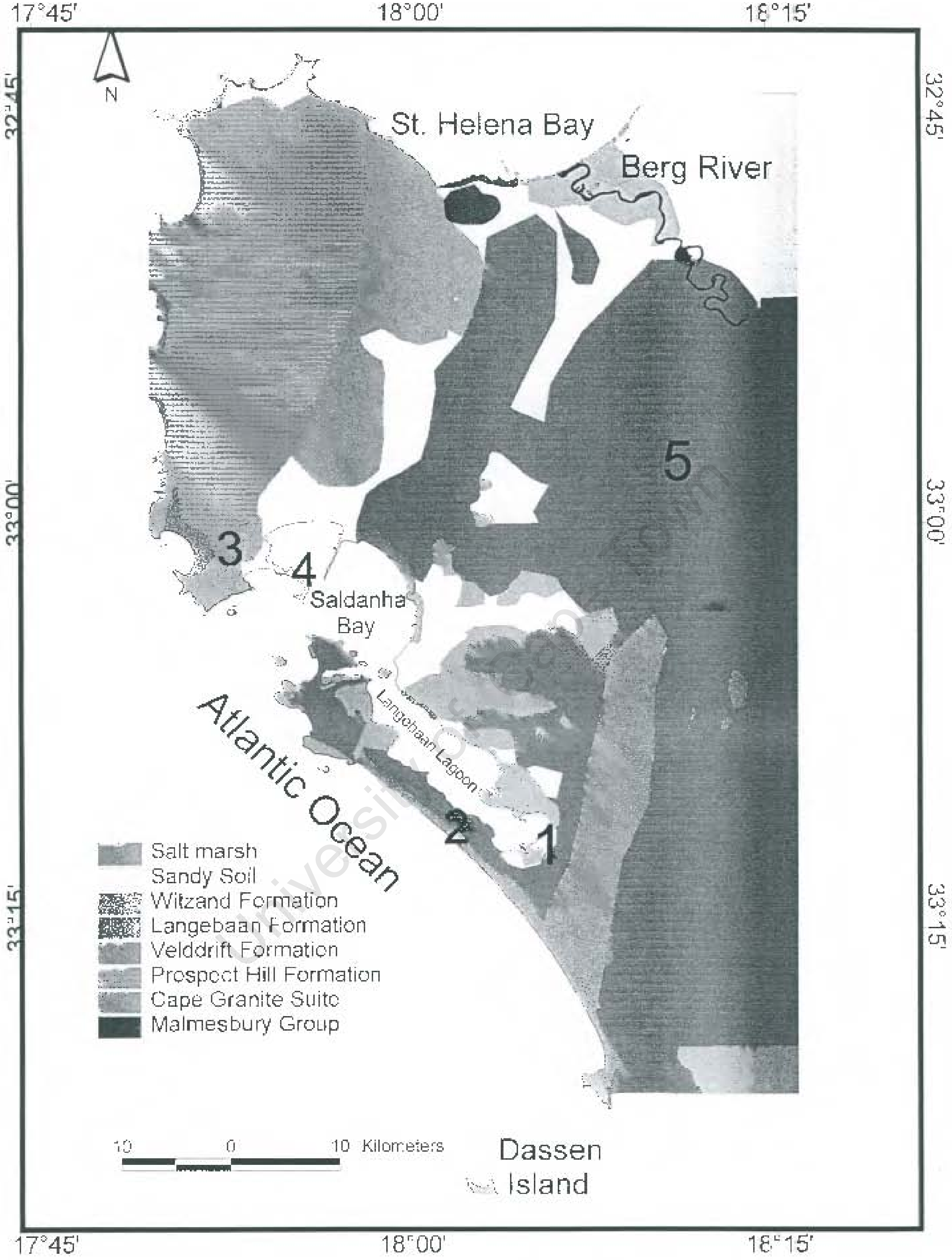


Fig. 1.2. Geology of the Cape Columbine area with the studied localities (1: Langebaan Lagoon salt marsh, 2: Sixteen Mile Beach complex, 3: Tabakbaai Quarry, 4: Bomgat Cave, 5: Langebaanweg Quarry). The Velddrift and Langebaan Formations are approved by SACS (1980), while the Witzand and the Prospect Hill are not approved by SACS (1980). Refer to Chapter 2 for discussion.

retreat. During sea-level lowstands, the coast moved further out to sea and subarial erosion took place on the emerged coastal plain as well as deposition of dune sand. With a rise in sea-level, the sea invaded these environments and deposition of marine strata occurred directly on the terrestrial units. Global sea-level changes during the Cainozoic show several cycles of fluctuations. The global sea-level curve applied to the interpretation of continental margin strata worldwide has been initially published by Vail et al. (1977) and later modified by Haq et al. (1987). This curve of sea-level changes was constructed from the correlation between chronostratigraphical, magnetostratigraphical and biostratigraphical data in different parts of the world. The global sea-level curve shows systematic patterns of changes in sea-level at different times. Vail et al. (1977) recognised first, second and third order cycles with time spans that range between many tens of millions of years for first-order cycles to a few million years for third-order cycles. Fifth (100 kyr – eccentricity), sixth (41 kyr – tilt) and seventh (20 kyr – precession) of Milankovich cycles of the Plio-Pleistocene are not depicted as part of the global sea-level curve. These cycles are, however, well documented from studies of oceanic cores and ODP cores, especially those that have measured the standard oxygen isotope stages (e.g. Chappell and Shackleton, 1986; Raymo et al., 1989; Shackleton and Opdyke, 1973, 1976). The fundamental problems of a global sea-level curve may be summarised in two points (Carter, 1998): 1) the fact that the most used correlation tool for the Cainozoic – micropalaeontology – has a resolving power no better that 1 Myr (Miller and Kent, 1987; Miall, 1991); 2) the degree to which tectonics interacts with relative sea-level rise or fall. Several studies undertaken to test the universality of the events suggested by the global sea-level curve have shown mismatches between stratigraphic data and the global model (e.g. Carter et al., 1991; Hubbard, 1988; Hubbard et al., 1985; Aubry, 1991, 1995). More encouraging results were, more recently shown, by a ocean drilling transect across the New Jersey (U.S.A) continental margin, in which good correlation exists between the mid-late Cainozoic global sea-level curve and the core data (Miller and Sugarmann, 1995; Pekar and Miller, 1996).

Changes in sea-level around southern Africa during the Cainozoic have been discussed by numerous authors (e.g. King 1967; Haughton, 1969; Truswell, 1970; Dingle 1973; Dingle and Scrutton, 1973; Tankard, 1976a, b; Siesser and Dingle, 1981; Pether, 1994; Pickford and Senut, 1999; Compton et al., 2002). In very general terms, these authors reported high sea-levels in the Late Palaeocene, Late Eocene, Middle Miocene and Early Pliocene, while low sea-levels in the Early Palaeocene, Middle Eocene, Oligocene, Late Miocene and Late Pliocene. The evidence for these sea-level changes comes from onshore marine sediments found in the east and west coast of South Africa, as well as unconformities observed in seismic profiles of the offshore sedimentary successions. The timing for sea-level changes in southern Africa are, however, diverse. The difficulties encountered in studying the sea-level changes in southern Africa are that marine onshore strata tend to be poorly fossiliferous and the time spans of these fossils is poorly understood (Pickford and Senut, 1999). Figure 1.3 highlights the main differences between the sea-level curves of Haq et al. (1987), Siesser and Dingle (1981), and Pickford and Senut (1999) in the Cainozoic.

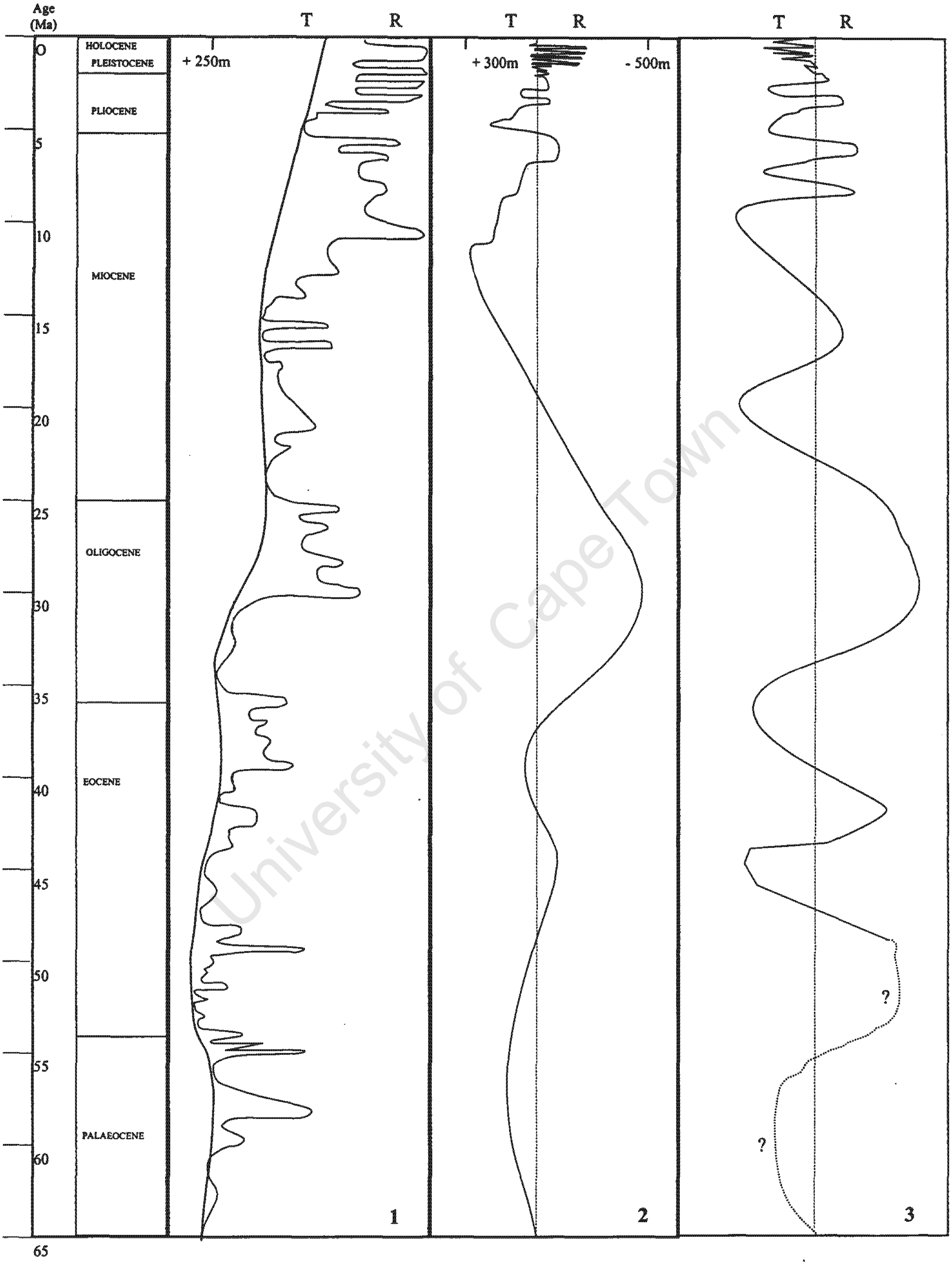


Fig. 1.3. Sea-level changes in the Cainozoic. 1 - The global sea-level curve (Haq et al., 1987). 2 - The Siesser and Dingle curve (1981) modified after Dale and McMillan (1999). 3 - The Pickford (1998) curve modified after Pickford and Senut (1999).

T= Transgression R= Regression

The curves obtained from sediment collected along the west coast (2 and 3, Fig. 1.3) differ for the Palaeocene, Eocene and Oligocene in the number of transgressive events. Siesser and Dingle (1981) note that the Oligocene-Early Miocene erosional surface was identified in the seismic records at a constant depth of 425 to 532 m, concluding that the Oligocene regression was in the order of 500 m. Pickford (1998) recognised three major highstands during the Miocene compared to only one at the end of the Miocene by Siesser and Dingle (1981). This is due to the fact that Neogene deposits found along the west coast were considered to be Plio-Pleistocene in age (Carrington and Kensley, 1969; Dingle, 1973), whereas these deposits were assigned to the Miocene by Pickford (1998) and Pickford and Senut (1999). The concordance in general of the Cainozoic curves for southern Africa with the global sea-level curve is an important indication that transgression and regression were global-scale marine events, and were not due to uplift or downwarping of the studied continental margin (Carrington and Kensley, 1969; Siesser and Dingle, 1981). The sea-level curve proposed by Siesser and Dingle (1981) has been often used in the literature for sea-level fluctuations in southern Africa. Considering that their sea-level curve includes a tectonic component, which is very poorly constrained for the Tertiary, the global eustatic curve of Haq et al. (1987) has been preferentially used in more recent literature (Compton et al., in prep.). For this thesis, mostly the Pickford and Senut (1999) sea-level curve has been used.

For the Quaternary, the curves presented in Fig. 1.3 are not comparable mostly because of the paucity of these strata along the west coast as well as the difficulties in dating them. However, Late Cainozoic strata were recognised along the west coast of South Africa as series of paleoshoreline deposits ("raised beaches") at different elevations above sea level (Pether, 1994). These paleoshoreline deposits yield evidence of fluctuating sea-level during the Miocene, Pliocene and Pleistocene, but their exact time of deposition has been very controversial (De Villers and Söngle, 1959; Stocken, 1962; Hallam, 1964; Keyser, 1972; Pether, 1986, 1994; Corbett, 1989, 1996). For example, Stocken (1978) estimated a Middle Miocene age for the highest 'raised beach' deposits (90 m asl), while others have proposed a Latest Miocene, Pliocene and Pleistocene for the 90 m asl deposits (Pether, 1986; Corbett, 1996). Leser, in Besler et al. (1994) offered an overview of the 'raised beach' deposit in the northern part of the west coast and unlike previous workers, he proposed a Pleistocene age for most of these deposits including one at Grootmis (Namibia) at 120 m asl. All these studies carried out in the last 50 years have shown that the interpretation of these deposits is not a simple matter. During the Quaternary, as discussed above, and according to oxygen isotope records of marine shells (Shackleton, 1987) and uplifted coral sequences (Chapell et al., 1996), sea-level fluctuations of large amplitude (on the order of ±100 m) and high frequency (roughly every 100,000 years) have occurred repeatedly. These glacial/interglacial cycles operate on an approximate 100,000 year cycle that is related to variations in Earth's orbital parameters as well as instabilities in the continental ice sheets and ocean circulation (Williams et al., 1995). The last complete cycle covering the last 140,000 years is shown in Figure 1.4. The sea-level curve used in the figures is estimated from changes in the oxygen isotopic composition of calcareous fossils (Shackleton, 1987) and from dated corals from uplifted islands in the southwest Pacific (Chappell et al., 1996).

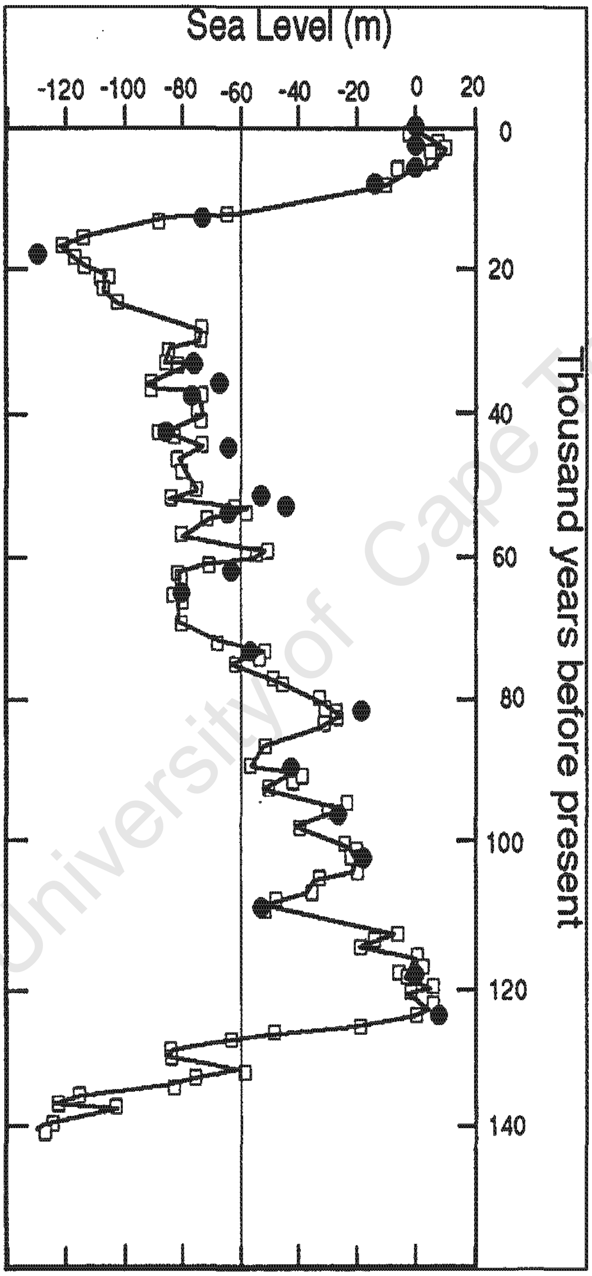


Fig. 1.4. Sea-level history of the last 140,000 years from the oxygen isotope record of marine shells (Shackleton, 1987; open squares) and uplifted coral sequences (Chapell et al., 1996; filled circles).

Changes in sea-level have greatly influenced the coastal evolution of the Saldanha Bay area and its palaeogeography as well as created different depositional environments. Recent work based on terrestrial vertebrate fossils along the west coast of South Africa (Pickford, 1998; Pickford and Senut, 1999) has indicated a sea level of 30-40 meters during the latest Pliocene-Early Pleistocene. A 40 m sea-level rise would have flooded most of the lowland areas with the creation of two major islands just north of Saldanha Bay (Fig. 1.5). A sea-level drop of 125 m (Last Glacial Maximum) would have extended the coastal area 20-30 km offshore (Fig. 1.6). The different position of the coastline would have created major changes in the Saldanha Bay area environments. In particular, the coastal dunes are significant and sensitive indicators of changing conditions because dunes are 'soft landform' which respond rapidly to the dynamic driving forces that make them (Rust, 1990).

The objective of this work is to study the coastal evolution, through time, of the Saldanha Bay area in relation to the previously discussed Late Cainozoic sea-level changes. To achieve this objective, modern coastal environments have been studied. The understanding of the factors influencing modern deposition and biota were then used to elucidate past depositional environments. By placing emphasis primarily on the sedimentology and evolution of modern lagoonal and aeolian deposits, this study differs from previous accounts of the southwestern coastal-plain, in which emphasis was placed on the marine onshore deposits (e.g. Tankard, 1975a, b, 1976a, b) or on aeolianites (Roberts and Berger, 1997; Pether et al., 2000; Roberts and Brink, 2003).

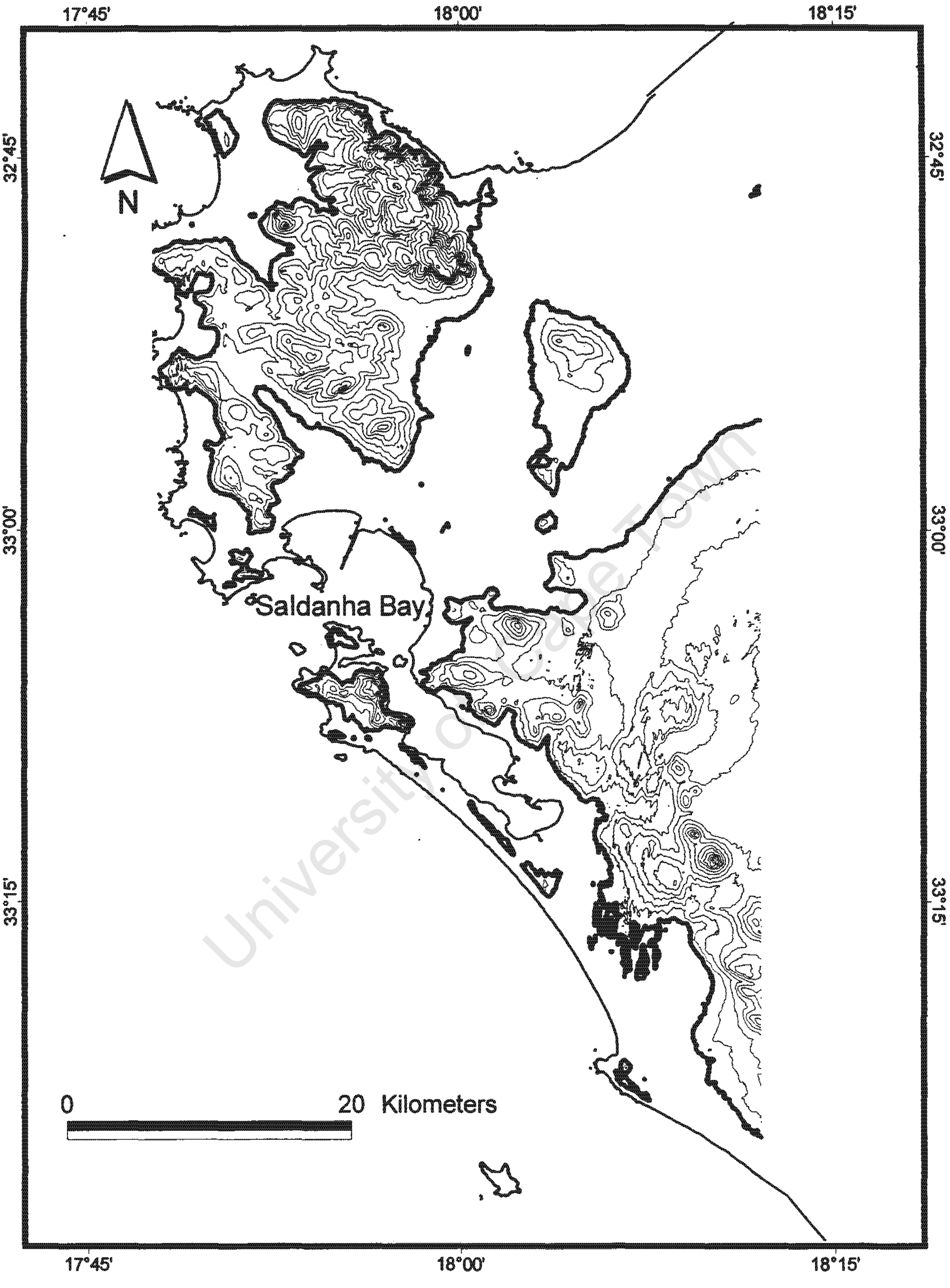


Fig.1.5. Palaeogeography of the Saldanha Bay area in a case of the sea level highstand of 40 m (contour lines every 20 m from 20 to 120 m above msl).

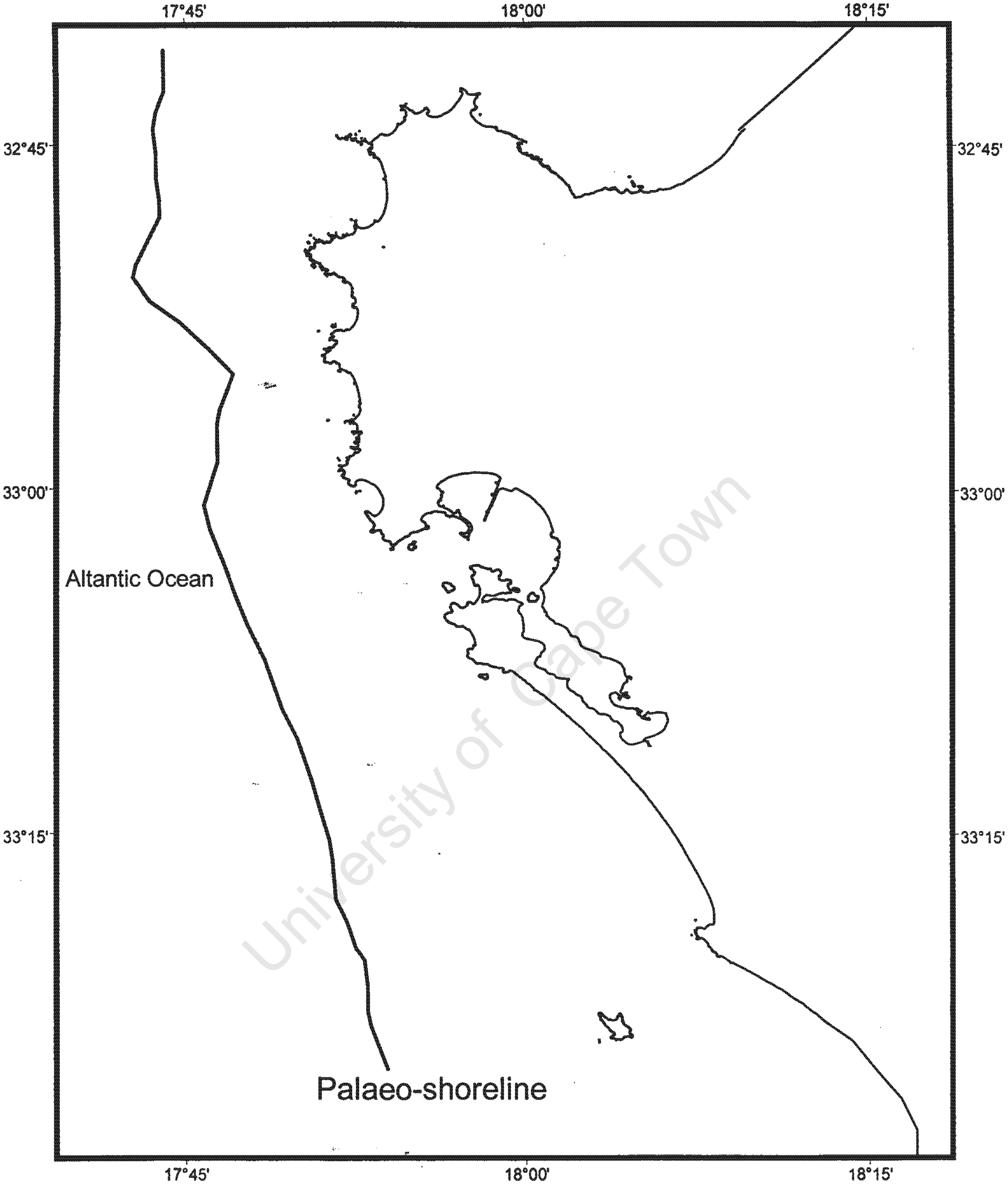


Fig.1.6. Palaeogeography of the Saldanha Bay area in the case of a sea-level lowstand of 125 m (Last Glacial Maximum).

1.2 OBJECTIVES

Within the Saldanha Bay region several localities have been selected (Fig. 1.2) where either no previous studies had been carried out (Sixteen Mile Beach complex, Langebaan Lagoon salt marsh), or scientific controversy indicates a variety of depositional environments and age of deposition (Langebaanweg Quarry, Tabakbaai Quarry, Bomgat Cave). The scope of the present study is (for locations refer to Fig.1.2):

The first objective of the present study is to describe the foraminiferal assemblages and the floral cover from the southern end of the Langebaan Lagoon salt marsh. This will be one of the few studies undertaken in southern Africa concerning foraminiferal distributions in modern environments. The information obtained from a transect in the Langebaan Lagoon salt marsh, will be then used as a comparison to a fossil deposit outcropping at Monwabisi Beach on the False Bay coast. The location of the Monwabisi deposit is 110 km south of the Langebaan Lagoon, therefore, outside the location of the central part of this thesis. However, the Monwabisi outcrop has been studied because it represents one of the few outcrops along the western coastal margin of South Africa that have preserved muddy layers containing macrofauna similar to the ones of the Langebaan Lagoon salt marsh.

The second objective is to understand the evolution of the Sixteen Mile Beach complex, with an emphasis on determining the origin and age of dune deposits. The Sixteen Mile Beach complex may be divided into a beach, coast-parallel dunes and a sand plume. The morphology and grain size composition of Sixteen Mile Beach is described with some hypotheses for the sources of sediments that form the complex as well as how sea-level changes during the Late Quaternary influenced dune morphology.

The third objective is to elucidate the depositional environment and age of deposition of the Prospect Hill Formation exposed at the Tabakbaai Quarry. The age the aeolianites exposed in the Quarry is controversial in the literature, ranging from Middle Miocene to Early Pleistocene. The use of strontium isotope stratigraphy on selected samples will help to detect the age of these aeolianites as well as reconstruct a coastal palaeogeography of the area.

The forth objective is to determine the age of onshore phosphorites from the Bomgat Cave and Langebaanweg Quarry. The ages of these phosphorite-rich deposits are also controversial in the literature. An understanding of their ages and depositional environements will add important information on sea-level changes in the area.

Ideas and methodologies used in this thesis provide a platform from which studies of the west coast of southern Africa can continue. There is no doubt that better refinement of age relationships is neccessary. It is hoped that further work will be undertaken and extended over a wider region, in particular to document the patterns in the grain size varations, carbonate content and fossil assemblages.

1.3 STRUCTURE OF THE THESIS

The remainder of this Chapter explains the types of coastal environments studied. The literature review and regional geology are summarised in Chapter 2. Chapter 3 describes the foraminifera of the Langebaan Lagoon and their application to the interpretation of depositional environments of a previously unstudied deposit at Monwabisi Beach. In Chapter 4 a detailed description of the Holocene evolution of the Sixteen Mile Beach complex, composed of Sixteen Mile Beach, coast-parallel dunes and an inland active dune plume, is presented. Chapter 5 presents a SIS evidence for the interpretation of the age of the aeolianites north of Saldanha and discusses the correlation between marine and aeolian deposits in the Tabakbaai Quarry area. Chapter 6 comprises the description of sedimentary and palaeontological features of the marine Varswater Formation outcropping in the Bomgat Cave and in the Langebaanweg Quarry, and includes Sr isotopic evidence of the age of these deposits. Chapter 7 is a concluding summary and discussion of the coastal evolution of the Western Cape with a section on suggested future research.

1.4 COASTAL ENVIRONMENTS STUDIED IN THIS THESIS

The major coastal environments studied in this thesis comprise: a) lagoons and salt marsh (Fig. 1.7), b) rocky and sandy shorelines and c) dunes (Figs. 1.8 and 1.9).

a) Lagoons and salt marsh

Lagoons form where coastal embayments or depressions are separated from the adjacent sea by a barrier (Cooper, 1994). The form of the coastal lagoon depends on the shape of the inlet or embayment enclosed and the configuration of the embayment that encloses it (Bird, 1972). Langebaan Lagoon (Fig. 1.2) parallels the Atlantic Ocean and has a slightly higher salinity than the open sea. The lagoon can be divided into four physiographic units that are closely related to the bathymetric response of specific energy levels (Flemming, 1977): 1- tidal channels, 2- tidal flats and sandbanks 3- salt marshes (Fig. 1.7). All around the lagoon, except where rocky coasts occur, the lagoon is bordered by salt marsh. Relative sea-level changes have important consequences on the distribution of the microbenthos and plants. O'Callaghan (1993) distinguished a lower marsh area with carpets of marine grass (*Zostera capensis*), a middle marsh area with *Triglochin bulbosa*, *Sarcocornia perennis*, *Limonium depauperatum*, *Chenolea diffusa* and an upper marsh assemblage of *Suada inflata*, *Sarcocornia pillansii*, *Disphyma crassifolium* and *Pulcinellia augusta*. Foraminiferal assemblages of the Langebaan Lagoon and their relation with vegetation cover and substrate are presented in Chapter 3. The understanding of the foraminiferal assemblages in the present-day lagoon has been used in order to reconstruct the palaeo-salt marsh deposit at Monwabisi. Foraminiferal assemblages from salt marshes have been little studied in southern Africa except for recent work of Dale and McMillan (1999) and Simpson (2003), and this contribution adds useful information that can be applied to studies of sea-level changes.

b) Rocky and sandy shorelines

Rocky coasts are the legacy of marine and subaerial processes that have been in operation for thousands of years (Trenhaile, 1987). The type and intensity of these processes varies with relative sea-level, climate and rock type.

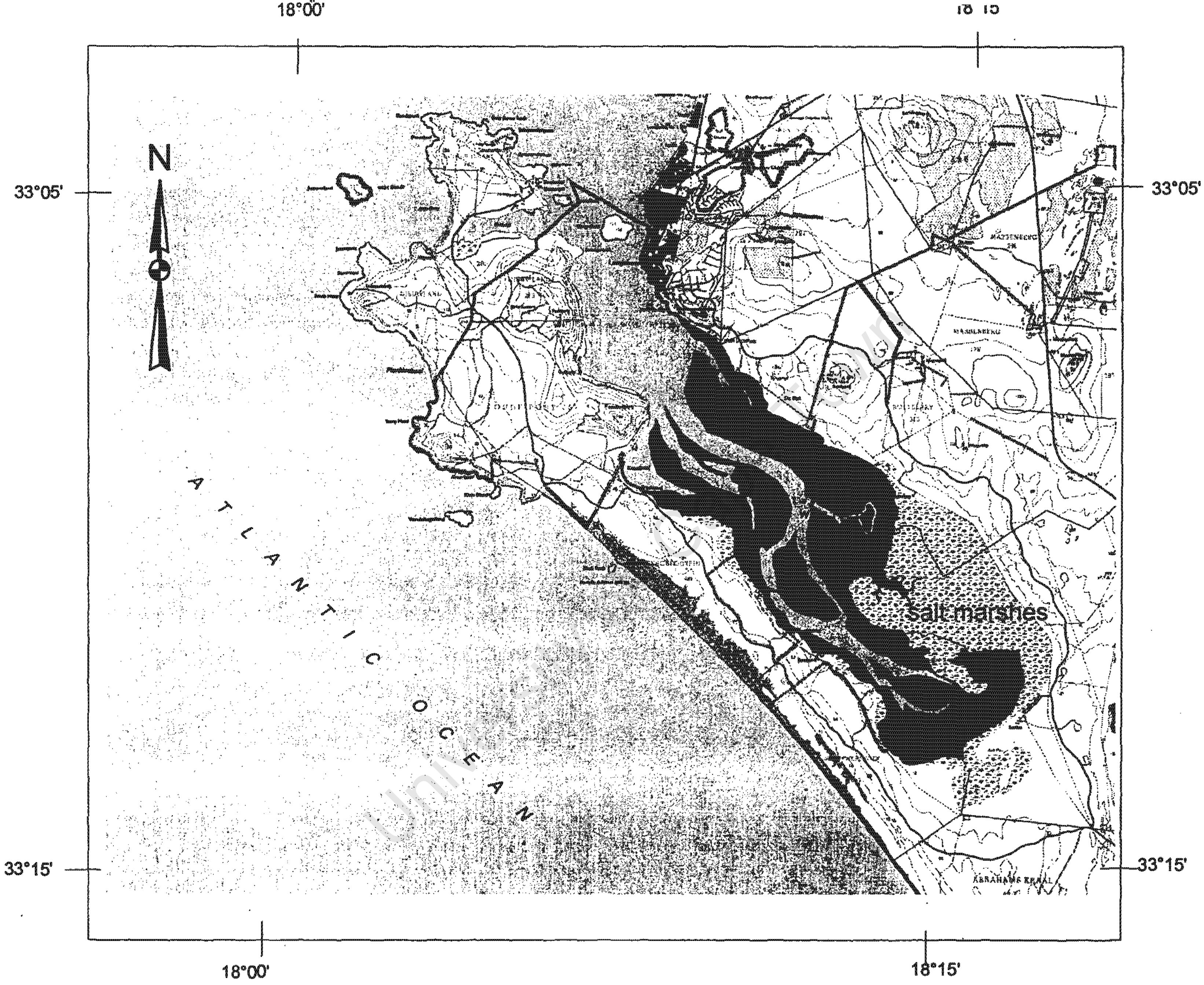


Fig.1.7. Map 1: 50,000 showing Langebaan Lagoon, the tidal channels, tidal flats and well developed salt marshes.

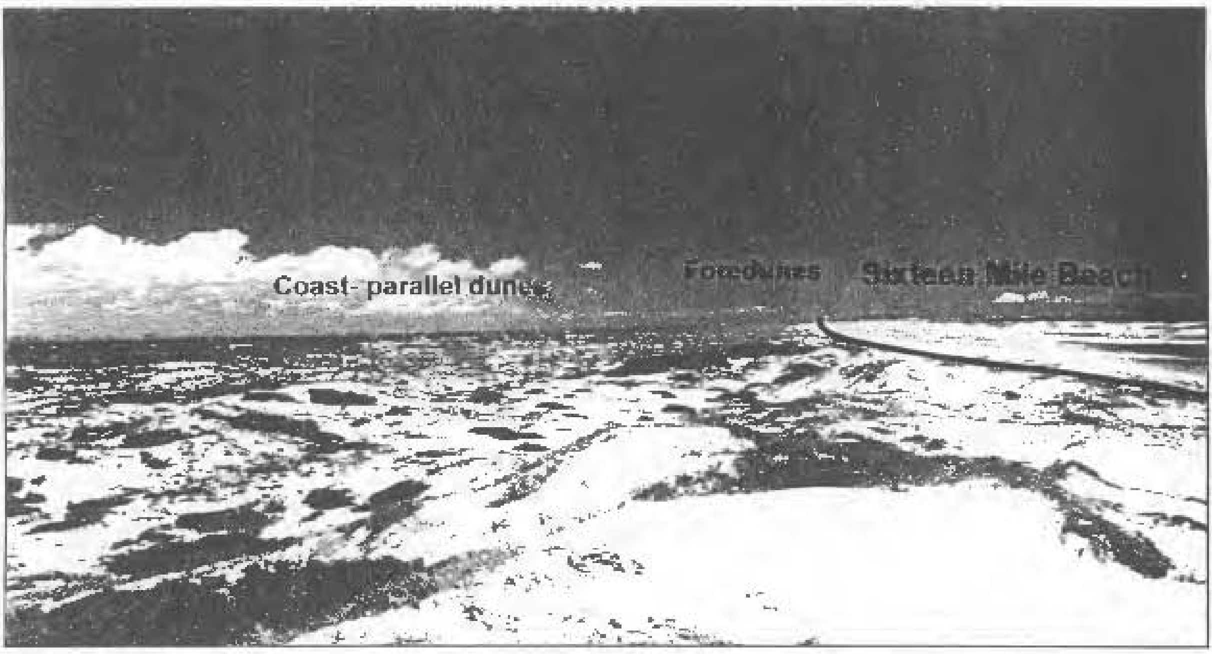


Fig. 1.8. Sixteen Mile Beach with coastal dunes.

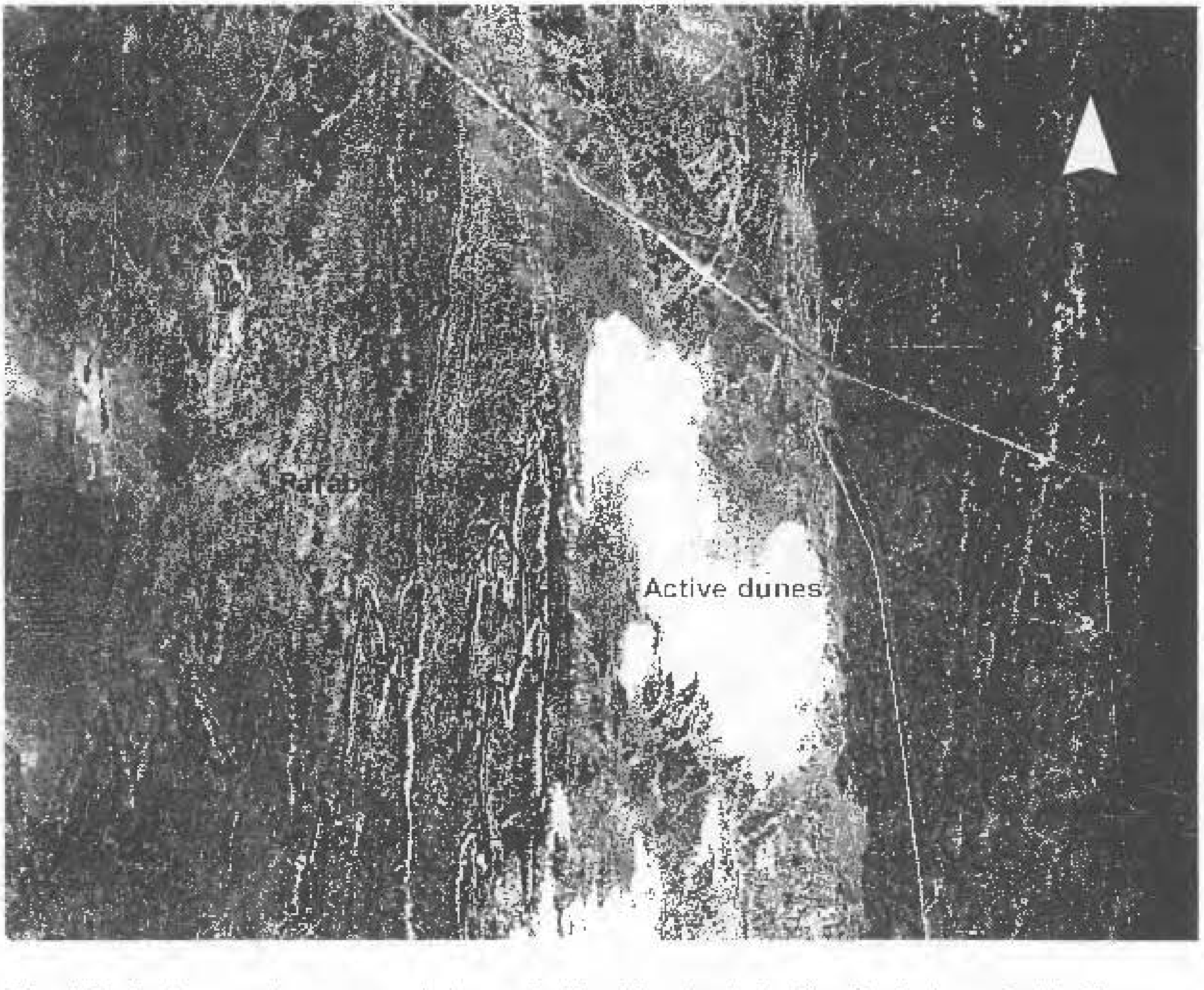


Fig.1.9. Active and vegetated dunes in the Yzerfontein-Geelbek dune field. The section is 2 km wide.

While modern coastal literature focuses on beaches that respond quickly to environmental changes, we can only speculate on the mode of development of rocky shores. The primary erosional agent on rocky coasts is mechanical wave action. Abrasion takes place as the material is washed, dragged and thrown against a coastal cliff. Another very important, sometimes dominant, factor in weathering of rocky shores is bioerosion. Algae, fungi and lichen are the pioneer colonisers in the inter and supratidal zones (Branch and Branch, 1981). They act as rock borers and their effect allows subsequent occupation by gastropods, chitons, echinoids and other grazing organisms (Branch and Branch, 1981). Bioerosion is accomplished by barnacles, sipunculoid and bivalve molluscs.

In rocky shores, animals are zoned in bands related to the highly stressed environment caused by the impact of tide and wave energy on the shore. These bands are significant when found fossilised because the depositional environment can be reconstructed. Along the west coast of South Africa four distinct zones have been recognised (Branch and Branch, 1981). At low tide level algal beds form the band called the infratidal zone. Above this, there is usually a different algal-dominated zone called the lower Balanoid (=Barnacles) zone. Only in the upper Balanoid zone are limpets and barnacles most abundant. Higher on the shore very few species of marine animals are found with the exception for *Littorina* spp. (Branch and Branch, 1981).

Rocky shores have been marginally studied in this thesis. Rocky outcrops border Sixteen Mile Beach where several rock pools are present. Foraminifera without signs of abrasion were collected in these rocky pools and this led to the conclusion that the surf zone along the study beach is too rough to allow these unicellular organisms to live (Chapter 4). Along the Western Cape coastline, in the proximity of rocky outcrops, shelly gravel beds are often found. These deposits are formed almost exclusively of shells and shell fragments mainly of *Patella* spp., black mussels and barnacles. The importance of these shelly gravels is discussed in Chapters 5 and 6.

Beaches are accumulations of sandy sediment deposited by waves and currents in the shore zone. The nature of the beach sediments is related to the rock composition of the adjacent cliffs. Sand can also be brought in the beach by longshore drift or by sand carried shoreward from the sea floor. The dynamics of beach sediment are therefore determined by the balance of supply from these various sources against the removal of sand by wind to build coastal dunes. Beach dynamics can be used as a model to represent and understand the condition under which coastal areas develop and produce coastal dune features. In Chapter 4, the evolution of the coastal area of the Sixteen Mile Beach complex is studied, using sedimentological and radiocarbon dating approaches. The provenance of the sediment, coastal evolution since sea-level reached its present-day position, and human utilisation of the coast are analysed and described. The evolution of this coastal complex is compared to those of other coasts, such as in the Eastern Cape (e.g. Illenberger and Verhagen, 1990). Australian studies are often cited in this thesis, partly because little work has been undertaken on coastal evolution in southern Africa, and partly because the coastal features of Australia have been extensively studied, and climate and often oceanic circulation are similar to that of South Africa.

On coasts exposed to ocean swell, the direction of the waves produces transverse swash and longshore transport. Understanding longshore transport is important for coastal studies and also for the location of harbours and as in the case of the west coast of southern Africa, for the exploration of diamond deposits. Large cliffed promontories or offshore islands can interrupt longshore drift and separate coastal sediments creating a striking difference in the nature of the beaches in the adjacent embayments. South African beaches are smoothly-curved, concave seaward, and they have been shaped by strong wave action (Tinley, 1985). Sixteen Mile Beach (Fig. 1.2) is a log-spiral beach facing the Atlantic Ocean. Grain-size analyses of the sand, beach face profiles and distribution of calcareous sediment have been studied along Sixteen Mile Beach (Chapter 4). Longshore drift provides most of the sand along this coast. Longshore drift along the Western Cape coastline area is to the north (Swart and Flemming, 1980), and it plays an important role in the type of sediments found in the different beaches of the Western Cape. Sandy beaches to the south of Saldanha Bay contain 45 wt% calcium carbonate, whereas sandy beaches to the north of Saldanha Bay contain up to 83 wt% calcium carbonate. Chapters 4, 5 and 7 offer a possible explanation linked to longshore transport for the striking difference in sand mineralogy and composition along the beaches of the Western Cape. The understanding of the different mineralogical composition of these beaches may be related to the offshore environments or to the extensive onshore coastal dune deposits that may trap the sand once removed from the beach. The continental shelf along the west coast is generally wide and deep having a defined shelf break that occures at depth of 400 m to the west of Cape Columbine (Birch, 1975). The majority of the continental shelf lacks a Quaternary sediment cover or has only a thin (usually less than two meters) veneer of Quaternary sediments (Rogers, 1977; Rogers and Bremner, 1991). The paucity of Quaternary sediments has been suggested to be the result of winnowing caused by strong currents during sea-level lowstands, that probably moved the sediments over the shelf break (Birch et al., 1991). The majority of the offshore Quaternary deposits are found off the deltas of major perennial rivers flowing along the west coast, namely the Orange, the Olifants and the Berg Rivers. Fluvial sediments from these rivers move northwards by longshore drift, while suspended material moves southwards, as far as Cape Town, by bottom currents (Birch et al., 1991).

c) Coastal dunes

Coastal dunes and dunefields form where there is an adequate sand supply and sufficient wind energy to move the sand. The coastline of southern Africa possesses both these attributes and hosts very impressive coastal dunes and dunefields (Tinley, 1985). In the Western Cape wind blown sand has been accumulating at least since the Miocene, producing extensive and often complicated sequences of dune topography (Tinley, 1985; Roberts and Berger 1997; Pether et al., 2000). Where the parent sand is calcareous, dunes can lithify as aeolianites and from pedogenic processes form calcretes and ferricretes. In the Western Cape, older dunes can be distinguished from younger ones because of the leaching of shell fragments and the deposition of iron oxides by percolating rainwater, that gives a reddish-yellow colour to the sand (Pether et al., 2000). In the young dunes the sand is fresh, white in colour and has not yet been leached of its shell content (Theron et al., 1992).

Coastal dunes occur in a variety of forms, depending on the orientation of the coast with respect to the wind and to the wind energy. Vegetation (which is directly related to the climate) plays a significant role in the development and evolution of coastal dunes, and especially significant is the ability of vegetation to cope with wind-blown sand. Coastal dunes in the Western Cape can be classified as: mobile, stabilised and cemented (aeolianites).

Mobile coastal dunes

In these dunes, the rate of sand influx is so great that plants are not able to grow and, as a consequence, the dunes are largely unvegetated and mobile. There are a large variety of mobile dunes depending on the interaction between wind and coastal orientation. In the active dunefield of the Sixteen Mile Beach complex, parabolic dune ridges and barchanoid dune ridges are present (Chapter 4). A parabolic dune is a U-shaped tongue of mobile sand with trailing ridges that are anchored by vegetation (Fig. 1.9). Parabolic dunes originate in a variety of ways, but generally develop from a point source of free-sand (Illenberger and Burkinshaw, 1996). Burning of coastal vegetation, phases of arid climate and excessive grazing by cattle may allow the reactivation of dunes that were previously fixed by vegetation. The evolution of these dunes is related to the onshore winds, and they can develop into parabolic dune ridges (Hesp and Thom, 1990). Parabolic dunes are often found disrupting a pattern of parallel dunes. Parabolic dunes retain their form as long as they remain vegetated in the trailing ridges (Bird, 1972). Barchanoid dunes are formed where winds are persistent from one direction. Barchanoid ridges are parallel rows of coalesced barchans with a single slipface on each arc (Tinley, 1985). In the Sixteen Mile Beach complex, parabolic (Fig.1.9) and barchanoid dune ridges are found in the Yzerfontein-Geelbek dune plume of the southern part of the complex. The morphological evolution as well as comparison with other active dunefields studies is addressed in Chapter 4.

Stable coastal dunes

In stable coastal dunes vegetation is able to cope with the sand supply and, as a consequence, plant growth stabilises them. The plants that form the fixed dunes can tolerate a limited amount of wind-blown sand, so if the onshore wind becomes too high the plants are destroyed and a mobile dune or dunefield starts to form. Examples of stable dunes in the Sixteen Mile Beach complex include pioneer dunes, foredunes and coast parallel ridges. Pioneer dunes or incipient/developing foredunes are the first set of dunes that form within pioneer plant communities. They may be seasonal if formed within annual plants and require invasion by perennial plants in order to survive (Hesp, 2002). Pioneer dunes are actively involved in the sediment dynamics of the coastal sand transport system, trapping sand in wind events and feeding this accumulated sand back into the system when they are eroded by wave action during storm events (Psuty, 1992). Pioneer dunes are seldom more than 50 years old and their age is governed by the interval between major storms (Illenberger and Burkinshaw, 1996). Foredunes or incipient foredunes, are shore-parallel dune ridges formed on the top of the backshore by aeolian sand which is trapped within vegetation. Foredunes range from flat terraces to markedly convex ridges. The morphology and evolution of the foredunes is complex and depends on several factors such as sand supply, sea-level, vegetation cover, wind forces and the extend of human impact and use (Hesp, 2002). Seaward progradation of the coast creates a succession of isolated relict foredunes that parallel the coast. As the coast continues to prograde the formation of a series of coast-parallel dunes reflects the characteristic patterns of the refracted ocean swell (Tinley, 1985). The height and spacing of coast-parallel dunes are a direct function of the rate of sand supply and the vegetation growth (Bird, 1972). In the Sixteen Mile Beach complex, coast-parallel dunes are present in the northern part (Fig. 1.10). Ages, morphology of foredunes and coast-parallel dunes in the Sixteen Mile Beach complex and their formation are discussed in Chapter 4.

Cemented dunes

Cemented dunes are moderately to well cemented by carbonate. Cemented dunes are often rich in bioclastic carbonate. Palaeowind directions can be inferred from cross-bedding. Old dunes comprising oxidised, leached and lithified sands occur along the west coast, and dune cordons have been found on the continental shelf at water depths of 110 m (Dingle and Scrutton, 1973). The ages of the cemented dunes in the Western Cape have been obtained from several absoluting dating methods (Partridge et al., 1984). The methods which have been used for dating cemented dunes in the Western Cape comprise, radiocarbon dating (^{14}C), uranium disequilibrium (U/Th), thermoluminescence (TL) and infrared thermoluminescence (IRSL) (Roberts and Berger, 1997; Conard, unpublished report SANParks, 2000).

In this thesis, radiocarbon dating and strontium isotope stratigraphy are used to infer the age of deposition of marine biogenic carbonate or phosphorites blown inland as constituents of the coastal dunes. Radiocarbon ages of Holocene dunes were obtained from the difference between radiocarbon ages of aeolian biogenic carbonate of coastal dunes and radiocarbon ages of carbonate beach sand (Chapter 4). Thermoluminescence dating has not been used in the Sixteen Mile Beach complex because the rapid turnover of active dunes exposes the sand to ultraviolet light, resetting the age of the grains. Strontium Isotope Stratigraphy (SIS) has been applied in this thesis for the Late Tertiary deposits (Chapters 4 and 5), where the age of the sediment is too old for using thermoluminescence. SIS is based on the fact that the $^{87}Sr/^{86}Sr$ ratio of dissolved marine Sr has changed slowly through geological time in response to changes in the input of Sr from continental weathering, hydrothermal circulation and from carbonate dissolution (Bralower et al., 1997; Howarth and McArthur, 1997). Because the residence time of strontium in the ocean is long (10^6 years) relative to the mixing time of the oceans (10^3 years) the $^{87}Sr/^{86}Sr$ value of the oceanic reservoir is considered to be homogenous (Hodell et al., 1990). This implies that SIS is independent of latitude, ocean basin or water depth if the strontium-bearing minerals have not been recrystallised after deposition. The strontium contained in carbonate shells of marine organisms, or in marine carbonate sedimentary rocks, records the ratio of $^{87}Sr/^{86}Sr$ of the ocean at the time that the shells formed and therefore can be plotted against the established marine Sr isotope record and used to derive a numerical age of formation. Considerable work has enabled an accurate documentation to be undertaken of the marine Sr isotope record, especially during the Cainozoic (De Paolo, 1986; De Paolo and Ingram, 1985; Hess et al., 1986; Koepnick et al., 1985). The nature of the $^{87}Sr/^{86}Sr$ ratio variation through time is particularly important in using SIS to solve stratigraphical and geochemical problems (Hodell, 1994). When SIS is used for dating, the quality of its numeric date depends upon factors such as the quality of preservation of the original $^{87}Sr/^{86}Sr$ ratio in the sample, the slope of the $^{87}Sr/^{86}Sr$ curve against numeric age and the accuracy of the age model used (Howarth and McArthur, 1997). The best-fit curve used in this work is the one proposed by Howarth and McArthur (1997). SIS has been used in this work, together with biostratigraphy, for dating a 20 km long stable and partly cemented dune plume with a type section exposed at the Tabakbaai Quarry (Chapter 5). In case of foraminifera-free sediments, SIS has been used for the first time in southern Africa for addressing the age of deposition and the age of reworking (Chapter 6).

Fig. 1.10. Holocene and Pleistocene coast-parallel dunes in the northern part of the Sixteen Mile Beach complex.

Chapter 2 - Literature review of the Late Cainozoic coastal deposits of the Saldanha Bay area

2.1 INTRODUCTION

Coastal evolution involves complex mutual processes that are dependent on several factors such as bedrock geology, tectonic setting, sediment type and availability, sea-level position, wave and current processes (Carter and Woodroffe, 1994). The bedrock geology of the coastal area controls the physiographic setting, as well as the abundance and mineralogy of sediments. Tectonic activity of the continental margins are related to sediment type (Partridge and Maud, 1987). Regional climate determines the energy regime that, together with the geological setting, influences waves, currents and intensity of physical weathering. During glacial sea-level lowstands material is transported from the coastal system over the shelf break to the abyssal plain, during marine transgressions shoreline wave action transports material from the shelf onshore (Bird, 1972). The interaction of all these processes shapes the coast as we see it today and it is often very difficult to separate the influence of one process from another. Tertiary and Quaternary records are extensive along the South African coastal plain (South Africa Commity for Stratigraphy, SACS 1980) (Fig. 2.1). The Western Cape has a wealth of geological, palaeontological, archaeological and pedological materials, the age of most of which is unknown or still controversial (Pether, 1994; Roberts and Berger, 1997; Dale and McMillan, 1999; Pickford and Senut, 1999; Pether et al., 2000; Roberts and Brink, 2003).

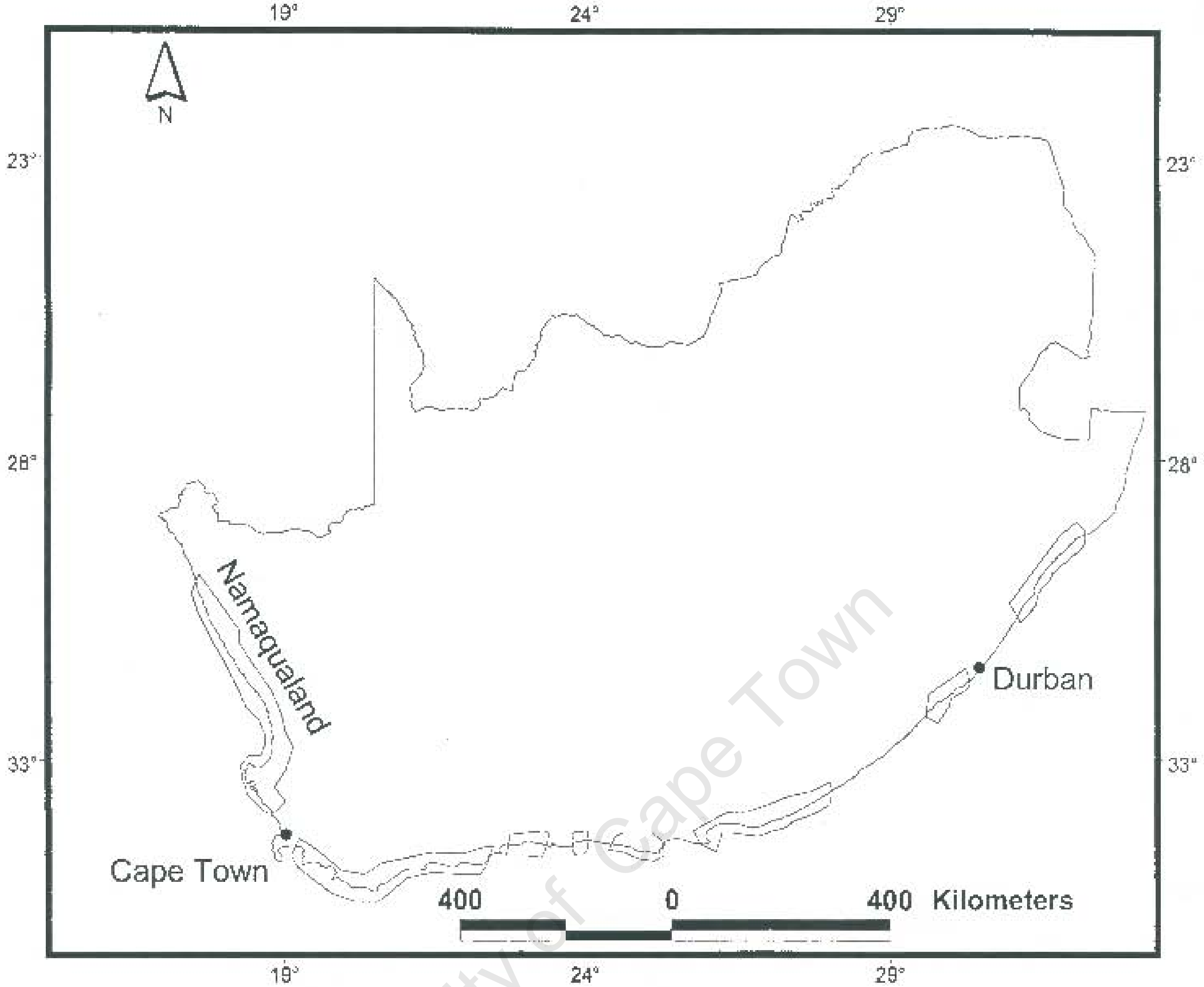


Fig. 2.1. Cainozoic strata along the South Africa coastline (after SACS, 1980).

2.2 REGIONAL GEOLOGY

The Palaeozoic basement in the Saldanha region comprises Late Precambrian Malmesbury slates and intrusive granites (Fig.1.2). An extensive low plain has developed in the less resistant Malmesbury metamorphic rocks between the coastal area and the Palaeozoic sandstone mountain ranges to the east (de la Cruz and Du Plessis, 1981). In this extensive coastal plain Tertiary to Recent sediments have been deposited. The working Group for the Cainozoic of the South African Committee for Stratigraphy (SACS, 1980) has tentatively proposed that the Cainozoic sediments of the west coast of South Africa be assigned the name *Sandveld Group* (Theron et al., 1992).

2.2.1 PRE-CAINOZOIC STRATA

The basement geology of the west coast varies considerably. In the Cape Columbine area the oldest deposits are the slates and greywackes and associated phyllites and quartzites of the Late Precambrian Malmesbury Group (Visser and Schoch, 1973). The Malmesbury basement is intruded by the Precambrian to Cambrian Cape Granite Suite (Fig. 1.2). The granites in the area have a general NW/SE trend subparallel to the coastline and give rise to the main topographic features of the region. Mafic (gabbros) and intermediate (diorites) intrusive rocks are also present within the Cape Granite Suite (Visser and Schoch, 1973). In the southern part of the Western Cape the Table Mountain Group outcrops. The thickness of the Table Mountain Group varies from 1200 to 2100 m, and it is subdivided into eight formations in which the sandstones of the Peninsula Formation are topographically the most predominant unit (Theron et al., 1992).

2.2.2 CAINOZOIC STRATA

Pre-Neogene strata are apparently absent onshore in the Western Cape (Pether et al., 2000). Offshore Cretaceous and Paleogene strata are present (Fig. 2.2). The Cretaceous sediments are mostly composed of shales, sandy mudstones and sandstones (Dingle et al., 1983). A distinct characteristic of the shales is the abundance of parallel and cross-bedded sand and silt laminae in the mudstones (Siesser, 1978a). Paleogene rocks are mostly composed of deltaic facies, nearshore marine glauconitic clays, quartzose limestones and phosphorites (Siesser, 1976; Rogers, 1980; Dingle, 1973).

Late Tertiary deposits in the Saldanha Bay area are very thin or absent and reflect the tectonic quiescence of the region (Pether et al., 2000). The age of these Late Tertiary deposits is controversial and very little is known except from boreholes and quarries (Theron et al., 1992). These deposits represent a variety of sedimentary settings including shallow marine, back-barrier, estuarine, fluvial and aeolian (Pether et al., 2000).

Tertiary deposits within the study area have been described and assigned to three formations (Table 1): Elandsfontyn Formation, Varswater Formation, and Prospect Hill Formation (Theron et al., 1992; Pether et al., 2000; Roberts and Brink, 2003).

Elandsfontyn Formation

This formation is described from boreholes and core descriptions (Rogers, 1980). It is nowhere subaerially exposed in the Western Cape (Theron et al., 1992; Pether et al., 2000). The formation comprises upward fining sequences of fine to coarse quartzose-sand with clay and lignite (Pether et al., 2000). The facies recovered record meandering river sedimentation (Rogers, 1980; Dingle et al., 1983; Theron et al., 1992). The Elandsfontyn Formation attains thicknesses up to almost 70 m east of Langebaan Lagoon (Pether et al., 2000).

The age of the Elandsfontyn Formation is controversial. Palynological and sedimentological studies were carried out by Coetzee and Rogers (1982) in

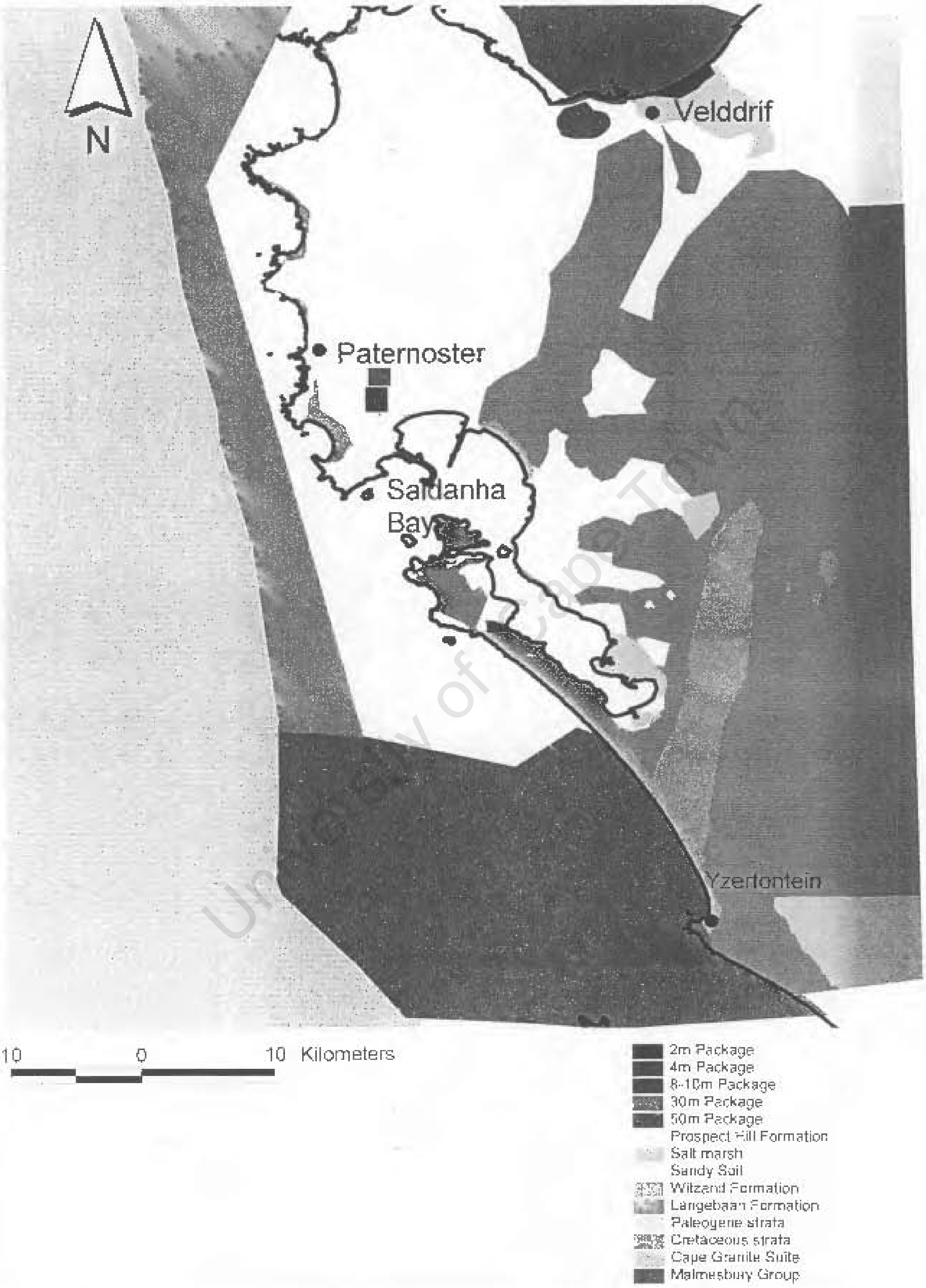


Fig. 2.2. Map showing the distribution of the strata on the Cape Columbine-Saldanha Bay area (modified after Rogers, 1980; Dingle et al., 1983; Pether et al., 2000). The position of the marine Packages in the Saldanha Bay area is based on the work of Dale and McMillan (1999).

AGE		FORMATION	MEMBER	
Holocene	SANDVELD GROUP	Witsand		widespread
Pleistocene		Langebaan (OIS 5c-5d)		
		Velddrif (OIS 5e)		
Middle Miocene)[a] OR (latest Pliocene / Early Pleistocene)[b] a: Pether et al. (2000); Roberts and Brink (2003) b: Dale and McMillan (1999)		Prospect Hill		limited extent
Miocene / Pliocene[a] a: vertebrate fossils stratigraphy (Hendey, 1981a,b, 1982; Dingle et al., 1983; Theron et al., 1992) (Dale and McMillan (1999) assign a Late Pliocene / Early Pleistocene biostratigraphic age)		Varswater	*Informal subdivision at Varswater Quarry:* • Calcareous Sand Member (Anyskop) • Pelletal Phosphorite Member • Quartzose Sand Member Gravel Member or Saldanha Formation (Middle Miocene)[a] a: Hendey (1976, 1981a, b), Tankard (1976a) and Dingle et al., (1983)	
Middle Miocene[a] OR Middle Cretaceous[a] a: Coetzee and Rogers b: Dale and McMillan (1999)		Elandsfontyn		

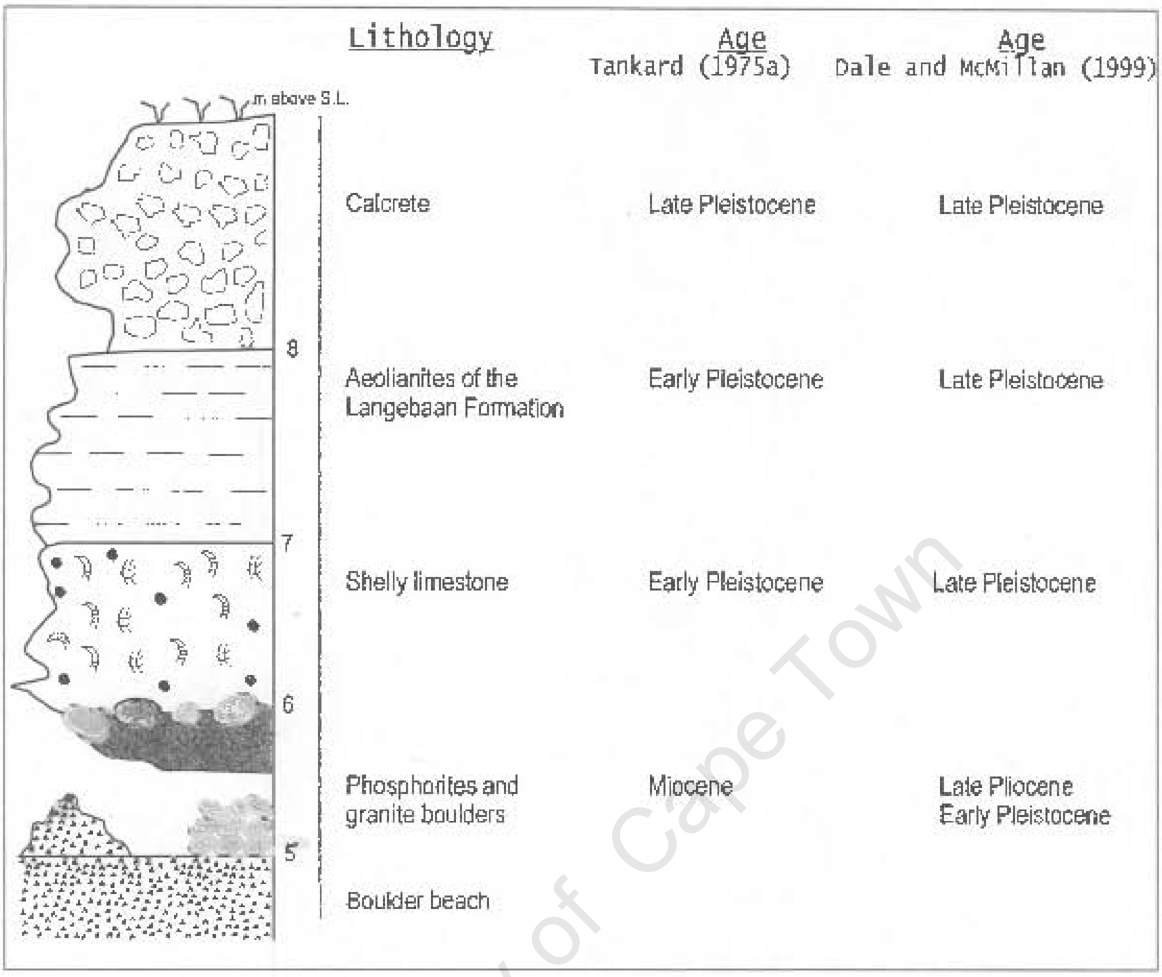
Table 2.1. A summary of the onshore Late Cainozoic geology of the Western Cape coast after Tankard (1975a, b, 1976a, b); Hendey (1976, 1978, 1981a, b, 1982); SACS (1980); Coetzee and Rogers (1982); Dingle et al. (1983); Theron et al. (1992); Roberts and Berger (1997); Pether et al. (2000); Roberts and Brink (2003).

the Saldanha-Hopefield region on clays recovered from boreholes. The pollen assemblages support a regressive succession of subtropical (from a tropical gallery forest to palm vegetation) to marsh during the Middle Miocene. Dale and McMillan (1999) sampled the Elandsfontyn Formation for a biostratigraphical study and, despite the lack of any identifiable foraminiferal tests, concluded that, based on the similarity in the lithologies with the offshore succession, the age of the Elandsfontyn Formation is Middle Cretaceous.

Varswater Formation

Late Miocene/early Pliocene strata are found in a phosphate mine at the Varswater Quarry in Langebaanweg (Fig. 1.2). Despite numerous studies carried out in this area, the lithostratigraphy remains confused and is not well understood. The Varswater Formation has been subdivided (Hendey 1981a, 1982, Dingle et al., 1979, 1983, Theron et al., 1992) into a Gravel Member (GM) a Quartzose Sand Member (QSM), which occurs on the northern side of the quarry, the Pelletal Phosporite Member (PPM) and the Calcareous Sand Member (CSM). A Middle Miocene age for the Gravel Member has been proposed (Hendey, 1976, 1981a, b; Dingle et al., 1983) on the basis of marine fossils found inside this member. The remainder of the Varswater Formation is Mio-Pliocene in age (5 Ma) (Hendey, 1976, 1978, 1981a, b; Dingle et al., 1983) and contains sparse warm water molluscan fauna (Hendey, 1981a, b). Hendey (1981a) postulates channel deposits of a proto-Berg river within the Quartzose Sand Member, which concentrated the bones of dead animals. Comparison with East African vertebrate remains has led Hendey (1981a) to this conclusion.

The Gravel Member of the Varwsater Formation was referred to as the Saldanha Formation consisting of a consolidated conglomeratic phosphorite that was first described by Tankard (1975a) from strata on the Hoedjiespunt Peninsula (Fig. 1.2). Figure 2.3 illustrates the exposure at Bomgat cave (Hoedjiespunt Peninsula) and the different ages proposed by Tankard (1976a) and Dale and McMillan (1999). The base of the deposit consists of phosphorites that are deposited on the Cape Granite. The overlying Early Pleistocene shelly marine limestone has preserved the articulated bivalve *Perna perna* and it is overlain by the Late Pleistocene limestone of the Langebaan Formation (Tankard, 1975a). The absence of warm-water marine organisms in the Saldanha coastline deposits dating back to Early Pleistocene, suggests that the oceanographic conditions were similar to those of the present day (Tankard, 1975a). Tankard (1976a) reported an abundance of foraminiferal tests in the phosphorite of the Gravel Member. Dale and McMillan (1999), using a variety of micropalaeontological rock-processing techniques, could not find any foraminifera in these phosphorites. They argue that Tankard (1976a) confused foraminifera for echinoid spines in cross-section, and that the abundant echinoid spines may indicate a Late Pliocene or Early Pleistocene age on the basis that echinoid spines are very rare in earlier successions found in the northern part of the Cape Province (Dale and McMillan, 1999). The calcarenites overlying the phosphorite have abundant *Ammonia* spp. that indicate lagoonal or estuarine environments (Dale and McMillan, 1999). A Late Pleistocene age for this deposit has been assigned by Dale and McMillan (1999), on the absence of *Ammonia* spp. in older deposit of the Western Cape.



Lithology	Age Tankard (1975a)	Age Dale and McMillan (1999)
Calcrete	Late Pleistocene	Late Pleistocene
Aeolianites of the Langebaan Formation	Early Pleistocene	Late Pleistocene
Shelly limestone	Early Pleistocene	Late Pleistocene
Phosphorites and granite boulders	Miocene	Late Pliocene Early Pleistocene
Boulder beach		

Fig 2.3. Idealised stratigraphical column at the Bomgat cave, Hoedjiespunt Peninsula, with the age of sediment proposed by Tankard (1975a) and Dale and McMillan (1999).

An idealised stratigraphy for the Varswater Formation based on Hendey's work (1981a, 1982) is summarised in Fig. 2.4. The Cape Granite in the Varswater Quarry is found at a depth between 40 m below to 20 m above the surface (Coetzee and Rogers, 1982) and it is overlain by the Elandsfontyn Formation. The Gravel Member is formed of well-rounded pebbles of quartzose phosphorite that is foraminifera-free and has not been directly dated by Dale and McMillan (1999). Dale and McMillan (1999), after analysing samples collected in the Pelletal Phosphorite Member, have concluded that, based on the foraminiferal assemblages, the age of the Varswater must be either latest Pliocene or Early Pleistocene. The Calcareous Sand Member aeolianites, interpreted to be a coastal barrier complex by Hendey (1981a), unconformably overlie the Varswater Formation. Recent research by Roberts and Brink (2003) has led to a proposal to name these aeolianites, best exposed at Anyskop in the Varswater quarry, the Anyskop Member of the Quaternary Langebaan Formation.

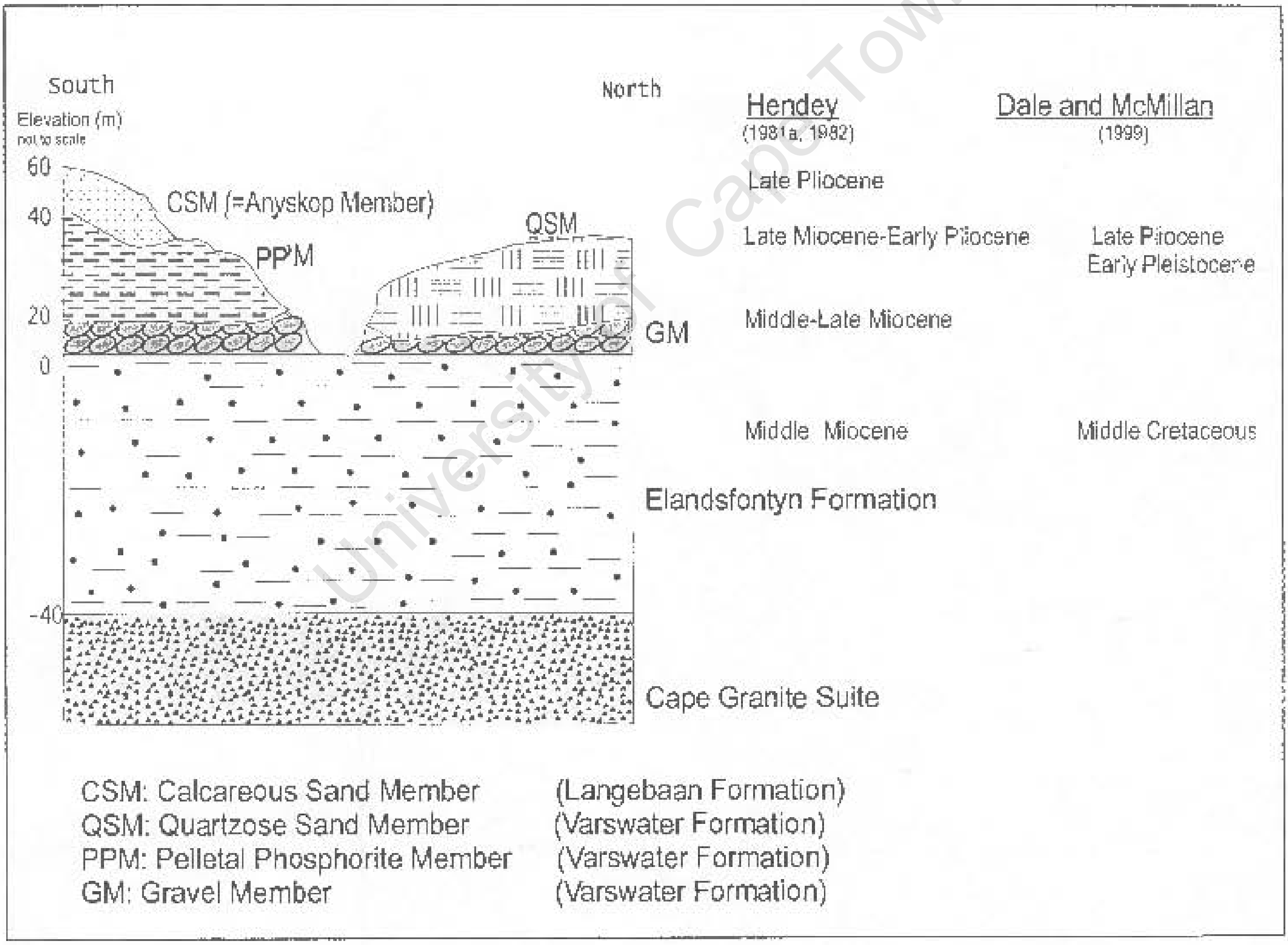


Fig. 2.4. Idealised stratigraphical profile across the Varswater Quarry after Hendey (1981a, 1982) and Dale and McMillan (1999).

Prospect Hill Formation

The Prospect Hill Formation (Fig. 1.2) is exposed in the upper Diazville Quarry (also known as Tabakbaai Quarry) and consists of aeolianites of a maximum thickness of 70 m that are banked against a granite ridge which parallels the shoreline (Pether et al., 2000). The recovery of the fossil ostrich eggshell of *Diamantornis wardii* in the upper section of the quarry, that in the Namib Desert was found in association with a Middle Miocene (10-12 Ma) fossil vertebrate fauna (Pickford et al., 1995, 1996; Pickford and Senut, 1999), suggests a Middle Miocene age for this formation (Pether et al., 2000; Roberts and Brink, 2003). The Middle Miocene age for the Upper part of the quarry is based on the presence of D. *wardii*, the nannofossil *Discoaster* sp. and of the large form of the dune snail *Trigoniphrus globulus.* (Roberts and Brink, 2003). The average size of the modern *T. globulus* is 5-6 cm while the avarage size of Early Miocene *T. globulus* was 10-13 cm (Roberts, pers. comm., 2001). Ward et al. (1993) suggested that the ubiquitous presence of this acavid snail in depoists dated from Early Miocene onwards, indicated that Western Africa has been subjected to a winter rainfall regime since the end of the Early Miocene. The reddish ferruginised colouration of the aeolianites (uncommon in the Western Cape) and the higher calcium carbonate contents (>90wt%) in the Prospect Hill Formation has been also considered as an indicator of a Middle Miocene age for this Formation. Infact, the Berg River discharges at Velddrif, whereas evidence recorded by the fluvial Elandsfontyn Formation (Cotzee and Rogers, 1982) and the fluvial channels in the Varswater Formation (Hendey 1974; 1981a), suggests that from the Late Miocene to the Mid-Pliocene the

Proto-Berg River discharged into Saldanha Bay. The Proto-Berg River would have added siliciclastic material to the source of the Prospect Hill Formation. Therefore, the high carbonate content indicates that this formation existed before the Proto-Berg river discharged into Saldanha Bay, underscoring a pre-Late Miocene age for the quarry deposits (Pether et al., 2000; Roberts and Brink, 2003).

Dale and McMillan (1999), in a detailed micropalaeontological study of the Saldanha region, described two different foraminiferal assemblages interpreted to be different in age. In the upper part of the Prospect Hill Quarry, the abundant presence of *Pararotalia nipponica* that in the Kleinsee area (about 500 km north of Saldanha) occurs in association with the Late Pliocene to present-day planktonic foraminifer *Globorotalia inflata* has led the authors to the conclusion of an age of latest Pliocene or earliest Pleistocene. In the lower part of the Prospect Hill quarry (20-25 m above sea level), the presence of the distinctive foraminifera *Uvigerina* sp. (refer to Plate 10, p. 30; Dale and McMillan, 1999) and of *Discorbis* '*algoaensis*', allowed Dale and McMillan (1999) to attribute an Early Pleistocene age to this deposit. The *Uvigerina* species differs in the fact that they are very thick-shelled and similar forms were not described or found elsewhere (McMillan, pers. comm., 2002). Dale and McMillan (1999) exclude a Miocene age for the quarry deposits and indicate that the vertebrate fossils. recovered only from the marine basal strata and not from the aeolianite rocks, are suspected to be reworked from an older rock succession, which has been subsequently destroyed through downwasting.

2.2.3 QUATERNARY COASTAL DEPOSITS

The Quaternary coastal deposits within the Saldanha Bay area consist largely of aeolian sand in the form of coastal-calcareous dune systems and aeolianites. Calcification of dune sands can occur rapidly in the area as a consequence of the high biogenic carbonate content that promote a rapid calcification of the arenites. The Quaternary coastal deposits in the study area consist of the Velddrif Formation, the Langebaan Formation and the Witzand Formation (Tankard, 1976a; Dingle et al., 1979, 1983; Hendey, 1976a, b, 1978, 1981a, b, 1982; Theron et al., 1992; Pether et al., 2000; Roberts and Brink, 2003).

Velddrif Formation

The type area of this formation is close to the Berg River mouth (Fig. 1.2) near Velddrif (Tankard, 1976a). It is composed of fine to coarse shelly sand and shell coquina beds (Tankard 1976a; Theron et al., 1992). In the western shore of the Langebaan Lagoon, the Velddrif Formation underlies the aeolian calcareous Langebaan Formation (Tankard, 1976a; Roberts and Berger, 1997). An IRSL age obtained from a sample collected from this formation along the shore of the Langebaan Lagoon yielded a Late Pleistocene age (118±18 ka; Roberts and Berger, 1997). This formation has been interpreted as littoral sediments deposited during the Last Interglacial when sea-level reached an elevation of +5 m (Tankard, 1976a; Theron et al., 1992) and it is limited to a maximum height of 7 m amsl (Tankard, 1976a; Pether et al., 2000).

Langebaan Formation

The Langebaan Formation is mostly composed of aeolianites and is generally medium grained, slightly greyish to cream coloured with comminuted shell and quartz grains (Theron et al., 1992). The Formation can be up to 88 m thick. Cross bedding is rarely seen, except at some outcrops on the western margin of the Langebaan Lagoon, that display extensive large-scale cross-bedding. The cross bedding indicates a predominantly southern wind direction similar to the prevailing summer wind direction today. The Langebaan Formation is formed by several generations of dunes superimposed upon one another. Aeolianites from the Langebaan Formation were dated with absolute dating methods at two sites: western shore of Langebaan Lagoon and Geelbek (Fig. 1.2). At Langebaan Lagoon, infrared stimulated luminescence and U/Th dating yielded dates of 107±7 ka and 103±7 ka, respectively and a U/Th date of 75±9 ka on a calcrete (Roberts and Berger, 1997). The Geelbek dunes suggest the existence of at least 2 chronologically distinct dune formations at 140 ka and 65 ka (Conard, unpublished report SANParks, 2000).

Witzand Formation

The Holocene deposits are formed by light-coloured, calcareous coastal-dunes that formed from deflation of modern beaches. These younger dunes moved inland from beaches that were not backed by cliffs and were exposed to southerly summer winds (Theron et al., 1992). The Witzand Formation rests on older Pleistocene aeolianites (Langebaan Formation) and elsewhere unconformably on the neo-Proterozoic Malmesbury Group or Cape Granite

Suite (Pether et al., 2000). Two major morphological dune types are recognised in the Western Cape (Illenberger and Burkinshaw, 1996; Roberts and Berger, 1997). The first are formed by dune systems where the dominant process is vertical accretion with a tendency to migrate onshore (Pether et al., 2000). The processes involved in the development of these dunes create coast-parallel dune systems ranging up to 20 m in height (Roberts and Berger, 1997). The second morphological type of dune category is transgressive dune plumes that migrate up to 20 km inland forming dune N-S corridors, which develop behind sandy beaches (Fig. 1.2).

2.3 MARINE PACKAGES

Along the west coast, and in particular in Namaqualand (Fig. 2.1), a sequence of elevated, fossiliferous marine packages has been described (Pether, 1994; Pickford, 1998; Pickford and Senut, 1999; Pether et al., 2000). These packages have been differentiated using molluscan fossils and foraminiferal assemblages (Dale and McMillan, 1999; Pether et al., 2000). Each of these packages comprises marine sediments deposited during regressive progradation seaward from the maximum elevation reached by the transgression (Pether et al., 2000). Each package is named after the elevation of its transgressive maximum. These marine packages have been extensively mined because their basal gravels are diamondiferous.

The older, warm-water groups include the 90 m Package, the 50 m Package and the 30 m Package. These warm water packages contain a unique suite of extinct fossil mollusc shells. *Isognomon gariesensis* (90 m Package), *Donax haughtoni* (50 m Package) and *Donax rogersi* (30 m Package) are the fossil indicators for the warm water packages (Pether et al., 2000). Barnacles (Pether, 1990) and brachiopods (Brunton and Hiller, 1990) have also been used in biostratigraphical work on these packages. The taxa found in these packages include species that today live on the east coast of southern Africa and in West Africa (Pether et al., 2000). The widespread occurrence of the warm water oyster *Crassostrea margaritacea* in the 50 and 90 m packages contributes to the hypothesis of warm water during deposition (Pether et al., 2000). The 90 m Package is composed of a basal gravel with abundant silcrete clasts and overlying red sand with heavy mineral laminations (Rogers et al., 1990). In the 90 m Package fossilised teeth of suids have been recovered from the gravel and have been dated as latest Early Miocene (Pickford and Senut, 1997). The 50 m Package is composed of fine sands overlying the basal gravels and phosphates. The fossils found in the 50 m Package in particular, the bear-dog *Agnotherium* sp., and the gomphothere *Tetralophon* sp. suggest a Late Miocene age (Pether et al., 2000). The presence of the benthic foraminifera *Rosalina "diazvillea"* and of the planktonic *Globorotalia inflata* in the 30 m Package and in the 50 m Package of Namaqualand has led Dale and McMillan (1999) to propose an Early Pleistocene age for both deposits. The 30 m Package extends near to the present-day shoreline (Dale and McMillan, 1999) and the upper shoreface facies has not been affected by terrestrial reworking (Pether et al., 2000). The age of the 30 m Package is controversial and it may correspond with the major sea level highstand in the Pliocene at 3.3 Ma

Pliocene (Pether et al., 2000) or it may be younger (Early Pleistocene, Dale and McMillan, 1999).

Younger, cold-water assemblages comprise the 8-10 m Package, the 4 m Package and the 2 m Package. These packages have shell assemblages similar to those inhabiting the west coast today. The 8-10 m Package is the first succession found along the west coast of southern Africa that shows signs of lagoonal or estuarine depositional environments (Dale and McMillan, 1999) with *Ammonia* spp. and *Elphidium* spp. the most abundant foraminiferal species. The age of the 8-10 m Package is Late Pleistocene (Dale and McMillan, 1999). The 4 m Package is dominated by marine foraminiferal assemblages such as *Elphidium crispum*, *Pararotalia nipponica*, *Hyalinea balthica* and *Cassidulina laevigata*. The 4 m Package is the mostly widely distributed along the south African coastline (Dale and McMillan, 1999). The age of the 4 m Package is latest Pleistocene. The 2 m Package accumulated when sea-level reached its highest position during the mid Holocene. The foraminifera found in this package indicate estuarine salt-marsh to sandy beach environments. In Fig. 2.2 a distribution of the marine packages in the Saldanha Bay area is presented.

2.4 SEA-LEVEL CHANGES IN THE SALDANHA BAY SINCE THE LATE PLEISTOCENE

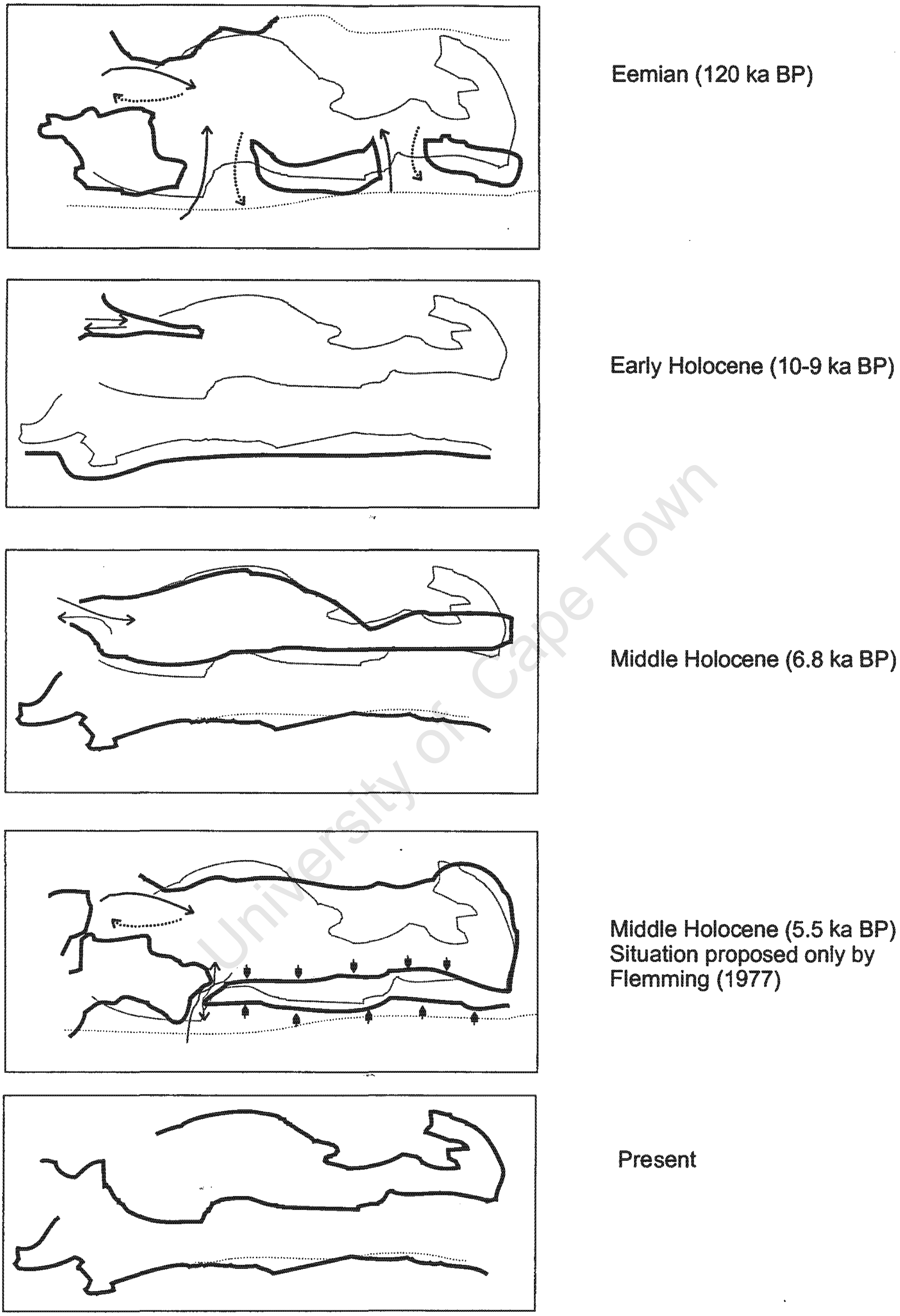
Reworking of older deposits has occurred widely during the Pleistocene. Pleistocene sea-level fluctuations have resulted in a complex depositional history in the Saldanha Bay area. From studies of fossil molluscs at Saldanha Bay, Tankard (1975b) argues that the Saldanha area was warmer during the

Last Interglacial than today. Most of the taxa recognised by Tankard (1975b) are extant and reflect shallow intertidal conditions. The present-day southern range of warm West African species is located at approximately 17° in the northern boundary of the Benguela Current. The tropical to sub-tropical west African species described by Tankard (1975b), suggests that they would have existed at least 16° south of their present-day geographical ranges in hyperthermal sheltered environments with temperature minima 5°C higher than today (Tankard 1975b). The mollusc assemblages indicate a marine transgression of 7m above the present sea-level, equivalent to the 4 m Package of Dale and McMillan (1999).

Different environments were recorded along the west coast during the Last Glacial, and temperatures were consistently lower than those of today (Tankard and Schweitzer, 1974; Tankard, 1976b). The Southern Polar Front shifted 10° equatorward lowering the Benguela Current temperatures to 10°C (Butzer, 1973). During the Last Glacial Maximum (LGM), the sea was approximately 125 m lower than the present day position (Fairbanks 1990; Yokoyama et al. 2000; Compton et al., 2002). On the shelf off southern Africa normally only a thin veneer of Quaternary sediments is found (Rogers 1977; Rogers and Bremner, 1991) and the accumulation of the fining-upward sediment, offshore of the Orange River mouth provides an important stratigraphical history from the Late Glacial Maximum to the Holocene (Compton et al., 2002). Recent study indicates a duration of 3000 years for the LGM between 22,000 to 19,000 years before present (Yokoyama et al., 2000). Between 19,000 and 7,000 ago, melting of ice sheets created a rapid rise in sea-level. Strata deposited from 6,000 years, were found at Rietvlei on the shore of Table Bay (Schalke, 1973), at Verlorenvlei north of St. Helena Bay (Baxter, 1997), at Groenvlei in the south coast (Deevey et al., 1959; Martin, 1968) and Langebaan Lagoon (Compton, 2001). The Flandrian Transgression flooded the pre-existing dune landscape and this resulted in the formation of the Langebaan Lagoon (Tankard, 1976b). Figure 2. 5 summarises the formation of the present day Langebaan Lagoon based on research from Flemming (1977) and Compton (2001). Rising sea level from the lowstand of –125 m during the post-glacial would have initially entered Saldanha Bay at –30 m in the Holocene between 10000 and 9000 (Bard et al., 1996). On the basis of radiocarbon analyses, Compton (2001), argues that by 6800 years ago, Langebaan Lagoon was flooded from 0 to 3 m above present sea level and that the sea level fell to the present-day position, remaining within a vertical range of ±1 m, 4900 years ago. Compton (2001) also indicates a sea-level lowstand of approximately 1 m between 2500 and 1800 years ago. A +0.5 m sea level rise was proposed by Flemming (1977) and Compton (2001) from 1500 to 1300 years in the Langebaan Lagoon and 80 km towards the north at Verlorenvlei (Baxter, 1997). A lowstand of 0.5 m from 700 to 400 year before present was also determined by Compton (2001) from cores collected in the southern part of Langebaan Lagoon.

2.5 TECTONIC UPLIFT

Tectonic uplift has been suggested both in the eastern and western part of South Africa. Major uplift, which elevated the eastern part of South Africa to



Eemian (120 ka BP)

Early Holocene (10-9 ka BP)

Middle Holocene (6.8 ka BP)

Middle Holocene (5.5 ka BP)
Situation proposed only by
Flemming (1977)

Present

Fig. 2.5. Late Quaternary evolution of the Langebaan Lagoon, after Flemming (1977) and Compton (2001).

present elevations, occurred during the Pliocene and has continued during the Quaternary (Truswell, 1970); and it may still be active today (McMillan, 1993; Dale and McMillan, 1999; McMillan, pers. comm., 2001). Evidence for the deformation is provided by the long profiles of major rivers of the southeast coast, which are convex upward, reflecting the influence of recent uplift and warping (Partridge, 1998). These data indicate a total uplift of the east coast of no less than 700-900 m along the crest of the axis of warping (Partridge, 1998). Offshore micropalaeontological data, combined with offshore seismic acoustic reflection data, indicate that these movements occurred within the last 5 Ma, i.e. from the Pliocene to the Holocene (Martin, 1987).

In the western part of the subcontinent, uplift is less marked and uncertain. A sequence of 'raised beach' deposits, mostly composed of shelly calcarenites (marine packages), often accompanied by aeolianites was described in the Saldanha region that accumulated since the Pliocene as this coastal area uplifted (Dale and McMillan, 1999). These authors have concluded that two portions of the continental margin in the Saldanha Bay area were uplifted during the Pleistocene in a different manner. Based on micropalaeontological observations, they have concluded that north of Paternoster and Velddrif (Fig. 2.2) and south of Yzerfontein (Fig. 2.2), the continental margin either subsided or showed no movement during the Pleistocene. A coastal strip from west of Saldanha to north of Paternoster and an inland strip from Yzerfontein to Langebaanweg and from Velddrif to Saldanha (Fig. 2.2) has been subjected to uplift.

2.6 DEPOSITION OF TERRIGENOUS SEDIMENTS IN THE SOUTH ATLANTIC AREAS

The Atlantic continental margins of Africa and South America are both tectonically passive (Dingle et al., 1983). After the break-up of Pangea, there was strong rifting activity which has been divided in to main phases (Light et al., 1992, 1993): Synrift I during the Jurassic and Synrift II which ended in the mid-Aptian. Following the break-up of Gondwana there was a period of very rapid deposition (up to 200 m/million years) corresponding to a rapid backwearing of the Great Escarpment (Maud and Partridge, 1987). The end of the Cretaceous was a time of fluctuating depositional rates and during the Cainozoic the sedimentation rates were generally less than 50 m/million years, with the Eocene and the Mio-Pliocene having a more rapid deposition (Maud and Partridge, 1987). The Oligocene was a period with low sedimentation and a stable, humid climate that promoted erosion and thick kaolinised bedrock profiles formed (Maud and Partridge, 1987). With the change in climate during the Early Miocene (Siesser, 1978b), south west Africa became increasingly arid with increments in the sedimentation rates offshore that were interpreted as increasing erosional rates on land (Maud and Partridge, 1987). No published studies are focusing on younger deposits.

Chapter 3 - Foraminifera of the Langebaan Lagoon salt marsh and their application to the interpretation of depositional environments of deposits at Monwabisi

3.1 INTRODUCTION

Understanding relative sea-level changes is an important topic in a great variety of environmental studies, including coastal-evolution models, and has practical applications related to exploration, mining and coastal engineering. One of the best records of relative sea-level change comes from micropalaeontological data through the vertical succession, and the contemporary zonation of microfossil assemblages across the tidal zone. Salt marsh benthic foraminifera are among the most valuable group of sea-level indicators, as their environmental distribution shows a narrow vertical zonation, which can be accurately related to sea-level change, salinity and vegetation cover. Consequently, sea-level canges through time can be accurately documented. Scott et al. (1990) show that salt marsh benthic foraminiferal assemblages around the Pacific Rim have the same distributions in the Northern and Southern Hemisphere. Recent work on salt marsh foraminifera includes studies from North America (Scott and Medioli, 1980; Scott and Leckie, 1990; Jennings and Nelson, 1992), South America (Scott et al., 1990; Scott et al., 1996; Jennings et al., 1995), Italy (Petrucci et al., 1983), United Kingdom (Horton, 1999; Horton et al., 1999) and Australia (Cann et al., 2000).

The research presented in this chapter focuses on the foraminiferal assemblages found in the Langebaan Lagoon salt marsh. This salt marsh is the largest pristine non-aeolian environment along the western coastline of southern Africa. Studies of foraminiferal distribution along the South African coastline are becoming crucial (McMillan, pers. comm., 2002) because they allow rock units to be dated and their depositional environment interpreted. The age relationships between different rock units and the depositional environments of these units are important, particularly economically because of the diamond deposits in some of these Quaternary and older units (Corbett and Burrell, 2001). To date, a very limited foraminiferal distribution database is available for southern Africa and thus the necessity and importance of an assessment of the present-day distribution of the foraminifera of the Langebaan Lagoon salt marsh. The only foraminiferal published work in southern Africa, focused on marine deposits (McMillan, 1974; 1986; 1987; 1990a,b,c; 1993; McLachlan and McMillan, 1979; Martin, 1981) or on river estuaries (Cooper and McMillan, 1987; Wright et al., 1990; Simpson, 2003). The Langebaan Lagoon area has been chosen for two reasons. The first being that a vegetation community distribution study has previously been undertaken in the area (O'Callaghan, 1993) and secondly to compare the present-day foraminiferal distribution with a deposit at Monwabisi, which was previously unstudied. The Monwabisi deposit is important because it's unique succession containing an unusually wide variety of depositional environments. Unfortunately, this deposit outcrops in the greater Cape Town area, and no outcrops exposing such a variety of depositional environments were found closer to the Langebaan Lagoon salt marsh. The study of the Monwabisi deposit has been chosed because similar macrofaunfal assemblages to that living in the Langebaan Lagoon were found. The study of the Monwabisi outcrop will help to refine the understanding of latest Pleistocene to Holocene sea-level changes in the Western Cape.

3.2 THE STUDY AREA

The study area lies in the southern end of Langebaan Lagoon, on the west coast of South Africa, 110 km north of Cape Town (Fig. 3.1). The lagoon is 15 km long and has a maximum width of 5 km (Flemming, 1977). Langebaan Lagoon is situated in a low lying part of the west coast, and the regional basement rock is Late Precambrian Malmesbury Group metasediments locally intruded by Precambrian to Cambrian Cape Granite Suite gabbro and diorite at Yzerfontein, and granite at Oude Post. Langebaan Lagoon is separated from the sea by Late Precambrian-Cambrian granite hills and Pleistocene-Recent dunes and aeolianites with extensive calcrete sheets (Tankard, 1976 a; Rogers, 1980; Dale and McMillan, 1999). Salt marshes exist along the southern, southwestern and eastern edges of the lagoon (Fig. 3.2). Samples used in this study were collected from a transect at the southern end of the lagoon near Geelbek (Fig. 3.2) and cover a range of environments from inter tidal flat to low, middle and high marsh. Here, a 3 km^2 salt marsh is well developed at the southern end of the lagoon and is separated from the open lagoon by a 2m high ridge that is cut by a channel through which tidal waters enter and leave the marsh.

3.2.1 CLIMATE AND HYDROLOGY

Langebaan Lagoon is situated in the equatorial extension of the Mediterranean climatic belt in the Western Cape Province (Schulze, 1965).

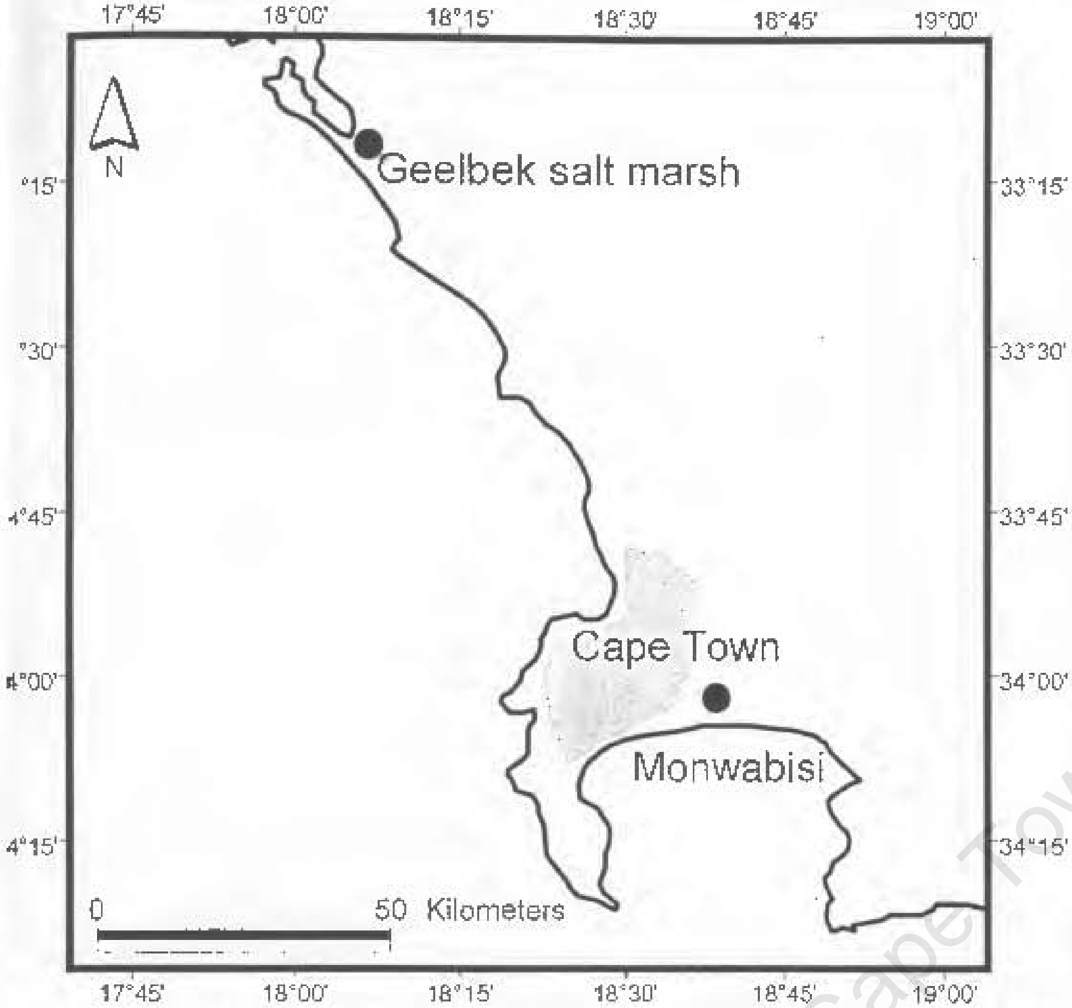


Fig. 3.1 Location of the Geellbek salt marsh and theMonwabisi outcrop.

Fig. 3.2. Aerial photograph (1999) of the Langebaan Lagoon salt marshes showing location of the transect near Geelbek and position of the salt pans.

Ranges in mean monthly minimum and maximum air temperatures are 8.7 °C-17.1°C and 14.6°C-21.0°C. Water temperature ranges between 13.5°C and 21.2°C. Annual rainfall of 240 mm is received mostly in winter months (SA Weather Bureau, pers. comm., 2001). High summertime temperatures and minimum rainfall promote high rates of seasonal evaporation and increased salinity. In addition, evaporation is exacerbated by the prevailing southwesterly winds that blow persistently during the summer months (September to April) and intermittently during winter months (Flemming, 1977). Although summer winds are frequently strong, reaching 25 km/h for over 90 days/year, they rarely reach gale force over the study area (SA Weather Bureau, pers. comm., 2001). Salinities range between 34.8‰ in the northern part of the lagoon near Saldanha Bay and increase progressively with distance from the tidal inlet to 38‰ at the southern end at Geelbek during the summer day months (Christie, 1981). During winter, due to winter rainfall, the salinity drops to 33‰ at the southern end at Geelbek (Christie, 1981). Tidal currents follow a semi-diurnal cycle and the region falls into the globally defined microtidal range (Davies, 1972). The system has a mean spring tide range of 1.4 m and a maximum astronomical tidal range of 2 m (Day, 1981a). Information on winter storm and surge heights are not available at present (Langebaanweg, weather office, pers. comm., 2002).

3.2.2 VEGETATION

The salt marsh surface is covered by a diverse and abundant macrophyte community, whose distribution is related to elevation and salt tolerance (Day, 1981b). The marsh of Langebaan Lagoon constitutes over 30%

of all salt marsh of South Africa (O'Callaghan, 1993). It has developed under unique conditions as there is no fluvial input into the lagoon (O'Callaghan, 1993). All other salt marshes developed along the South African coast occur in estuarine systems where salinity and tidal characteristics result from interactions between the sea and rivers (O'Callagan, 1993). Vegetation interacts chemically and physically with environmental variables and can influence foraminiferal abundance (Horton, 1999). O'Callaghan (1993), studied two transects near Geelbek in the south east of the Langebaan Lagoon distinguished a lower-marsh plant assemblage with *Zostera capensis*, a middle-marsh assemblage of *Triglochin bulbosa*, *Sarcocornia perennis*, *Limonium depauperatum* and *Chenolea diffusa*, and an upper-marsh assemblage with *Suaeda inflata*, *Sarcocornia pillansii*, *Disphyma crassifolium* and *Pulcinellia angusta*.

3.3 METHODS

Samples from the Langebaan Lagoon salt marsh (Table 1) were collected in wet (August 1999, October 2000) and in dry (November 1999, March 2000) seasons during low tide. The position of the studied transect has been chosen in the south east of Langebaan Lagoon because it was in proximity to the vegetation study of O'Callaghan (1993). Vegetation identification has been done using the plant collection located at the University of Cape Town as well as the National Botanical Institute of South Africa at Kirstenbosch. O'Callaghan's (1993) work is limited to the salt marsh area and does not include tidal channel-tidal flat areas. The exact position of his original transect could not been established on the ground. The sample sites were established where there were marked changes in topography or vegetation, and the distance from a marked station has been used as reference point. Environmental variables recorded during the present study include salinity, substrate and vegetation cover (Fig. 3.3). A standardised volume of 10 cm^3 (10 cm^2 by 1 cm thick) was taken from each site. The relative abundance (%) of each floral species and total cover were estimated in each vegetation zone from a 1 m^2 area around each sampling point. After collection, each sample was firstly washed through a 500 μm screen to remove large plant debris that may inhibit counting. The residue was then gently wet sieved through a 63μm sieve to concentrate the sand fraction. Wet samples were examined under a binocular microscope, generally at around 50 X magnification. Approximately 300 foraminifera were counted from each sample, the quantitative data were standarised to a volume of 10 cm^3 and presented as percent of foraminifera species present in each sample (Table 1). Microphotographs were taken using the Scanning Electron Microscope (SEM) at the University of Cape Town.

There is much debate about which assemblage constituents to use for foraminifera population studies. Many researchers indicate that total foraminiferal population (life plus death assemblage) most accurately represents general environmental conditions because it integrates with seasonal and temporal changes (Scott and Medioli, 1980; Buzas 1990; Scott and Leckie, 1990; Jennings et al., 1995; De Rijk, 1995a, b). However, Murray (1971, 1973, 1982, 1991) argues that the use of total population does not take in consideration the changes that will affect the life population after their death.

He therefore, suggested that only foraminiferal life assemblages can be used to interpret environmental conditions. The aim of this chapter is to document the relative distribution of benthic foraminiferal species within sediments of Langebaan Lagoon salt marsh in order to apply this data to fossil foraminifera extracted from sediments and investigate palaeo-environments and palaeo-sea level events. In order to compare present-day foraminifera with fossilised assemblages it is essential to understand and document the foraminiferal assemblages related to a referenced tide level. Considering that total assemblages in general have a good fossilisation potential (Goldstein and Watkins, 1999), the use of total population has been regarded as appropriate.

3.4 RESULTS

The transect sampled shows the variation of communities of salt marsh vegetation from tidal channel to high salt marsh (Fig. 3.3). The tidal channel contains a muddy sand severely burrowed by prawns (*Callianassa kraussi* and *Upogebia africana*). The tidal flat is composed of muddy sand populated by *Zostera capensis* and it is also heavily burrowed by prawns. Landward of this quartzose muddy sand there is low marsh populated by pioneer *Spartina maritima,* and a narrow strip with *Chenolea diffusa* and *Salicornia meyeriana.* Landward of the low marsh there is an upland (5 cm, refer to Fig. 3.3) community with a vegetation cover of 100%. Vegetation cover of *Chenolea diffusa*, *Salicomia meyeriana, Triglochin bulbosa*, *Pulcinella* sp. and *Sarcornia pillansii* characterise the middle marsh. *Chenolea diffusa* and *Salicornia meyeriana* dominate the high marsh.

Sample	**Location**
Sample 0	tidal channel
Sample 1	tidal channel-transition
Sample 2	tidal flat
Sample 3	tidal flat-transition
Sample 4	low marsh
Sample 5	middle marsh
Sample 6	high marsh
Sample 7	high marsh-transition

	August 1999								November 1999								October 1999							
SAMPLE NUMBER	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7	0	1	2	3	4	5	6	7
NO. OF INDIVIDUALS/10cm^3	570	620	925	785	1527	1173	1795	855	597	635	1003	665	1620	1080	1847	803	485	510	755	850	1645	905	1803	697
Ammonia japonica	20	19	21	23	1				19	21	20	20	2	1			23	24	23	23	1			
Ammonia parkinsoniana	26	25	25	26					25	25	25	27	1				27	28	27	27	1	1		
Ammonia sp.	4	5	3	4					4	4	4	5					2	2	2	3				
Elphidium articulatum	29	30	31	28	2	1			31	30	29	29	1	1			29	28	28	28	1			
Elphidium sp. A	16	15	15	14	1				15	15	15	15					16	15	15	16	1			
Jadammina macrescens					21	22	2	1					19	22	2	1					20	24	2	1
Quinqueloculina sp.	5	6	5	4					6	5	7	4					3	3	4	3				
Trochammina inflata				1	75	77	98	99					77	76	98	99			1		76	75	98	99

	March 2000							
SAMPLE NUMBER	0	1	2	3	4	5	6	7
NO. OF INDIVIDUALS/10cm^3	472	537	891	700	1715	835	1824	676
Ammonia japonica	23	22	23	23	1			
Ammonia parkinsoniana	28	27	27	26	1	1		
Ammonia sp.	2	3	2	3				
Elphidium articulatum	28	29	29	29				
Elphidium sp. A	16	15	15	15				
Jadammina macrescens					23	23	2	1
Quinqueloculina sp.	3	4	4	3				
Trochammina inflata				1	75	76	98	99

	Salt Pan 25‰		**Salt pan 30‰**		**Salt pan 37‰**	
SAMPLE NUMBER	8	9	10	11	12	13
NO. OF INDS/10cm^3	95	109	82	76	37	48
Ammonia japonica	52	59	58	63	1	2
Ammonia parkinsoniana	48	41	42	37		
Elphidium articulatum					99	98

Table 1. Percent abundance and number of individuals/10 cm^3 in samples collected along a transect in the Langebaan salt marsh and in 3 salt pans (see to Fig. 3.2).

Table 1 summarize trends in foraminiferal density in the transect collected on the Langebaan Lagoon salt marsh. Of the 32 samples collected along this transect, 16 samples were collected in the tidal channel-tidal flat area (samples 0, 1, 2, 3, twice in the wet seasons -August and November and twice in the dry seasons -October and March; Table 1), 4 samples in the low marsh (sample 4 in dry and wet seasons; Table 1), 4 samples in the middle marsh (sample 5 in dry and wet seasons; Table 1) and 8 samples in the high marsh (samples 6 and 7 in dry and wet seasons; Table 1). Total foraminifera abundances ranged between 472 and 1847 individuals/10 cm^3 (Table 1). Foraminiferal assemblages (Table 1) are dominated by a few prolific agglutinated species (*Jadammina macrescens*, *Trochammina inflata*) and by calcareous species (*Ammonia japonica*, *Ammonia parkinsoniana*, *Ammonia* sp., *Elphidium articulatum*, *Elphidium* sp. A and *Quinqueloculina* sp.). Results of the foraminiferal analysis on the transect enable the data to be separated into three zones (Zone I, Zone II and Zone III). The calcareous species *Ammonia japonica* (range between 19 and 24%, Table 1), *Ammonia parkinsoniana* (range between 25 and 28%, Table 1), *Ammonia* sp. (range between 2 and 5%, Table 1), *Elphidium articulatum* (range between 28 and 31%, Table 1), *Elphidium* sp. *A* (range between 14 and 16%, Table 1) and *Quinqueloculina* sp. (range between 3 and 7%, Table 1) dominate Zone I (tidal channel and tidal flat). The agglutinated species *Jadammina macrescens* (range between 19 and 24%, Table 1) and *Trochammina inflata* (range between 75 and 77 %, Table 1), with subordinate presence of *Ammonia japonica* (range between 1 and 2%, Table 1), *Elphidium articulatum* (range between 1 and 2%, Table 1) and *Elphidium* sp. A (range between 1 and 2%) dominate Zone II (low to middle marsh). A monospecific *Trochammina inflata* (range between 98 and 99%, Table 1) assemblage characterises Zone III (high marsh) with scattered presence of *Jadammina macrescens* (range between 1 and 2%, Table 1).

3.4.1 SALT PAN FORAMINIFERA

Several pans, elevated 30 to 50 cm above the salt marsh, exist along the edges of the lagoon. They are flooded by seawater during winter storms, or by freshwater runoff from winter rains. Consequently, salinity in these pans ranges between 25‰ to 40‰ during winter and between 40‰ to 280‰ during summer. Three samples were collected during wet season in August 1999 (Fig. 3.2; Table 1). The foraminiferal assemblages can be divided into two major groups: one found in salinities between 25‰ and 30‰ is characterised by *Ammonia japonica* (range between 52 and 63%, Table 1) and *Ammonia parkinsoniana* (range between 37 and 48%, Table 1). The assemblage found in a salinity of 37‰ contains *Elphidium macellum* (range between 98 and 99%, Table 1) and *Ammonia japonica* (range between 1 and 2%, Table 1).

3.4.2 ENVIRONMENTAL VARIABLES

Salinity of the sediment porewater is determined by evaporation and infiltration of seawater, rainwater and fresh surface runoff, and therefore the salinities vary between winter and summer months. Horton (1997) observed that English marsh sediments are noncalcareous and have salinities between 35‰ and 42‰ year around, whereas salt pan sediments are calcareous and have porewater salinities of around 100‰. The salinities measured in the Langebaan Lagoon range from 41‰ in summer in the tidal flat to 50‰ in the lower marsh. In winter the salinities are 38‰ in the tidal flat and 41‰ in the low marsh.

The sediment of the tidal flat is a muddy sand (70% sand, 30% mud). From the low marsh to the high marsh, the sand fraction decreases, the high-marsh sediment consisting of 50% sand and 50% mud. The increase in the mud content is related to the increase in the vegetation cover that traps fine sediments. The sand fraction of the sediments is almost exclusively composed of reworked aeolian quartz grains plus traces of calcareous bioclasts (calcium carbonate less then 1%). The mud fraction consists primarily of quartz, plant debris, diatoms and clay minerals.

3.5 DISCUSSION

The results reported here show that foraminiferal assemblages can be accurately used to discriminate between the sediments of different environments within the lagoon. The distribution of foraminifera in lagoonal environments is a direct function of altitude, with the duration and frequency of intertidal exposure as the most important factors (Scott and Medioli, 1978; Scott and Leckie, 1990; Jennings et al., 1995). Faunal Zone I coincides broadly with the tidal sand-flat and it is characterised by the highest foraminiferal diversity coinciding with low marsh and tidal flat floral zones. Its assemblage is composed of numerous calcareous species and dominated by *Ammonia japonica, Ammonia parkinsoniana, Elphidium articulatum* and *Elphidium* sp. A

(Table 1). Similar studies from Europe also identified tidal flat faunal zones dominated by calcareous species (Horton, 1999; Patterson, 1990; Scott and Leckie 1990; Jennings and Nelson, 1992). *Ammonia* is common in lagoonal environments world wide, although not restricted to them (Dale and McMillan, 1999). In southern Australia, *Ammonia beccarii* and *Elphidium articulatum* occur in saline lakes and coastal lagoons (Cann and De Deckker, 1981; Cann et al., 1999).

Faunal zone II (*Trochammina inflata* and *Jadammina macrescens)* characterises the low to middle marsh. The faunal zone is dominated by agglutinated foraminifera with a low species diversity, and sparce (range between 1 and 2%) of calcareous-walled *Ammonia japonica*, *Ammonia parkinsoniana*, *Elphidium articulatum*, *Elphidium* sp. A (Table 1). Faunal zone III occurs in the high marsh and is characterised by the presence of the monospecific assemblage of *Trochammina inflata* with subordinate precence of *Jadammina macrescens* (range between 1 and 2%). Faunal zones dominated by agglutinated species at low species diversity have been well documented from other marshes. *Trochammina inflata* was identified by Williams (1989) as the major species of the high and middle marsh of the Frasier River delta in British Columbia (Canada). A more detailed study of the same area has successively revealed that *Trochammina inflata* is co-dominant with *Jadammina macrescens* in samples collected in sites with decreased freshwater input from the Fraser River (Patterson, 1990). High salt marsh faunal zone dominated by *Trochammina inflata* and *Jadammina macrescens* were also described by Boomer (1998), Funnell and Boomer (1988) in the

North Norfolk (UK) saltmarshes. In the Langebaan Lagoon salt marsh assembleges from Faunal zone III exhibit a decrease in foraminiferal concentration (Table 1). The presence of a high high-marsh Faunal zone IIIm also refered to as a subzone in the foraminifera salt marsh literature, on the basis of high percentages of *T. inflata,* has been observed in several other studies (Coles, 1977; Coles and Funnell, 1981; Smith et al., 1984). The Langebaan Lagoon salt marsh is relatively flat (Fig. 3.3), but possesses a variable microtopography. For instance, the middle marsh is 5 cm elevated from the low to high marshes. This may be an indication that the distribution of foraminifera is not just a direct function of the altitude as hypothetised by Scott and Medioli (1978; 1986), Scott and Leckie, (1990) and Jennings et al. (1995); but also reflects changes in environmental variables that influence the salinity (such as flooding and precipitation) as suggested by De Rijk (1995a,b) and De Rijk and Troelstra (1997). A more detailed sampling regime might lead to the identification of more subzones or site specific assemblages. However, the main aim of this project is to document for the first time the occurrence of foraminifera in the Langebaan Lagoon as a test hypothesis for recontruction of sea-level changes in older fossilised deposits.

The findings for environmental zonation in the southern part of Langebaan Lagoon are, in part, similar to earlier observation of the distribution of species within vibracores collected in the lagoon, but there are also some important differences. Abundant valves of the Holocene ostracods *Sarcypridopsis aculeata* and *Gomphocythere* cf. *capensis* were found by Compton (2001) in several cores through the salt pans, but were not found

			Salinities (‰)			Vegetation
	Samples	Distance (m)	Summer	Winter	Altitude (cm)	
A'	0	0	40	39	0	
	1	200	41	38	0	*Zostera capensis* 90%
	2	306	41	38	0	*Spartina maritima*
	3	383	50	41	0	*Chenolea diffusa 60%, Salicornia meyeriana*
	4	394			30	*C. diffusa 60%, S. meyeriana 30%, Trigloshin bulbosa 10%, Pulcinella sp.*
	5	395.5			35	*Chenolea diffusa 50%, Sarcornia pillansii 50%*
	6	396			30	*Sarcornia pillansii*
A	7	398.5			30	*Chenolea diffusa 60%, Salicornia meyeriana*

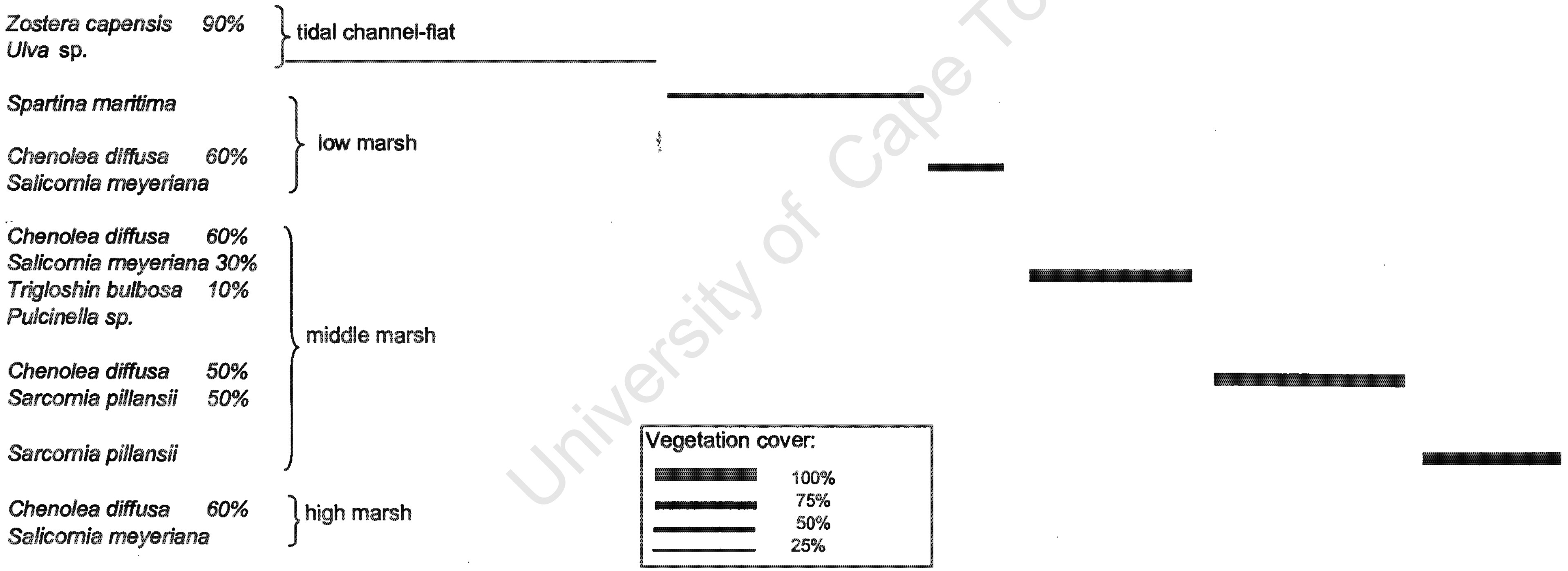


Fig. 3.3. Descriptive details of sample sites number 0 to 7 along the transect with vegetation cover. The location of the transect is shown in Fig. 3.2. The relative distribution of species of foraminifera is presented in Table 1.

living in the pans, and the only ostracods found show abrasion and may well be reworked (Dingle, pers. comm., 2000). Dingle and Hönigstein (1994) and Martens et al. (1996) argue that these ostracods are typical of temporary fresh water pools and thrive after high rainfall. They do not appear to live in the present-day lagoonal environment but indicate a change to hypersaline environments at present in Langebaan Lagoon salt pans and surrounding areas.

3.6 INTERPRETATION AND STRATIGRAPHY OF SEDIMENTS AT MONWABISI

The Monwabisi outcrop is located in the Cape Town metropolitan area on the False Bay side of the Atlantic Ocean, 110 km to the south of Langebaan Lagoon (Fig. 3.1) Although the Monwabisi outcrop is fairly distant from the Langebaan Lagoon, this represent the only area in the Western Cape, and probably along the West Coast of southern Africa, having preserved horizons composed of muddy material (Units 5 and 6 of Fig. 3.4). The macrobenthos of these green mud units is composed of *Assiminia globulus* and *Tomichia ventricosa*, presently found near the high water mark on the Langebaan Lagoon mudflat (Branch et al., 1994; Compton, unpublished data, 2001). The Monwabisi outcrop has never been studied before and no reference to previous work is available. The decision to study this outcrop was taken after the finding of a macrofaunal assemblage similar to the ones from the Langebaan Lagoon salt marsh. The aim of this part of the thesis is to use the information obtained

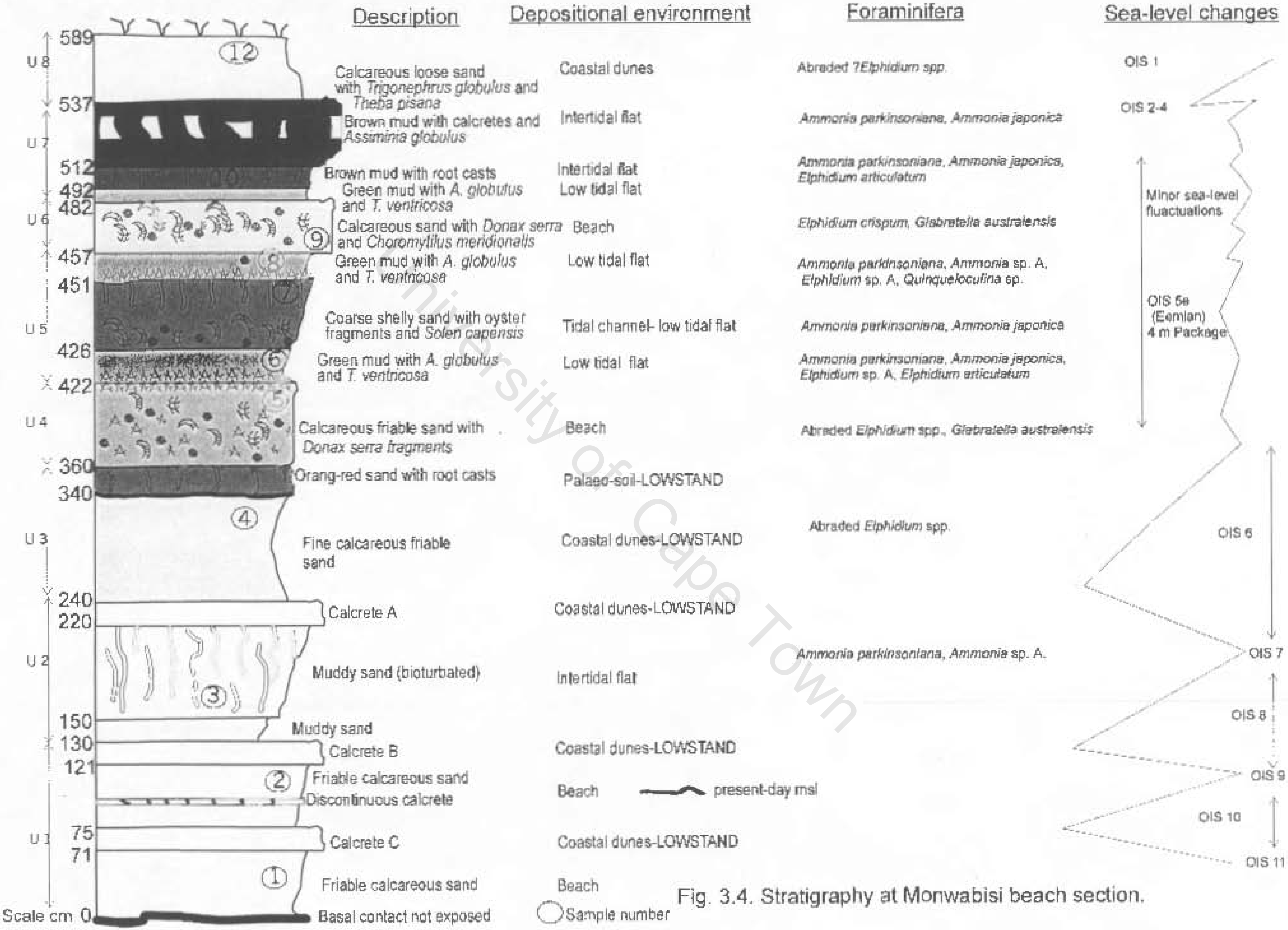


Fig. 3.4. Stratigraphy at Monwabisi beach section.

on the foraminifera from the salt marsh-tidal area as comparison with the fossil assemblages.

The Monwabisi section is characterised by a sandy cliff almost 6 m high. Eight stratigraphic layers were defined on grain size, colour and foraminiferal assemblages (Unit 1 to 8, Fig. 3.4). Twelve samples were collected in different strata of the Monwabisi outcrop (Fig. 3.4). After collection, the samples, in order to facilitate disaggregation were soaked in tap water for few days and wet sieved through a 63 µm sieve. The sub samples were then processed for a count of 300 tests. The percent of foraminiferal species in the differents units is presented in Appendix 1. The basal unit (Unit 1, Fig. 3.4) is formed by two calcrete layers (Calcrete C and B) inter-bedded by friable calcareous sand. The calcium carbonate of the friable sand is 3 wt% and no foraminifera were found. This basal unit is interpreted to be a beach deposit in which most of the carbonate has been leached out by rainwater. Above the basal unit, there is a heavily bioturbated muddy sand (Unit 2, Fig. 3.4). The foraminiferal assemblage (Appendix 1) recovered in the muddy sand is composed of *Ammonia parkinsoniana* and *Ammonia* sp. A that indicate a tidal flat depositional environment. The bioturbated muddy sand is topped by a well developed calcrete (Calcrete A, Fig.3.4). Above this calcrete there are cross-bedded fine calcareous friable sands (Unit 3, Fig. 3.4) with a well developed 20 cm thick orange soil at the top. The maximum exposed thickness of this orange sandy soil is 1 m. This unit contains no foraminifera and has a low percent of calcium carbonate (<3 wt%). Interpretation of this unit, based on the grain-size, on the cross-bedding and on the absence of large shell fragments, suggests that it is a dune deposit. The unit above the orange soil is a calcareous friable sand 60 cm thick (Unit 4, Fig. 3.4) with scattered *Donax serra* shell fragments. The foraminiferal assemblage here is composed of abraded *Elphidium* spp. and *Glabratella australensis* (Appendix 1). The depositional environment as indicated by the presence of the white mussel *Donax serra* is sandy beach. This unit gradually passes up into a green soft mud with a basal lag rich in the gastropods *Assimina globulus* and *Tomichia ventricosa* (Unit 5, Fig. 3.4). The foraminiferal assemblage is made up of *Ammonia parkinsoniana*, *Ammonia japonica*, *Elphidium* sp. A, *Elphidium articulatum* (Appendix, 1). The depositional environment is tidal flat as indicated by the micro and macro benthos. In the Langebaan Lagoon similar macro benthos assembleges has been recorded (Compton, unpublished data, 2001) at the high-water mark. Above the green mud there is a coarse shelly sand with oyster fragments and the razor clam *Solen capensis*. The razor clam has been reported as a fossil in the Langebaan Lagoon (Tankard, 1976a; Compton 2001) and is indicative of a sandy tidal flat. The foraminiferal assemblage here is composed of *Ammonia parkinsoniana* and *Ammonia japonica* (Appendix 1). Shells and shell fragments are concentrated in the basal part of this unit (Fig. 3.4). The top part is characterised by root casts and a layer rich in *Assiminia globulus* and *Tomichia ventricosa*. The foraminiferal assemblage is composed of *Ammonia parkinsoniana, Ammonia* sp. A, *Elphidium* sp. A and *Quinqueloculina* sp. The depositional environment as indicated by the benthos is tidal flat. Above the green mud there is a medium to coarse calcareous sand (Unit 6, Fig. 3.4) with *Donax serra* and black mussel fragments (*Choromytilus meridionalis*). This unit is very rich in carbonate (70 wt%) and the carbonate fraction is composed mainly of shell fragments, ostracods and echinoderm spines. The foraminiferal assemblage is composed of *Elphidium crispum* and *Glabratella australensis* (Appendix 1). *D. serra* and *C. meridionalis* indicate a mixed rocky and sandy shoreline. Abrasion of some of the foraminifera tests indicates a high-energy surf zone environment. Above the shelly gravel there is a green mud 10 cm thick (Unit 7, Fig. 3.4). *Assiminia globulus* and *Tomichia ventricosa* compose the macrobenthos while the foraminiferal assemblage is dominated by *Ammonia parkinsoniana, Ammonia japonica* and *Elphidium articulatum*. The depositional environment is tidal mud flat. Up sequence this unit becomes a brown mud with root casts and calcretes. The calcium carbonate of the mud layers is 3-5 wt% and these units lack any foraminifera. The contemporaneous presence of calcrete layers indicates that the calcium carbonate has been leached by rain water. These brown muds were originally deposited in an tidal flat environment as shown by the foraminifera assemblages recovered in the basal green mud. Friable medium to coarse brown sand composes the uppermost part of the section (Unit 8, Fig. 3.4). The presence of the terrestrial snails *Trigonephrus globulus* and *Theba pisana* indicates an aeolian depositional environment.

The succession of sedimentary units in Monwabisi must be explained in terms of sea level changes. Eight units (Unit 1 to 8) were distinguished in relation to sea level changes and depositional environments (Fig. 3.4). Repeated sea level fall and rise induced Unit 1 to be deposited as alternation of beach sand and calcretes. Calcretes are authigenic carbonate accumulations which are caused by in situ cementation or replacement of the host material (Botha, 1999). Thick mature calcrete forms under optimal semi-arid conditions with annual rainfall of less than 550 mm (Nettenberg, 1969). Calcretes thicken with time, as scattered filaments join together and develop a finely laminated horizon. Calcrete horizons therefore indicate sub-aerial exposure, and radiocarbon dating suggests that thick calcretes are at least 100,000 years old (Gile and Hawley, 1969). Nettenberg (1969) described and dated several calcretes in southern Africa, mostly on the eastern side of the continent. He suggested that calcrete 10 cm thick are probably at least 150,000 years old. The low carbonate content in the beach sand indicates that, as sea level was dropping, the beach was sub-aerially exposed and the carbonate leached, then redeposited as calcrete. Unit 2 is interpreted to be a tidal flat on the basis of the microbenthos and the bioturbation of the sand. This unit is similar to what is observed in the tidal flat and tidal channels of Langebaan Lagoon that are heavily bioturbated by the prawn *Calianassa kraussi* and *Upogebia africana* (Branch et al., 1994). A change in sea-level is detected in Unit 3 where dune deposits cover the basal units. Paleosol development and root casts indicate that the coastal dunes were stabilised by vegetation. Considering that this dune deposit in more than 1 m thick (Fig. 3.4) and shows evident signs of beeing vegetated, it is suggested that a sea-level drop must have occurred in order to expose the area subaerially in order for the vegetation to grow. Unit 4 is a sandy beach deposit (as indicated by the presence of *D. serra*) that was deposited after a rapid sea-level rise that drowned the coastal dune deposit. The top part of the unit has abundant *Assiminia globulus* that mark the beginning of deposition of lagoonal deposits (Unit 5). These deposits are composed of soft mud layers and shelly sand. The mud layers are characterised by the presence of the macrobenthos *Assiminia globulus*, are also present today in Langebaan Lagoon, and occurs near the high-water mark on lagoonal mudflats (Branch et al., 1994; Compton, unpublished data, 2001). In the shelly sand, *Solen capensis* and oyster shell fragments were found. *Solen capensis* is not currently living in the Langebaan Lagoon, but has been recorded as a fossil in Mid Holocene deposits (Tankard, 1976a; Compton, 2001). The foraminiferal tests recovered from the mud layers are *Ammonia japonica*, *Ammonia parkinsoniana*, *Ammonia* sp. A, *Elphidium articulatum, Elphidium* sp. A, *Quinqueloculina* sp. These foraminifera have been found living today in the Langebaan Lagoon and are indicators of tidal conditions. Unit 6 is a sandy beach (as indicated by *Donax serra)* with rocky outcrops (as indicated by *Choromytilus meridionalis)* that were laid down probably after a drop in sea level. Exposed subtidal calcretes may be a point of attachment for the black mussels. In subtaidal channels of Langebaan Lagoon *Choromytilus meridionalis* and *Mytilus gallopronvincialis* have been observed attached to calcretes presently permanently under water (P. Nel, SANParks, pers. comm., 2002). Unit 7 is composed of lagoonal deposits with green mud at the bottom and brown mud with root casts at the top indicating a relatively slow sea level drop until the deposition of the coastal calcareous dune sand (Unit 8) that covers the section (Fig. 3.4).

The age of the deposit recognised at Monwabisi has been inferred from the biostratigraphy. The shelly-calcareous sand with oyster fragments and

Solen capensis yields a 4m Package foraminiferal assemblage that has been regarded as Eemian (Dale and McMillan, 1999). The abundance of *Elphidium crispum*, never found in earlier Pleistocene deposits (Dale and McMillan, 1999), suggests a Late Pleistocene age for the deposit. Eemian deposits (OIS 5e) have been documented in detail from the foraminifera biostratigraphy by McMillan (1987a, 1990a) with *Elphidium crispum* (very abundant), *Pararotalia nipponica, Ammonia japonica, Ammonia parkinsoniana, Hyalina balthica, Cassidulina laevigata.* The deeper elements such as *Hyalina balthica* and *Cassidulina laevigata* are locally present, but never found together with *Ammonia* spp. (Dale and McMillan, 1999). The elevation of the units 4, 5 and 6 (Fig. 3.4) agree with other Eemian deposits found along the west coast (Tankard, 1976a, b; Dale and McMillan, 1999). Speculation on the age of the other lower units may be inferred from Late Pleistocene sea-level fluctuations (Fig. 1.4) as well as from ages of well developed calcretes. Unit 3 is formed by the Calcrete A and by 1 m of fine calcareous sand. This unit may have been deposited during OIS stage 6, while calcretes B and C both were probably formed during OIS stages 8 and 10 (Fig. 3.4). With these assumptions the age of the condensed section exposed at Monwabisi beach dates back to 600 ka. However, the ages of these lower units as yet cannot be well constrained, and in part are largely speculation. Luminescence dating methods, and particularly the most recently developed optical dating techniques may provide further age control for sediments spanning the last-interglacial-glacial cycle (0-150 ka), and possibly a number of cycles prior to that. Unfortunately, there is no access to these techniques from the University of Cape Town.

3.7 CONCLUSIONS

The present study of foraminiferal assemblages from Langebaan Lagoon shows a vertical zonation, supporting the studies of North American areas, which concluded that foraminifera are related to vegetation cover and altitude.

- Contemporary foraminiferal assemblages from the salt marsh in Langebaan Lagoon can be subdivided into three zones. Zone I is dominated by calcareous species, Zone II by agglutinated foraminifera, and Zone III is characterised by a monospecific assemblage of the agglutinated *Trochammina inflata*.
- The zonation of the salt marsh and salt pans in the Langebaan Lagoon provides an important tool for interpreting former sea levels from fossil environments. Compton (2001) recovered vibracores from salt pans in the southern part of Langebaan Lagoon. The abundant ostracods and *Quinqueloculina* cf. *seminulum* found in the mid-Holocene microfossil assemblages (Compton, 2001) no longer live in the lagoon, and this can be related to the hypersaline condition of the present-day lagoonal environment perhaps related to a rise in sea level over the last 400 years (Compton, 2001).
- This study describe for the first time the foraminiferal assemblages of the tidal-salt marsh area of the Langebaan Lagoon. This foraminifera may help to elucidate past sea-levels when found fossilised as well as depositional environments.
- Sediment from the outcrop of Monwabisi were described. Foraminifera have been used to infer the depositional environment and the age of deposition. The Eemian age of the deposit has been assigned based on the abundance of *Elphidium crispum* that is considered to charactirised the Eemian-Weichselian

period (Dale and McMillan, 1999). The depositional environments change from marine and non-marine.

3.8 TAXONOMIC NOTES ON THE FORAMINIFERA COLLECTED IN THE LANGEBAAN LAGOON

Generic names of the foraminifera are in accordance with Loeblich and Tappan (1964, 1974). Species are listed here alphabetically by genus.

Ammonia japonica (Hada, 1931)

Plate 1

Rotalia japonica Hada, 1931: 137, fig 93a-c.

Ammonia japonica (Hada) Matoba, 1970: 48, pl.5 (fig. 14a-c), pl.6 (fig 1a-c). McMillan, 1987a: 37, text-fig.7a-d. McMillan, 1990a: 166, fig.16c-e.

Ammonia beccarii (*non* Linné) Martin, 1974: 84, fig.14-1 (part.). Salmon, 1979: 77, fig. 3p. Martin 1981:48, pl.3 (figs 2-3).

Ammonia beccarii (Linné) var. *inflata* (non Seguenza) McMillan, 1974:62, pl.6 (fig. 2a-c).

Ammonia parkinsoniana (d'Orbigny, 1839a)

Plate 1

Rosalina parkinsoniana d'Orbigny, 1839a: 99, pl. 4 (figs 25-27).

Ammonia parkinsoniana (d'Orbigny) forma *typica* Poag, 1978: 397, pl.1 (figs 5-9, 13-1, 19-21).

Ammonia beccarii (*non* Linné) Martin, 1981: 48, (part.).

Ammonia parkinsoniana (d'Orbigny) s.l. McMillan, 1987a: 35, figs 3a-r, 4-5.

Elphidium sp.A
Plate 1

Elphidium cf. advenum (non Cushman) McMillan, 1987b, pl. 17 (figs 1-2).
Elphidium sp. A McMillan, 1990a, 160 (fig. 14I, 15A).

Elphidium articulatum (d'Orbigny, 1839b)
Plate 1

Polystomella articulata d'Orbigny, 1839b. 30, pl. 3 (figs 9-10).
Elphidium articulatum (d'Orbigny) Boltovskoy, 1963: 61, pl.6 (fig. 15). Boltovskoy et al., 1980: 29, pl.13 (figs 1-4).

Jadammina macrescens (Brady, 1870)
Plate 2

Trochammina inflata (Montagu) var. *macrescens* (Brady, 1870)

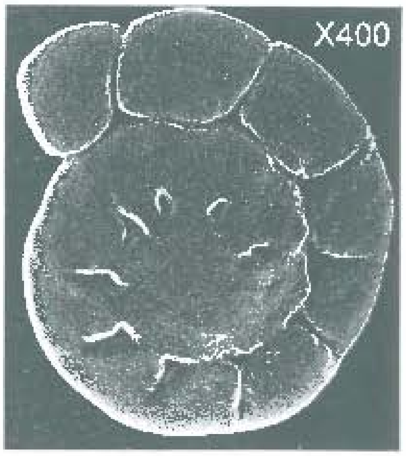
Quinqueloculina sp. (non *seminulum,* Linné 1758)
Plate 1

These specimens were not identified to species level.

Trochammina inflata (Montagu)
Plate 2

Nautilus inflatus Montagu, 1808: 81, pl. 18 (fig. 3).
Rotalina inflata Williamson, 1858: 50, pl. 4 (figs. 93-94).
Trochammina inflata (Montagu) Carpenter et al., 1862: 141, pl. 11 (fig.5). Scott and Medioli, 1980: 44, pl. 3 (figs. 15-17).

Ammonia japonica



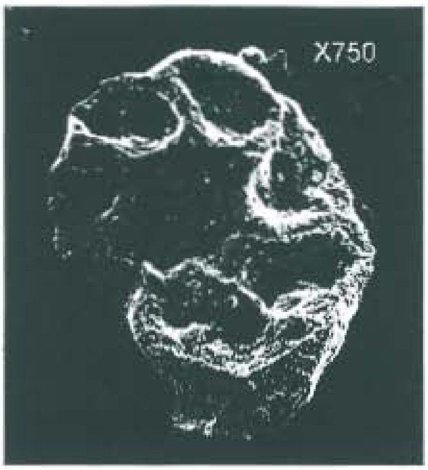
Ammonia parkinsoniana

Elphidium cf articulatum

Elphidium sp.A

Quinqueloculina sp.

PLATE 1



Jadammina macrescens

Trochammina inflata

Trochammina inflata

PLATE 2

Chapter 4

Holocene evolution of the Sixteen Mile Beach complex

4.1 INTRODUCTION

Models of coastal evolution and dune development have been described by many investigators including the recent publications of Hesp (1988a, b), Pye (1983, 1990, 1993), Pye and Bowman (1984), Psuty (1988a, b), Short and Hesp (1982, 1984) and Winspear and Pye (1996). Although the development of geomorphological studies of coastlines acknowledged the need to understand how coastal changes occurred, the factors which determine the morphology and evolution of aeolian sand bodies in South Africa remain poorly understood (Corbett, 1989). Along the west coast of southern Africa, no studies have been carried out to understand the dynamics of these processes. It is therefore important to understand the source of sediment that form the beach and the nearshore environments. Is the sand forming the Sixteen Mile Beach complex coming from marine transgressions, from older dunes or from the break down of modern shells? In the last decade of literature published on coastal dunes, many authors have suggested that a sea-level rise or fall may have major impact on dunefield initiation or response (e.g. Thom, 1984). But how does a change in sea-level influence the morphology of the Sixteen Mile Beach complex? Another question that is addressed in this chapter does not concern the provenance of the material, but rather the transport mechanisms. Can radiocarbon dating be used for dating beach sediment and can this interpretation be use to speculate on sand movement along Sixteen Mile Beach? If we can answer these questions, we can then create a depositional model for the Sixteen Mile Beach complex that may be applicable to understand the interrelationships between offshore and onshore environments.

Coastal dunes are prominent features along much of the coastline of southern Africa (Tinley, 1985). Large coastal sand masses occur at several localities in the Western Cape on the Cape Flats, near Atlantis and along the Sixteen Mile Beach Complex (Fig. 4.1). These dunes have formed from a long-term accumulation of sand transported northward along the inner shelf. Very little of the Western Cape coastline is without coastal dunes, although in some cases these dunes are poorly developed. The Sixteen Mile Beach complex is an example of a system accumulating along an open coastline with strong wind from the south and south-west in summer, north-east winter wind and net annual longshore drift to the north (Swart and Flemming, 1980). Coastal archaeological sites show that early human activities may have decreased dune stability (Tinley, 1985) and dune stability is an environmental issue in many coastal areas today, including the Cape Peninsula in the vicinity of Hout Bay (Holmes and Luger, 1996). South African and Australian coastal dunefields have prograded seaward since the mid-Holocene sea-level maximum as episodic pulses of sand (Illenberger, 1988; Thom and Roy, 1985). Radiocarbon dating of shell material associated with dunes (Illenberger and Verhagen, 1990; Miller et al., 1993), and thermoluminescence and radiometric dating of dune paleosols (Lees et al., 1995) and aeolianites (Roberts and Berger, 1997) have increased our understanding of the dynamics of coastal dunes.

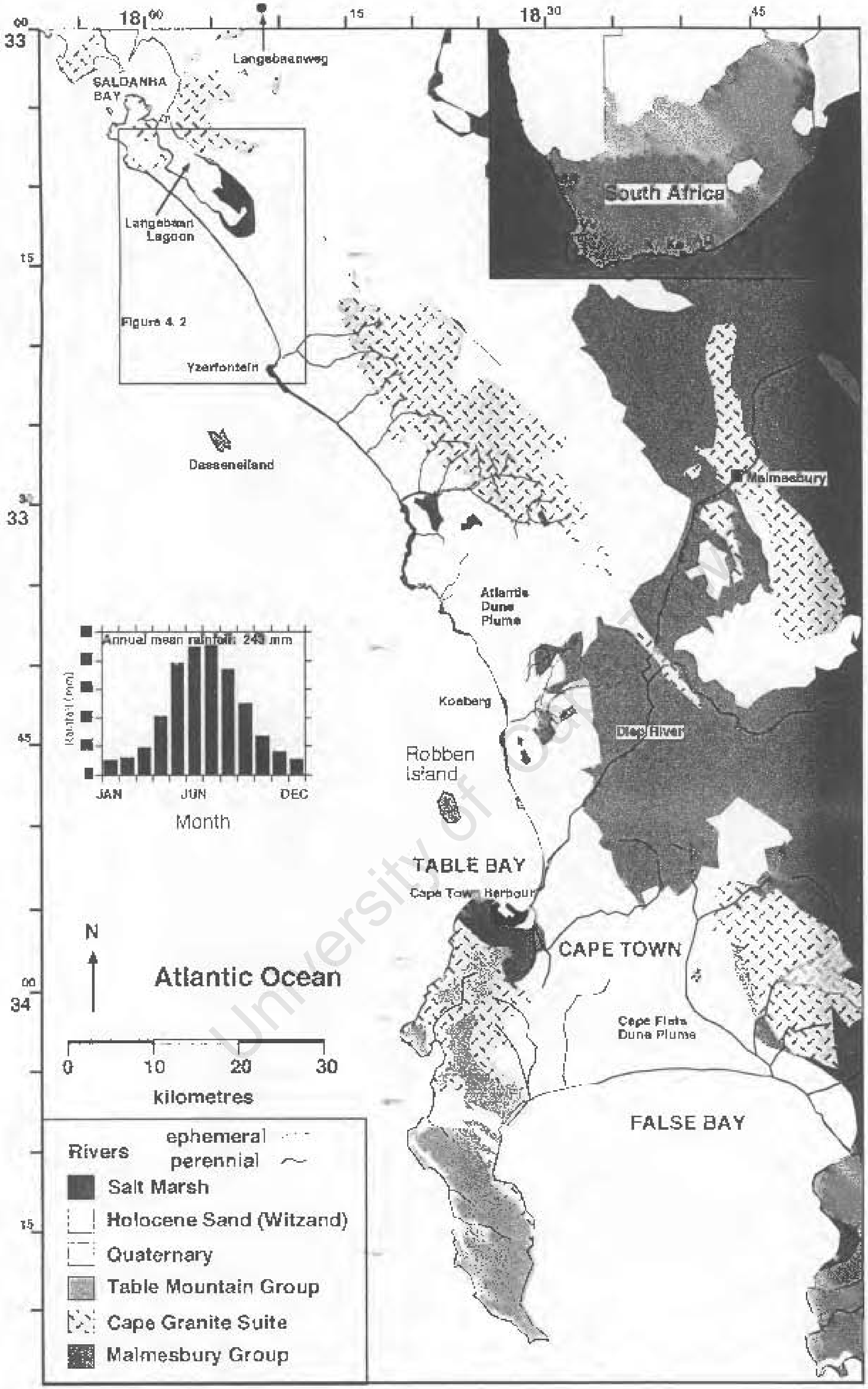


Fig. 4.1. Location of the Sixteen Mile Beach complex in the southwestern Cape, based on the 1990 1:250,000 Council for Geoscience map. Mean average montly rainfall at Langebaanweg for the period 1915 to 1998 (SA Weather Bureau, pers. comm., 1998). SR is the Swartlintjies River mouth,VV is Verlorenvlei, Ad is Algoa Dunefield, K is Knysna, KE is Keurbooms.

The main objective of this chapter is to describe the morphology and composition of the Sixteen Mile Beach complex, to create some hypothesis on the source of the sediment and to see how sea level changes influenced the dune morphologies. The approach of this chapter has been firstly to document the textural and grain size composition of the sediment along Sixteen Mile Beach, the coastal foredunes and the Yzerfontein-Geelbek dune plume (section 4.4). The information obtained is then used to interpret the sediment dynamics, provenance and distribution along the Sixteen Mile Beach complex (section 4.5). Secondly, conventional radiocarbon dating both on carbonate sediment and whole shells has been used to investigate the age of this complex and a model of sand supply and transport is proposed for the area (section 4.6). Thirdly, conclusions are drawn to aid in the understanding of human utilisation of the area.

4.2 THE STUDY AREA

Sixteen Mile Beach is one of a series of log-spiral sandy beaches in South Africa (Bremner, 1983). Sixteen Mile Beach has a transgressive dune plume at the southern end and coast-parallel dunes at the northern end (Fig. 4.1). This study extends from the rocky headland of Gabbro Point at the southern end to Tsaarbank located 26 km north of Gabbro Point (Fig. 4.2). Three rocky pool areas occur along the beach at Yzerfontein, at Gabbro Point and the northern end of the beach, at Tsaarbank. A rocky point is also present at Black Rock, although it is exposed only during spring tide. These outcrops are of the Late Precambrian to Cambrian Cape Granite Suite and range in composition from granite to gabbro.

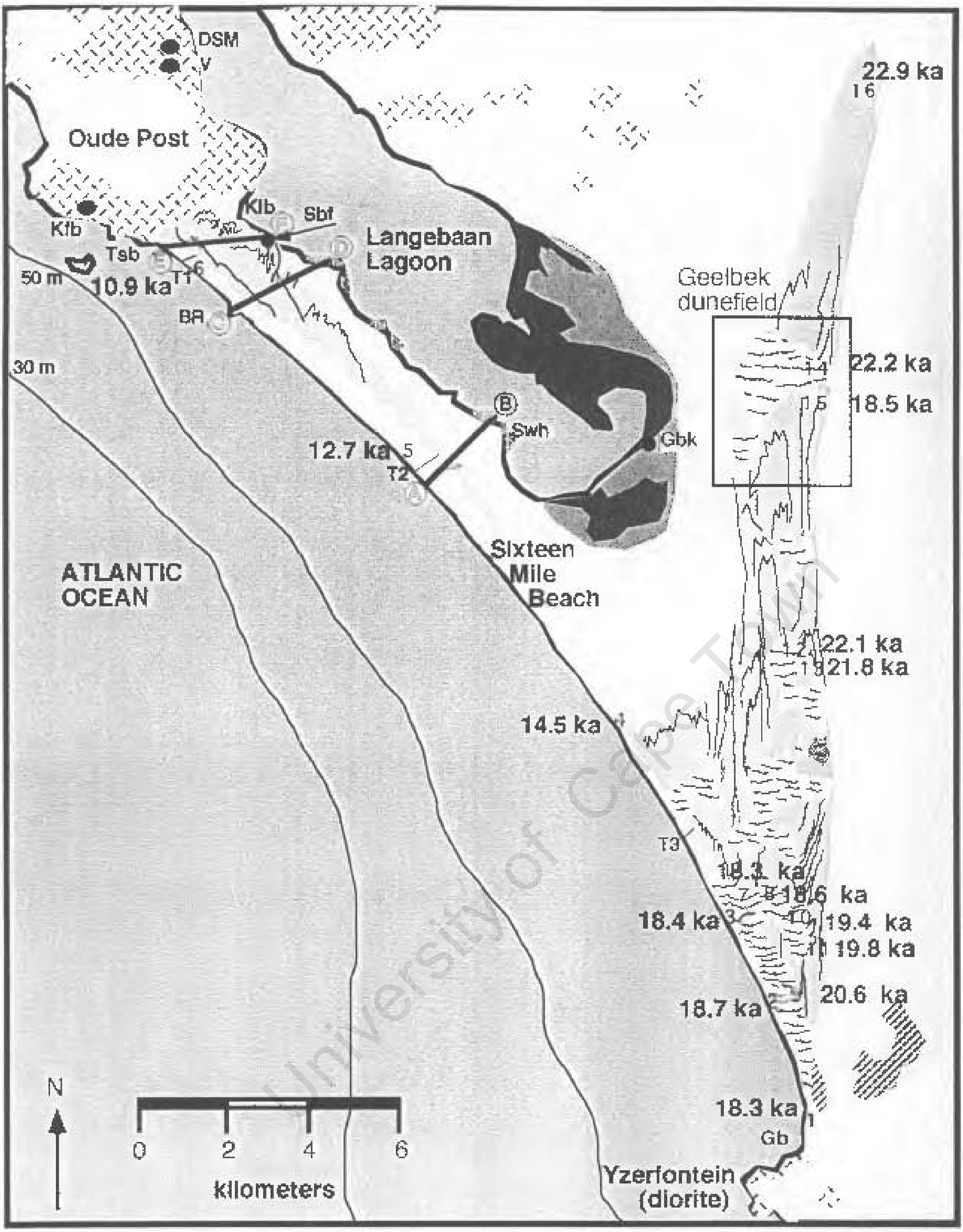


Fig. 4.2. Features of the Sixteen Mile Beach complex between Yzerfontein and Kreeftebaai based on aerial photographs taken between 1938 and 1993. Circled letters indicate location of cross section of the coast-parallel dunes (Fig. 4.8). Kb=Kraalbaai, Krb=Kreeftebaai, Tbs=Tsaarbank, Br=Black Rock, Gbk=Geelbek, Gb=Gabbro Point and archaeological sites: Sb=Stofbergsfontein, Sw=Schrywershoek, Kt=Kreeftebaai, V=Vlaeberg and DSM=Drie Susrers Main. Red radiocarbon ages are from active dunes while green ages from vegetated dunes.

The region is covered extensively by Pleistocene aeolianites and calcarenites (Tankard, 1976a; Rogers, 1980; Dale and McMillan, 1999; Pether et al., 2000). The variably cemented, intertidal shelly beach sands of the Eemian Velddrif Formation are at Kraalbaai (Fig. 4.2) overlain by aeolianites and calcrete horizons of the Langebaan Formation. The age of the 10 to 60 m thick aeolianite succession of the Langebaan Formation at Kraalbaai is 117 to 79 ka and includes fossil human footprints near the base of the formation (Roberts and Berger, 1997). Along with igneous rock headlands, the Pleistocene and Holocene dunes make up the western peninsula that separates Langebaan Lagoon from the Atlantic Ocean (Fig. 4.2). The dunes contain several roads and fences and have been partially planted for stabilisation by the Department of Forestry. Otherwise the area is generally undeveloped and is today part of the West Coast National Park.

The area is located in a Mediterranean, semi-arid climate with a mean annual rainfall of 240 mm received mostly during the winter months between May and August (Fig. 4.1). The mean winter temperature is 14°C and rarely drops below 5°C, whereas the mean summer temperature is 22°C and rarely exceeds 30°C. In the south Western Cape the winds are highly variable (Fig. 4.3). In Cape Town the winds are predominantly from the south-southeast, whereas in Langebaanweg the predominant wind direction is from the south to south-west (Fig. 4.3). Average wind speeds of 20-40 km/h are attained for 25% of the year in the Cape Columbine area, 35 km north of the studied area, but gale-force winds exceeding 52 km/h are experienced less than 4% of the year (SA Weather Bureau, pers. comm., 1998).

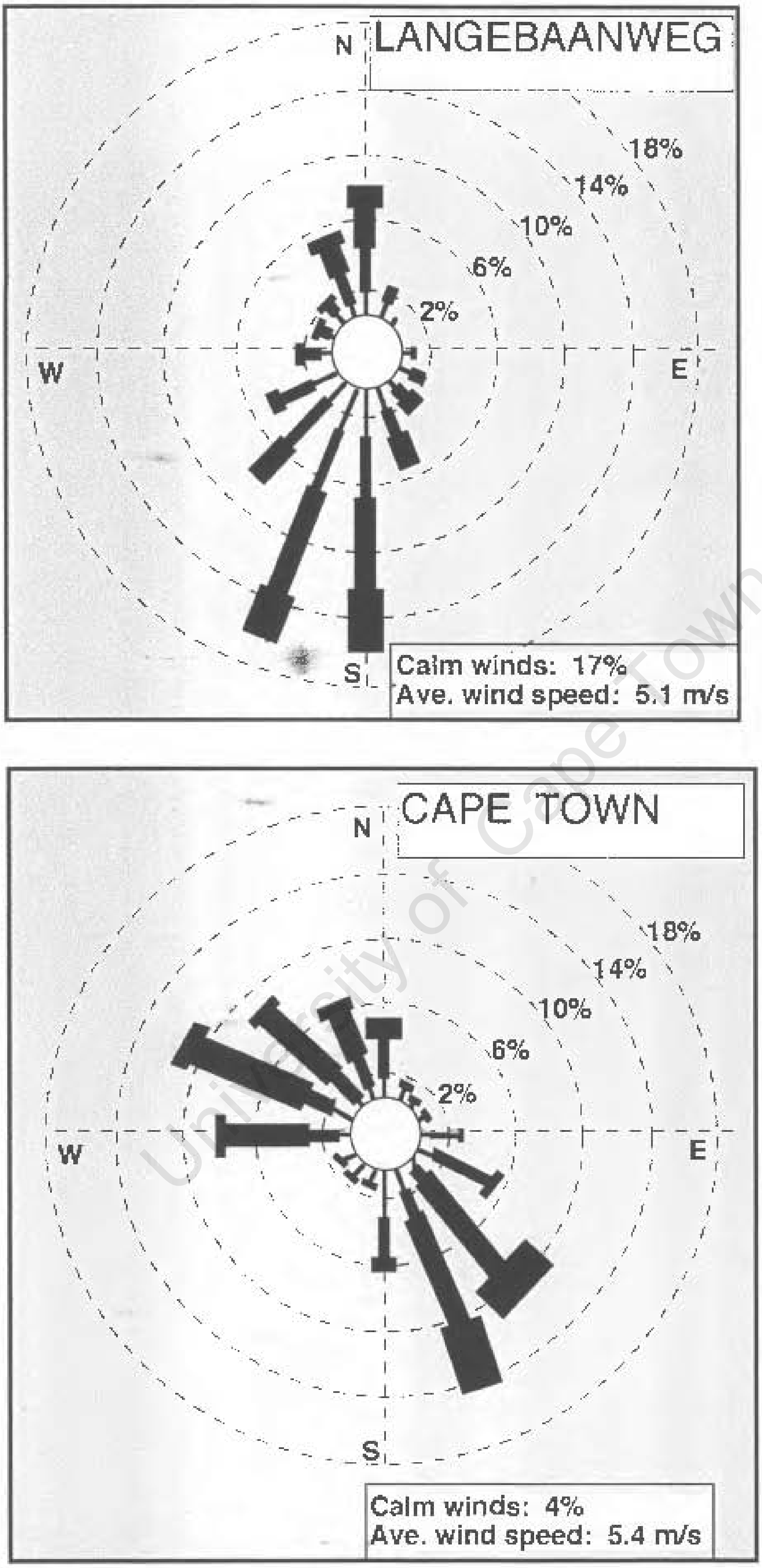


Fig. 4.3. Mean annual average wind direction and velocity at Langebaanweg and Cape Town harbour for the years 1975-1998 (SA Weather Bureau, pers. comm.,1998).

The coast is microtidal and is exposed to moderate to high wave energy, with 90% of waves having heights of 1 to 3 m with a wave period of 13-15 seconds; net annual longshore drift is to the north (Swart and Flemming, 1980).

4.3 METHODS

A total of 27 samples of 1 kg of beach sand were collected every kilometre along Sixteen Mile Beach from 10 cm deep pits below the surface at mean high tide level, approximately 0.7 m above mean sea level. Eighty-six surface samples of 0,5 kg of beach sand from three transects, perpendicular to the beach, were collected at the southern end (T1), in the middle (T2) and at the northern (T3) end of the beach located 6 km, 16 km and 26 km north of Gabbro Point, respectively (Fig. 4.2). Sand samples were collected in rocky pools at Yzerfontein, Gabbro Point and at Tsaarbank. Beach profiles were measured using a 50 m long tape and a staff. Dune sand was sampled from 50-60 cm below the surface of the active and vegetated Yzerfontein-Geelbek dune plume at 6 km, 12 km, 18 km and 24 km from the coast. Dune samples from 50-60 cm below the surface were collected from ridge crests and troughs of the coast-parallel dunes at the northern end of Sixteen Mile Beach (Fig. 4. 2).

Shell and shell fragments, greater than 20 mm in size, of the white mussel, *Donax serra* and several species of limpets (mostly *Patella argenvillei*, *P. granatina* and *P. granularis*) were hand-picked from the coast-parallel dunes for radiocarbon analyses. Conventional radiocarbon ages of bulk beach and dune samples as well as whole and partial shells were determined by the Quaternary Dating Laboratory at the Council for Scientific and Industrial

Research in Pretoria (Table 1). The CAL14C (WC93) program was used to obtain calibrated ages of the material (Talma and Vogel, 1993). The WC93 program uses the marine data set of Stuvier and Braziunas (1993) and assumes a reservoir age of 550 yrs for upwelled surface waters off the west coast of South Africa. Calibrated ages are reported as ka, thousands of years before the present (1950).

Bulk beach sand samples were dried and the organic material, mostly fragments of kelp *Laminaria pallida* and *Ecklonia maxima* was hand picked and weighed. The beach sand was then dry sieved through 1000 µm, 500 µm, 250 µm, 125 µm and 63 µm-mesh sieves. The calcium carbonate content of the bulk sand was determined by digestion in 10% HCl. The grain-size distribution of the bulk samples and of the carbonate-free samples collected along the Yzerfontein-Geelbek dune plume were analysed in the settling column of the Department of Geological Science at the University of Cape Town. Foraminifera were picked from the beach and dune samples (Appendix 2) and identified using a Scanning Electron Microscope in the Electron Microscopy Unit at the University of Cape Town.

4.4 RESULTS

The Sixteen Mile Beach complex can be divided into a beach, coast-parallel dunes and a sand plume. Sixteen Mile Beach is a 26 km long log-spiral sandy beach of varying width (Fig. 4.4). In the northern part of the beach there is an active foredune and numerous coast-parallel vegetated relict dune ridges.

Sample	Material analysed	Analytical No. Pta-	δ^{13}C%o PBD	^{14}C Age yr BP	^{14}C Age Cal yr BP	2 σ range Cal yr BP
B 3- 1	Beach sand	8141	0.0	16,000±160	18,364	18,656-18,052
B 2-2	Beach sand	8165	0,6	16,390±70	18,725	18,595-18,858
B 1-3	Beach sand	8138	0,6	15,900±160	18,269	17,949-18-568
L 15-4	Beach sand	8248	0.5	12,920±130	14,465	14,127-14,844
L 14-5	Beach sand	8245	0.4	11,270±110	12,651	12,421-12,861
L 13-6	Beach sand	8239	-0.9	10,380±100	10,890	10,933-11,562
Fd n-7	Dune sand	8146	0.6	16,000±170	18,364	18,595-18,858
LS-8	Dune sand	8133	0.6	16,250±70	18,595	18,725-18,466
Fd s-9	Dune sand	8192	0.1	17,900±210	20,617	21,187-20,004
6 km-10	Dune sand	8170	0.3	17,010±70	19,375	19,550-19,211
6 kmV-11	Dune sand	8166	0.0	17,300±170	19,750	20,238-19,315
12 km-12	Dune sand	8188	0.2	19,040±80	22,100	22,288-21,903
12 kmV-13	Dune sand	8190	0.3	18,820±60	21,820	21,978-21,676
18 km-14	Dune sand	8146	-0.4	19,100±210	22,172	22,641-21,650
18 kmV-15	Dune sand	8189	-0.5	16,100±180	18,456	18,790-18,112
24 km-16	Dune sand	8194	-0.2	19,800±250	22,937	22,401-no data
L 1	Dune sand	8226	-1.2	10,710±45	11,866	12,065-11,662
L 2	Dune sand	8230	0.3	16,300±150	18,641	18,926-18,364
L3	Dune sand	8233	0.3	16,800±180	18,926	19,563-18,772
L 4	Dune sand	8234	-0.2	14,450±130	16,672	16,042-16,346
L 5	Dune sand	8241	0.1	15,200±150	17,538	17,864-17,201
L 6	Dune sand	8250	0.1	15,900±170	18,269	18,586-17,928
L 7	Dune sand	8260	-0.1	13,700±130	15,670	16,042-15,260
L 8	Dune sand	8252	-0.02	12,070±100	13,439	13,664-13,229
L 9	Dune sand	8257	0.9	12,460±120	13,884	14,177-13,607
L 10	Dune sand	8263	-0.2	10,690±100	11,810	12,215-11,403
L 11	Dune sand	8254	-0.6	12,660±120	14,127	14,438-13,837
L 12	Dune sand	8240	0.5	14,735±50	17,010	17,127-16,894

Sample	Material analysed	Analytical No. Pta-	δ^{13} C‰ PBD	^{14}C Age yr BP	^{14}C Age Cal yr BP	2 σ range Cal yr BP
M5	Surface midden shell, *Patella* sp.	7540	+1.3	2210±60	1608	1489-1760
M8	Surface midden shell, *Patella* sp.	7546	+1.6	1020±50	489	421-541
M 12	Surface midden shell, *Patella* sp.	7548	+0.4	1590±160	960	896-1071
3m TL	Surface shell, *Patella* sp.	7513	+1.1	5780±70	5998	5881-6182
3mT	Subsurface (0.2-1.2 m) shell, *Donax* sp.	7523	+0.8	4570±70	4544	4394-4800
JSC 8	Surface shell, *Patella* sp.	7776	-0.7	1810±50	1221	1098-1289
JSC 6D	Surface shell, *Donax* sp.	7781	+0.6	3780±60	3510	3371-3655
JSC 6p	Surface shell, *Patella* sp.	7768	+0.9	5915±25	6179	6148-6240
4mT	Subsurface (1m) bone	7552	-19.6	1140±50	976	928-1083
6mT	Subsurface (0.2-1.2 m) shell, *Donax* sp.	7527	+2.1	2890±60	2416	2306-2676
9mT	Subsurface (0.2-1.2 m) shell, *Donax* sp.	7528	+0.5	5950±80	6208	6017-6372
11mT	Surface shell, *Patella* sp.	7529	+0.5	5640±70	5881	5705-5998
11mC	Surface shell, *Patella* sp.	7539	+0.5	110±45	Post AD 1966	

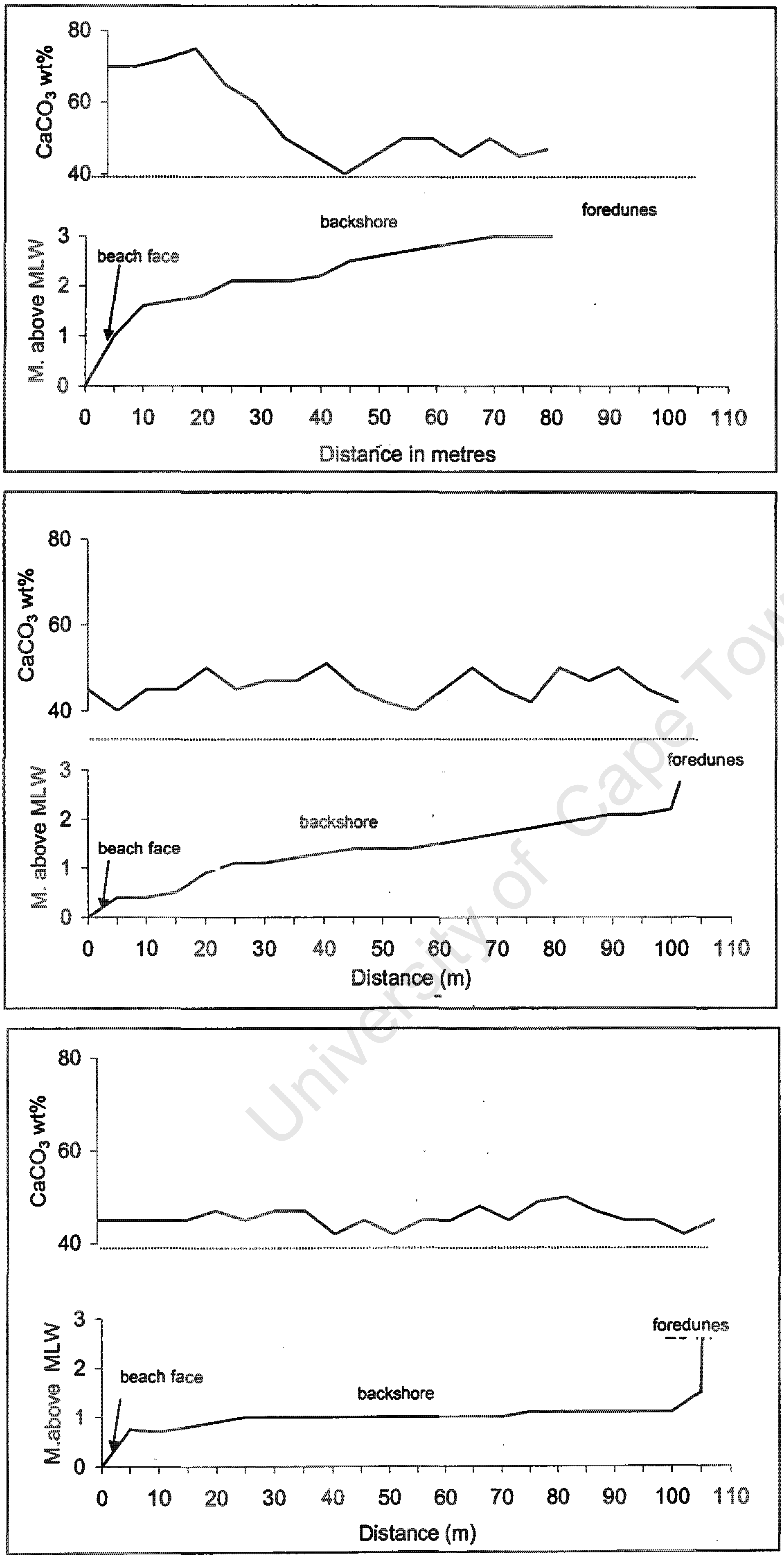
Table 1. Radiocarbon analyses of bulk samples and shells recovered from Sixteen Mile Beach and surrounding coastal dune areas. The location of the samples is shown on figures 4.2 and 4.8.

In the southern end of Sixteen Mile Beach a plume of vegetated and non vegetated parabolic dunes extends 24 km inland (Fig. 4.2).

4.4.1 SIXTEEN MILE BEACH

The southern part of Sixteen Mile Beach has a wide beach (105 m) with pioneer dunes that range from 3 to 25-30 m high. The steepness of the beach face and backshore increases from south to north (Fig. 4.4). The beach sand is primarily composed of quartz and shell fragments (Fig. 4.5). The weight percent of calcium carbonate in the bulk sand collected at mean high water (MHW) ranges from 41 to 55 wt% with an increasing trend from 41 wt% to 55 wt% between 9 and 26 km north of Gabbro Point. Carbonate shell fragments are primarily derived from molluscs and echinoderms that inhabit the sandy and rocky intertidal and subtidal areas. The predominant shell on Sixteen Mile Beach is the white mussel (*Donax serra*), whereas the black mussel (*Choromytilus meridionalis*) is locally abundant near rocky shorelines. Several species of gastropod and barnacle are also present. The calcium carbonate content becomes increasingly variable from south to north and there is an overall increase in the percent carbonate in the sand from south to north with a distinct increase between Black Rock and Tsaarbank (Fig. 4.4).

Grain-size analysis of bulk sand collected at MHW shows a northward coarsening (Fig. 4.6). The southern end of the beach from Gabbro Point to 6 km north consists of very homogeneous (95%) fine sand. The medium sand size fraction increases rapidly from 3% to 58% between 6 km and 9 km (Table 2). The medium sand fraction increases gradually northward from 58% to 89%, whereas the fine sand fraction decreases from 41% to 10% between 9 km and



26 km north of
Gabbro Point
(Tsaarbank)
T1

16 km north of
Gabbro Point
T2

6 km north of
Gabbro Point
T3

Fig. 4.4. Beach profiles along Sixteen Mile Beach and calcium carbonate weight percent along the three transects.

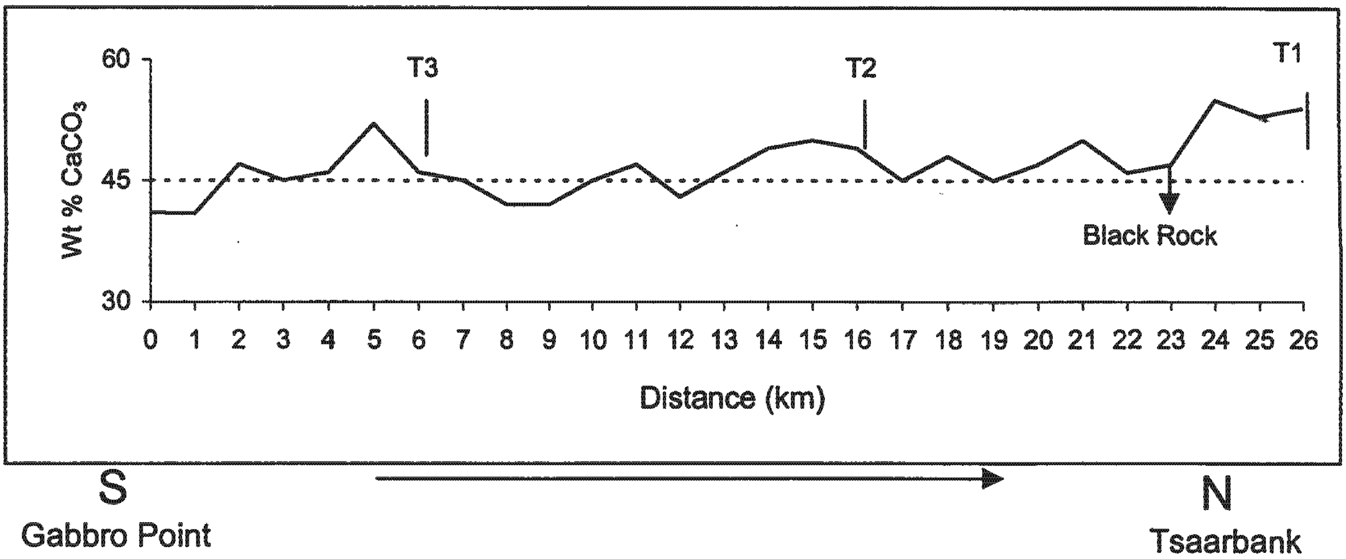


Fig. 4.5. Calcium carbonate weight percent of the bulk sand from MHW along Sixteen Mile Beach. Position of the three transects (T1, T2 and T3) of Fig. 4. 4 are shown.

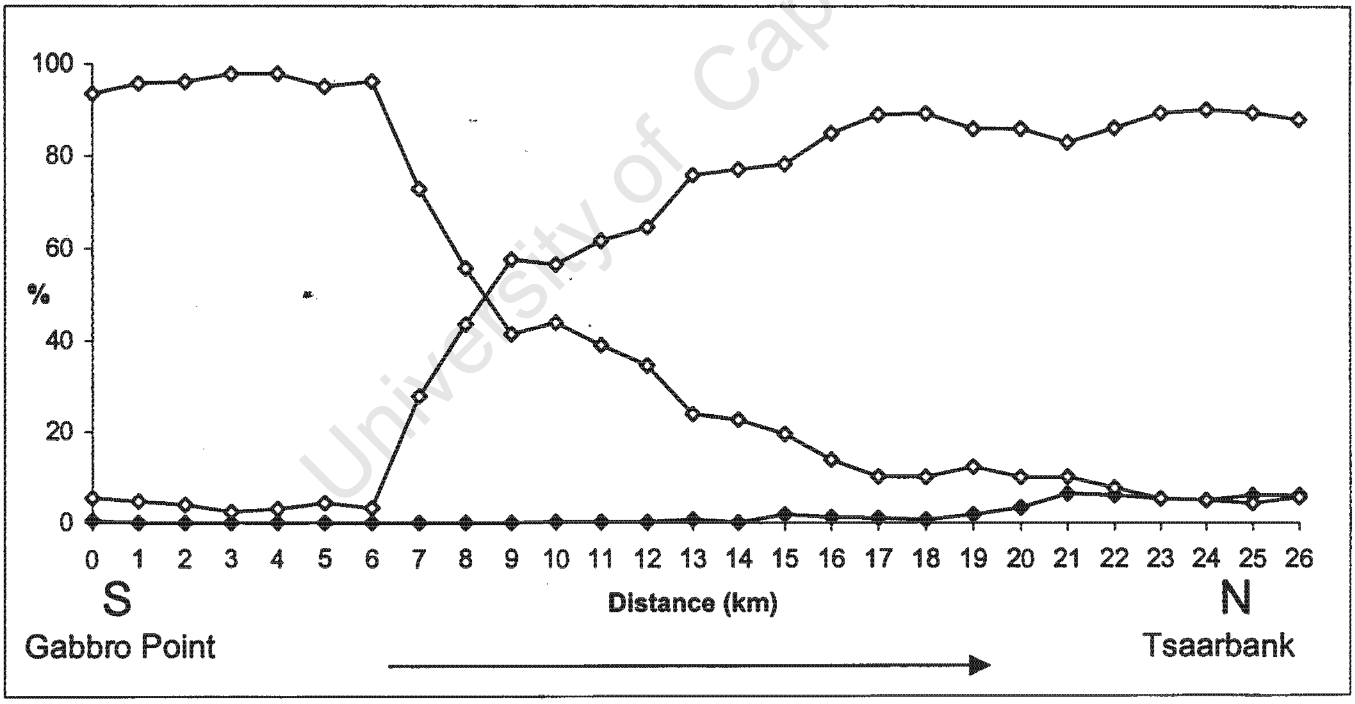


Fig. 4.6. Grain size distribution along Sixteen Mile Beach. The sediment has a coarsening trend northward. The sand is composed of 95 % of fine sand and 5% of medium sand with fairly uniform grain-size to 6 km north of Gabbro Point. A rapid change in grain size occurs from 6 km to 9 km north of Gabbro Point. A gradual coarsening to medium sand occurs between 9 km and 18 km. At the northern end of the beach (23-26 km) the sediment is composed of medium (89%), coarse (6%) and fine (5%) sand.

Sample	very coarse	coarse	medium	fine	very fine
	>1 mm	1 - 0.50 mm	0.50 - 0.25 mm	0.25 - 0.125 mm	0.125 - 0.0635 mm
0	0.00	0.52	5.41	93.71	0.06
1	0.00	0.00	4.76	95.28	0.00
2	0.00	0.00	3.98	96.14	0.00
3	0.00	0.00	2.41	97.84	0.03
4	0.00	0.10	3.01	97.05	0.00
5	0.00	0.00	4.32	95.54	0.00
6	0.04	0.00	3.23	96.49	0.03
7	0.00	0.00	27.87	72.19	0.00
8	0.00	0.00	43.87	55.87	0.00
9	0.00	0.00	57.77	41.93	0.09
10	0.00	0.23	56.56	43.29	0.00
11	0.00	0.22	61.09	39.06	0.00
12	0.12	0.16	64.67	34.77	0.07
13	0.00	0.68	75.89	23.69	0.00
14	0.11	0.09	77.12	22.64	0.00
15	0.00	1.78	78.25	19.48	0.39
16	0.00	1.22	84.98	13.80	0.00
17	0.00	0.98	88.96	10.06	0.00
18	0.00	0.62	89.29	10.04	0.05
19	0.00	1.74	85.98	12.28	0.00
20	0.67	3.31	86.01	10.01	0.00
21	0.43	6.39	83.09	10.09	0.00
22	0.21	6.02	86.16	7.61	0.00
23	0.09	5.23	89.39	5.29	0.00
24	0.02	4.92	90.11	4.85	0.10
25	0.30	5.98	89.49	4.23	0.00
26	0.35	6.06	88.03	5.56	0.00

Table 2. Grain-size distribution along Sixteen Mile Beach determined from dry sieving.

17 km (Table 2). The northern part of the beach from 17 km north of Gabbro Point to Tsaarbank is composed of 83-90% medium sand. The coarse sand fraction increases and the fine fraction decreases between 19 and 22 km (Table 2). The sand from 23 to 26 km is a homogeneous medium sand containing 6% coarse sand and 5% fine sand. The maximum height in the pioneer dunes

varies between 5 and 10 km north of Gabbro Point and coincides with the rapid decrease in the fine-sand fraction (Fig. 4.7).

Carbonate in bulk beach sand samples from Sixteen Mile Beach youngs northwards. From Gabbro Point to 3 km north, the age of the carbonate shell fraction in the sand is fairly uniform ranging from 18.7 ka to 18.2 ka (Table 1). The carbonate shell fraction becomes younger towards the northern end of the beach with calibrated radiocarbon ages of 14.4 ka at 10 km , 12.6 ka at 16 km and 10.8 ka at the northern end of Sixteen Mile Beach (Table 1; Fig.4. 2).

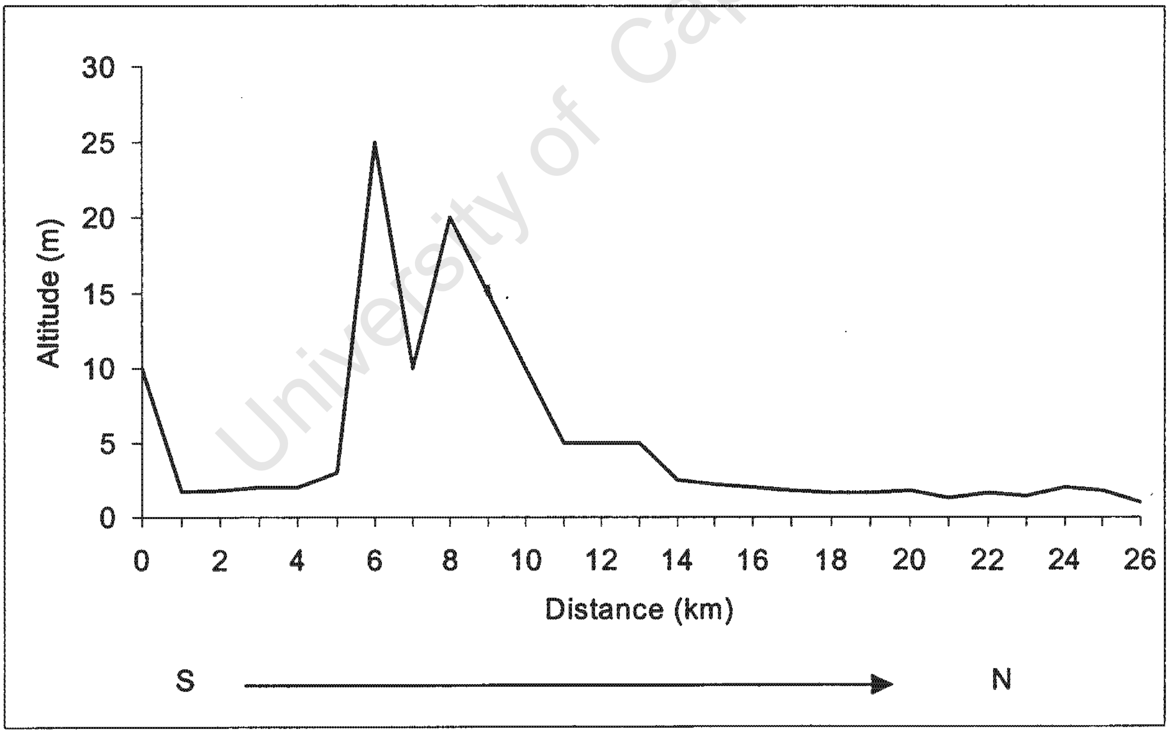


Fig. 4.7. Height above msl of the pioneer dunes along Sixteen Mile Beach.

A total of 3 non-abraded genera of benthic foraminifera were recovered from all of the rocky pool areas (Appendix 2). *Ammonia* and *Elphidium* were consistently the most abundant, comprising 90% (by number) of the fauna collected, followed by *Glabratella*. Similar trends in microfossil abundance were observed along the beach, but all specimens were transported (Plate I) and non-abraded foraminifera were found in sandy beach samples collected along Sixteen Mile Beach.

4.4.2 COASTAL FOREDUNE AND COAST-PARALLEL DUNE RIDGES

The contact between the high-energy beach and the foredune is, in most places, marked by an erosional escarpment 1 to 2 m high. In the northern part of the Sixteen Mile Beach complex, the initial vegetated dunes (pioneer dunes) run parallel to the coast with elevations of 2 to 3 m and are composed of quartz grains and shell fragments (calcium carbonate varying from 35 to 65 wt%). Above the pioneer-vegetated dune, the face of the main foredune rises steeply to elevations of 15 to 30 m. The face of the foredune consists of a non-vegetated, wind-deflated shell layer. Sand is windblow from the beach to form vegetated small dunes and parabolic ridges on top of the foredune. The shell layer of the wind-deflated foredune surface is 1 or 2 shells thick and is composed largely of *D. serra*, and in places the black mussel *C. meridionalis* and the terrestrial dune snails *Trigonephrus globulus* and *Theba pisana* are also present. The shell layer on the face of the foredune accumulates primarily from the dropping of *D. serra* and *C. meridionalis* by gulls (Siegfried, 1977). Significant *C. meridionalis* shells on the deflated foredune face are restricted to within 0.5 km south of the rocky shore at Tsaarbank (Fig. 4.2). The crest of the foredune is defined by a decrease in slope and 0.5 to 2 m high, partially vegetated dunes. *D. serra* shells are absent from the foredune crest, except for scattered shells in the troughs of some of the smaller surface dunes. A mixture of *D. serra* fragments, collected from the landward (eastern) edge of the foredune crest, had a calibrated radiocarbon age of post AD 1966 (profile A-B; Fig. 4.8). The lee side of the foredune is steep and partially vegetated. Aerial photographs show that most parabolic blowout activity is focused in the north and central areas of Sixteen Mile Beach, where the lee slope of the foredune has advanced landwards by 20 to 100 m between 1938 and 1989. In the southern region, the foredune has not changed position since 1938 but vegetation cover has increased from ~5% in 1938 to ~50% in 1989, mostly as a result of artificial planting of the dunes.

North of Black Rock the foredune face becomes increasingly irregular, punctuated by parabolic dunes (Fig. 4.2). The parabolic dunes are generated by U-shaped blowouts, where loss of vegetation or desiccation allows strong winds to deflate the dune surface down to a stable, wet sand surface at the water table (Tinley, 1985). Parabolic dunes have elongated lateral ridges on either side of a central deflation hollow that slopes steeply upward downwind into a sand ramp (Cooper, 1958). Middens were identified by the presence of limpet shells (*Patella* spp.) on the deflated foredune faces and, more commonly, on parabolic hollow surfaces, either scattered over an area of 5 m^2 or concentrated within an area of 1 m^2. Most shell middens occur within 10 m of firestones. Cobble-size firestones occur scattered over an area of 1 to 4 m^2 and consist of Saldanha quartz porphyry altered to an orange to grey colour, and occasionally

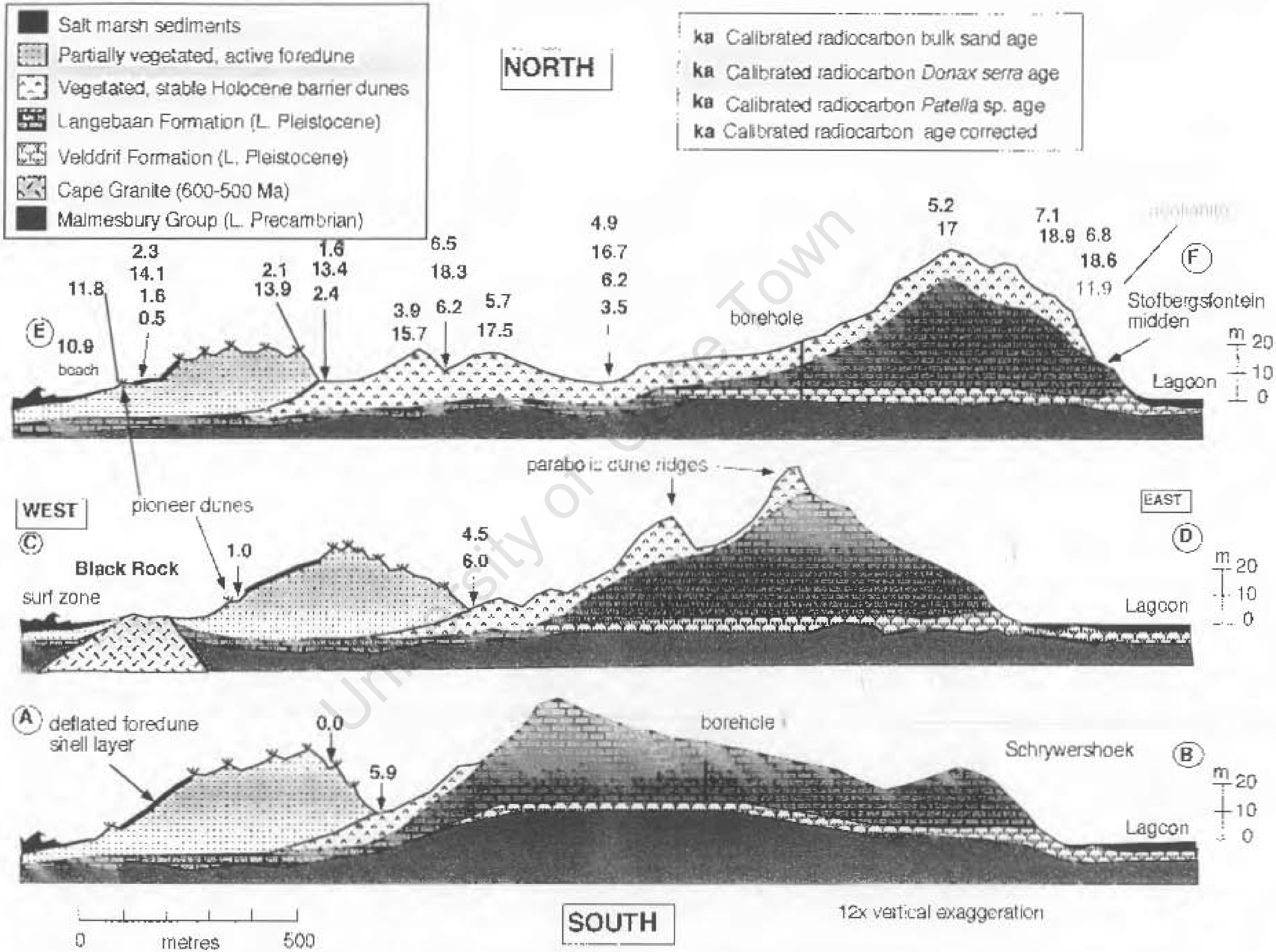


Fig. 4.8. Cross section (x12 vertical exaggeration) of the coastal dunefields along Sixteen Mile Beach showing the location of radiocarbon dated samples. Profiles derived from 1:10,000 orthophotographs.

shelly limestone of the Velddrif Formation altered to a grey to black colour are also found. Middens also contain minor amounts of ostrich eggshell fragments, black mussel (*C. meridionalis*), perlemoen (*Haliotis midae*), Saldanha quartz porphyry stone tools, partly worked fine-grained silcrete and whale vertebra, but no pottery or beads were found. Altogether, 10 middens were observed, exhumed on the foredune surface between Black Rock and Tsaarbank, at elevations of 6 to 12 m above sea level. *Patella* spp. shells collected from three of the foredune middens have calibrated radiocarbon ages of 1.6, 1.0 and 0.5 ka (Table 1).

The coast-parallel foredunes are composed of quartz and shell fragments. The calcium carbonate weight percent generally decreases downwind from 45 wt% in the pioneer dune to 33 wt% in the most distal dunes at Stofbergsfontyn south of Kraalbaai (Fig. 4.9). The fine sand fraction increases rapidly landward of Sixteen Mile Beach from 5% in the pioneer dune to 63% on the crest of the active foredune (transect E-F, Fig. 4.8; Table 3). In the vegetated coast-parallel dunes there is a gradual increase of the fine sand fraction from 63% to 76%.

Landward of the active foredune are stable (vegetated), less calcareous Holocene dunes with coast-parallel troughs and ridges, cut by relict parabolic blowout structures that are clearly discernible from aerial photographs. The elevation of the active foredune decreases and the width of the vegetated, Holocene dunes increases between the south and north transects (Figs 4.2 and 4.8). Holocene vegetated dunes are differentiated from Pleistocene vegetated dunes on the basis of soil colour.

Sample	very coarse	coarse	medium	fine	very fine
	>1 mm	1 - 0.50 mm	0.50 - 0.25 mm	0.25 - 0.125 mm	0.125 - 0.0635 mm
1	0.02	4.92	90.21	4.85	0.00
2	0.00	0.30	64.64	35.06	0.00
3	0.00	0.73	35.56	63.71	0.00
4	0.00	0.00	25.67	72.90	1.43
5	0.00	0.00	34.40	65.60	0.00
6	0.00	0.00	24.87	75.13	0.00
7	0.35	0.00	23.61	75.98	0.06
8	0.00	0.00	24.76	73.79	1.45
9	0.03	0.40	23.57	76.00	0.00
10	0.09	0.00	23.16	76.81	0.03
11	0.00	0.00	12.34	87.56	0.10
12	0.00	0.00	5.31	94.46	0.23

Table 3. Grain-size percentages along the E-F transect determined from dry sieving.

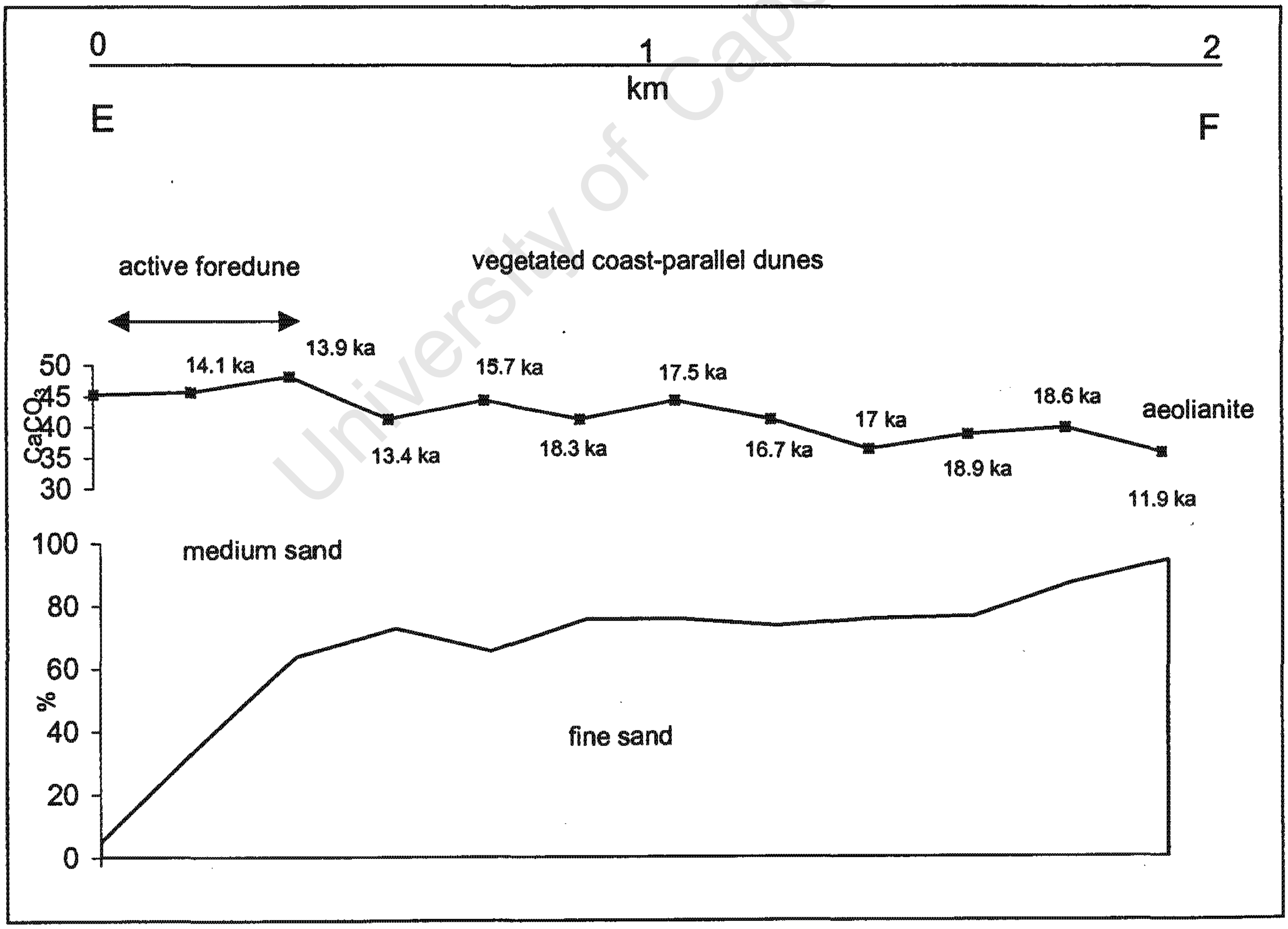


Fig. 4.9. Calcium carbonate weight percent and grain size distribution along the E-F transect across the coastal dunes from Tsaarbank on the Atlantic Ocean coast to Kraalbaai beside Langebaan Lagoon (Fig. 4.2) for location.

Holocene vegetated dunes have 10 to 50 wt% carbonate and are lighter in colour than Pleistocene dune soils which are composed primarily of quartz sand and organic matter and have carbonate contents <1 wt%, except for an occasional surface float of calcarenite or calcrete. Pleistocene yellow aeolian sand has also been described in southwestern Australia (Semeniuk and Glassford, 1988). The yellow sand is mostly composed of quartz and may crop out at the coast or be buried by Holocene dune deposits (Semeniuk and Glassford, 1988).

Scattered over the vegetated dune surface are abundant burrow mounds, up to 0.5 m high, excavated by the large Cape mole-rat *Bathyergus suillus.* Pitted and organic-stained fragments of *D. serra* and *Patella* spp. shell were found as surface float and in the subsurface of some landward dune troughs. Shells are generally absent from the dune ridges adjacent to the troughs. Calibrated radiocarbon ages of *D. serra* and *Patella* spp. shells collected from landward dune troughs and relict parabolic dune hollows range from 6.2 to 2.4 ka (Table 1; Fig. 4.8). The ages of shells from troughs generally young seaward. No shell material was found on the Pleistocene dunes except at archaeological sites along the western cliff of Langebaan Lagoon (Fig. 4.2). Calibrated radiocarbon ages of *Patella* spp. shells, collected from middens at Stofbergsfontein and Schrywershoek, are 1.5 and 1.3 ka in age, respectively (Table 1).

Radiocarbon analyses of bulk carbonate sand, collected from the coastal dunes, give ages of 11.8 ka for the pioneer dune, 14.1 ka for the shell deflated surface and 13.9 ka for the leeward side of the active foredune (transect E-F,

Fig. 4.8). Carbonate sand of the sediment recovered from the vegetated coast parallel dunes gives ages of 13.4 ka, 18.3 ka, 16.7 ka in the troughs and 15.7 ka, 18.3 ka and 17 ka on the crests (Table 1; Fig. 4.8). Carbonate sand of the bulk sediment collected from vegetated dunes on the western margin of Langebaan Lagoon gives ages of 18.9 to 18.6 ka and cemented aeolianite has a bulk radiocarbon age of 11.9 ka.

4.4.3 YZERFONTEIN-GEELBEK DUNE PLUME

Holocene aeolian sand occurs along much of the west coast with large dune plumes on the Cape Flats, west of Atlantis and north of Yzerfontein (Fig. 4.1). The Yzerfontein-Geelbek dune plume has an area of ~43 km^2 and consists of vegetated parabolic ridges and non-vegetated, active barchanoid dunefields. The Yzerfontein-Geelbek dune plume extends 24 km inland in a N/NNE direction and has active barchanoid dunefields located approximately 0 to 8, 9 to 11, 13 to 14 and 17 to 19 km from the coast (Fig. 4.2). Comparison of a series of aerial photographs taken between 1938 and 1993 indicates that movement of barchanoid dunefields is highly erratic but, that on average, active dunefields have migrated at a rate of 3.6 m/y. Surveyed archaeological sites within the Geelbek dunefield show that individual 15 m high barchanoid dunes have migrated inland 5 m in the past year (N. Conard, unpublished report SANparks, 2000). The aerial extent of the non-vegetated dunes has decreased by approximately 25% since 1938; several of the smaller active dunes are now stabilised by vegetation by human plantings (Sieben, pers. comm., 2001).

The calcium carbonate content of the active dune plume sand varies from 45% at Sixteen Mile Beach to 41% at 6 km, 40% at 12 km, 14% at 18 km and 3% at 24 km inland (Fig. 4.10). The vegetated dunes show the same trend, but the percentages are lower (from 31% to 2%). The skeletal fraction is mainly composed of bivalve fragments, echinoid spines, foraminiferal tests (mostly *Elphidium* and *Ammonia*) and barnacle plates. Grain-size analyses of the bulk dune samples show a modal size of 180-150 µm for the active plume (Fig. 4.11). The samples collected at 6 km, 18 km and 24 km have almost the same grain-size distribution with a mean value in the fine sand fraction. The sample collected 12 km inland has a greater amount of very fine sand than the other samples (Fig. 4.11). Carbonate-free samples also have a mean grain size of 180-150 µm (Fig. 4.11). However, there is a decrease in the 250-212 µm size fraction from 6 km to 24 km in the carbonate-free samples. Dune samples from vegetated areas, both in the bulk and the carbonate-free samples, also have a mean grain size of 180-150 µm and show a decrease in the medium size fraction between 6 km and 24 km (Fig. 4.12). The organic material ranges from 1 wt% at 6 km from the beach to 3 wt% at 24 km inland.

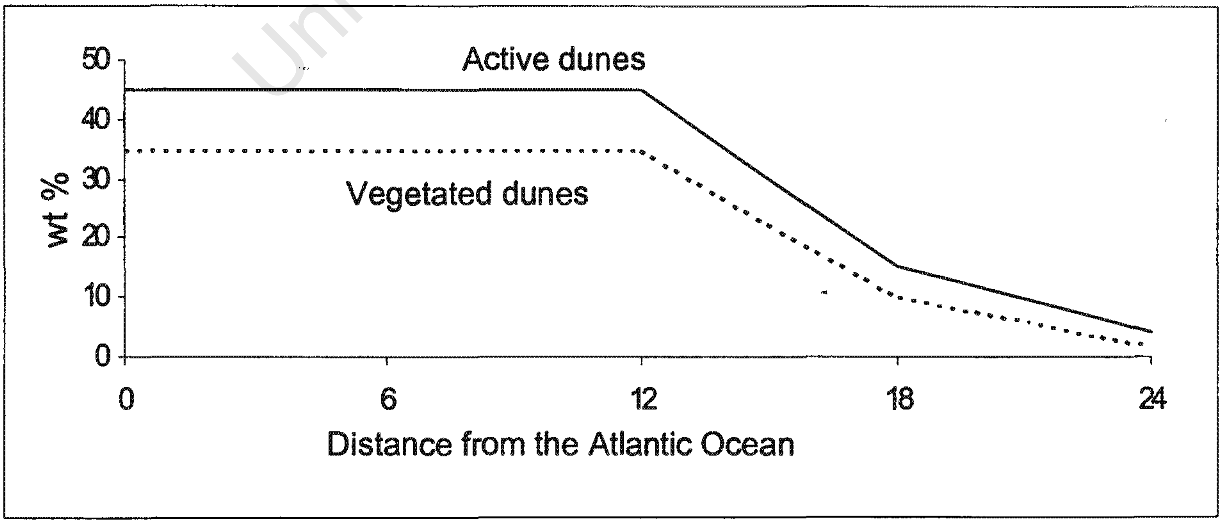


Fig. 4.10. Calcium carbonate weight percent for active and vegetated dune samples. The calcium carbonate decreases from 45% to 3% in the active dune plume and from 31% to 2% in the vegetated dunes.

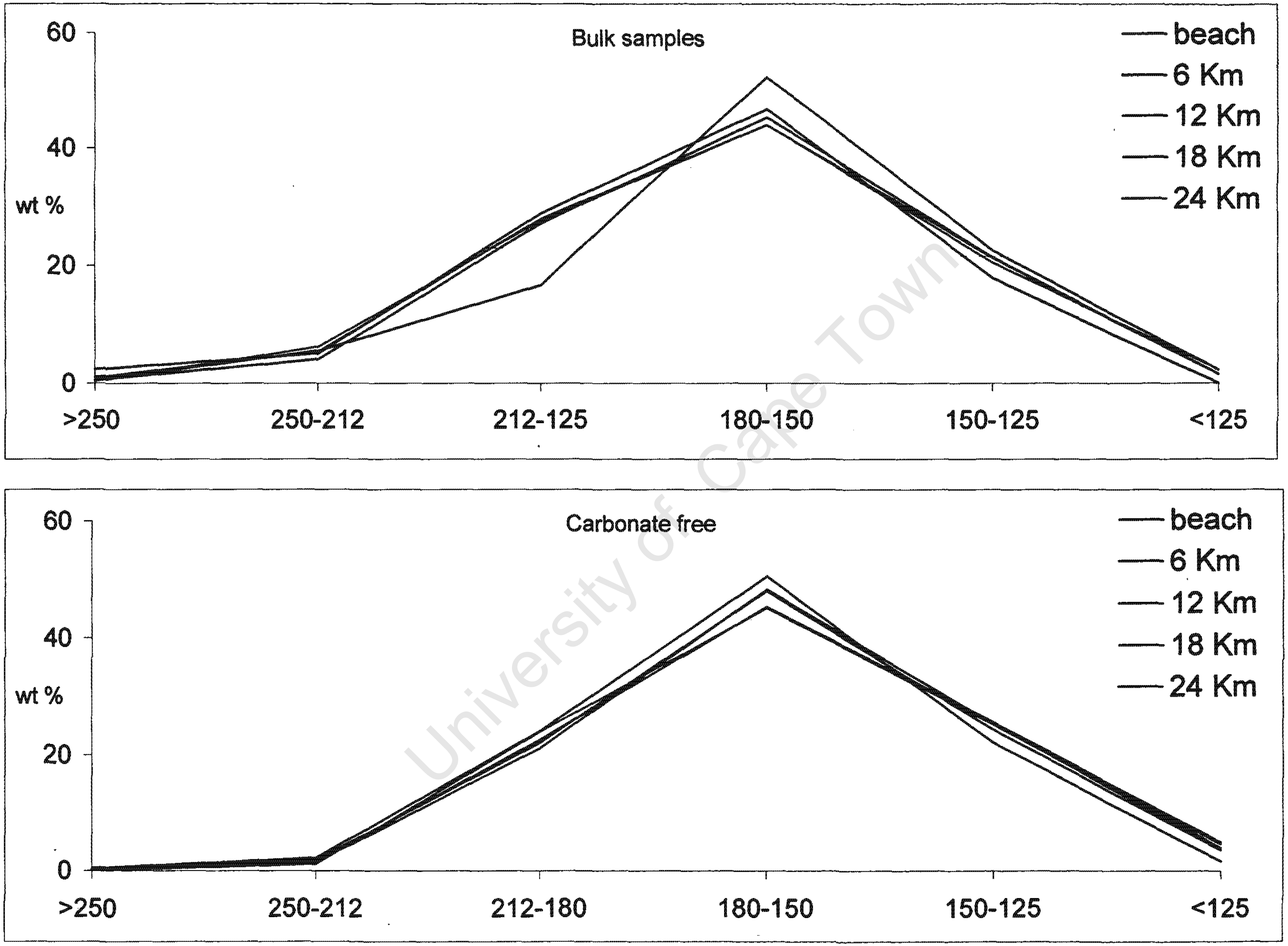


Fig. 4.11. Grain size distribution for the active plume that runs from Yzerfontein to Geelbek.

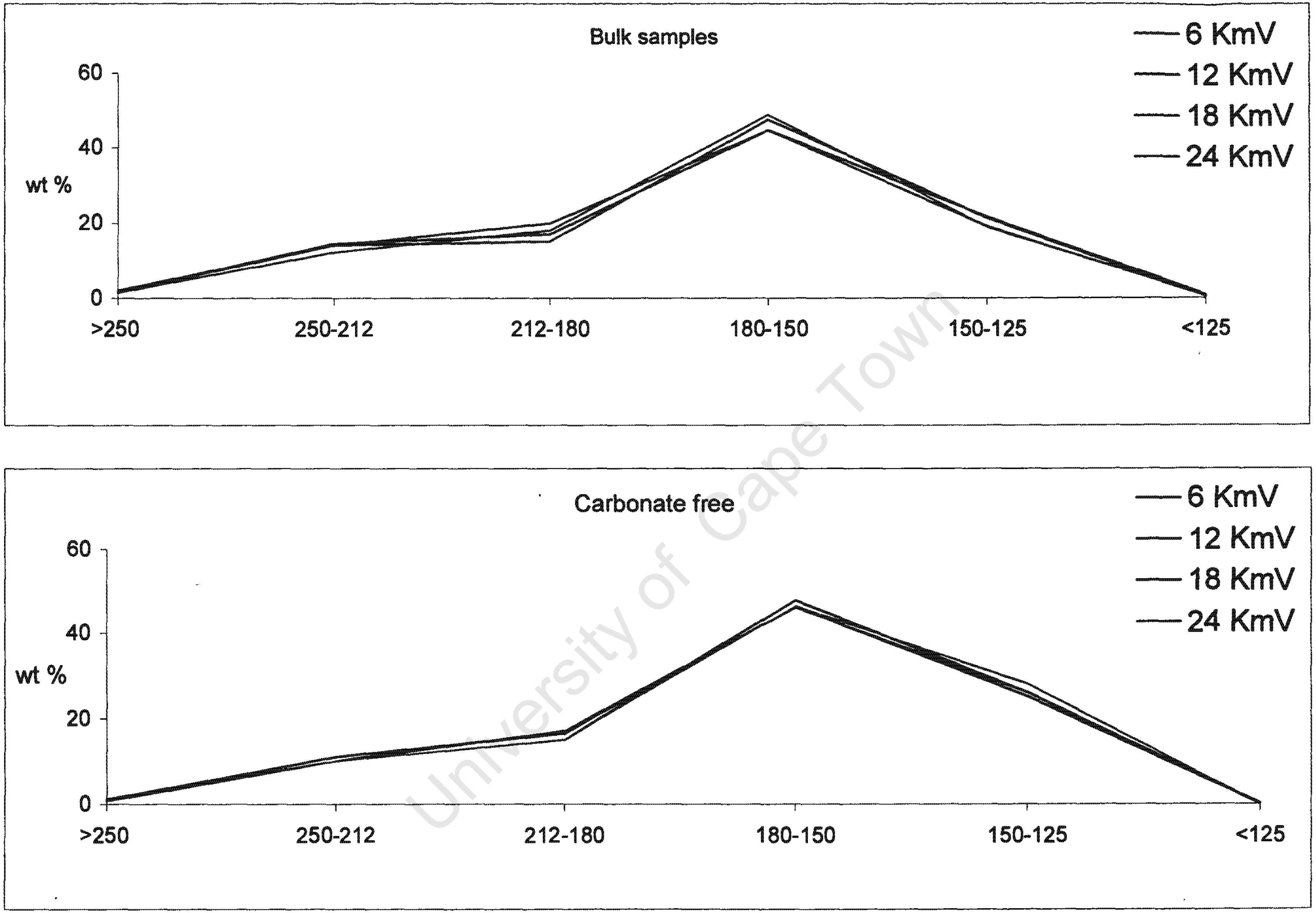


Fig. 4.12. Grain size distribution for the vegetated plume that runs from Yzerfontein to Geelbek.

SEM photographs of microfossils show a progressive abrasion of the foraminiferal tests in the downwind direction of sand transport. Foraminiferal tests can be recognised at the species level at 6 km inland (Plate I). At 12 km inland they become more and more abraded (Plate II) and are difficult to distinguish at species level at 18 km inland (Plate III). No foraminiferal tests were found at 24 km inland.

Radiocarbon ages of the bulk carbonate fraction of sand samples from the dune plume range from 18.3 to 22.9 ka (Table 1; Fig. 4. 2). In the active dune plume at 6 km inland the radiocarbon age of the carbonate fraction is 19.4 ka, at 12 km inland 22.1 ka, at 18 km 22.2 ka and at 24 km inland 22.9 ka. A sample collected 1 km north of Gabbro Point from the pioneer dune gives an age of 20.6 ka. Samples collected from the vegetated dunes give ages of 19.8 ka at 6 km inland, 21.8 ka at 12 km inland and 18.5 ka at 18 km inland

4.5 INTERPRETATION OF SEDIMENT DYNAMICS OF THE SIXTEEN MILE BEACH COMPLEX

There is currently no direct river input to the coast at Yzerfontein and sand is primarily delivered by longshore drift from the south. Sixteen Mile Beach is located about 100 km from major perennial sources of river sand to the south and it is assumed to have a fairly uniform sand supply based on the thousand-year time scales of longshore transport and shell breakdown. The net longshore drift determined over a two-year period at Koeberg Beach, 40 km south of Yzerfontein, is estimated to be 0.2 million m^3/y (Swart and Flemming, 1980).

If the sand undergoing northward longshore drift is transported as a wedge of sand 3 m-thick at the beach and 1 m-thick 1 km offshore, then a net longshore drift of 0.2 million m^3/y would imply a longshore drift velocity of roughly 100 m/y and a transit time of 1 ky from Table Bay to Sixteen Mile Beach. Large seasonal variations in the volume of sand out to the 15 m bathymetric contour were observed, but loss of sand to water depths greater than 15 m was negligible at Koeberg Beach (Swart and Flemming, 1980). The uncertainty in net coastal sand movement is large, but the data of Swart and Flemming (1980) indicate an aeolian sand loss of 0.1 million m^3/y, which is consistent with the estimated accumulation, since 7 ka, of 0.4 to 0.9 billion m^3 of sand in the Atlantis dune plume adjacent to Koeberg Beach (Fig. 4.1). False Bay and Table Bay have perennial rivers that drain large catchment areas receiving an average annual rainfall of 600 mm (SA Weather Bureau, pers. comm., 1998), whereas rivers that drain the semi-arid west coast are ephemeral and have small catchment areas (Fig. 4.1). The decrease in aerial extent of the Cape Flats (243 km^2), Atlantis (88 km^2) and Yzerfontein-Geelbek (43 km^2) dune plumes reflects the decrease in sand supply from south to north.

Sixteen Mile Beach can be divided into three distinct regimes, based on the variation in beach sand grain size. The southern end of Sixteen Mile Beach from Gabbro Point to 6 km north is almost entirely composed of fine sand. Between 6 and 9 km north of Gabbro Point, there is a rapid decrease in the fine sand fraction from 96% to 43% with a distinct break in grain size between 6 and 7 km north of Gabbro Point where the fine sand decreases from 96% to 76% in one kilometre (Table 2; Fig. 4.6). The abundance of fine sand is consistent with the gentle gradient of the foreshore and backshore along the southern part of Sixteen Mile Beach. In the Western Cape, Marker (1987) describes a series of beaches that are the results of two variables, regional gradient and bedrock geology. Evidence from the Knysna Coast led Marker (1987) to postulate that coastal gradient in particular influences the grain size distribution along beaches. Along Sixteen Mile Beach the wave energy of the predominant S-SW swell is largely absorbed by Dassen Island, south west of Yzerfontein (Fig. 4.2) and creates low-energy wave diffraction at the southern end of Sixteen Mile Beach, where fine sand is dominant. The 50 m contour bathymetry line is 9 km offshore of Yzerfontein and just 4.5 km offshore of Tsaarbank (Fig.4. 5). The Holocene dune plume that extends from the southern part of Sixteen Mile Beach inland to Geelbek is a result of strong southwesterly onshore winds that blow across a large area of beach composed mostly of fine sand. Persistent strong summer winds move the fine sand rapidly inland and allow the development of the extensive inland plume. The transition from the dune plume to the large coast-parallel foredunes coincides with a rapid increase in medium sand and a decrease in fine sand along the beach from 8 km north of Gabbro Point. The marked change in morphology appears mostly to reflect the increase in grain size of the beach sand and the extent to which the wind can transport the sand inland. A downwind decrease in the medium sand fraction in the plume suggests that a coarser sand lag has developed near the beach. The downwind decrease in carbonate content reflects dissolution of carbonate by rain combined with reworking of Late Pleistocene low-carbonate sands. In the active dune plume, the bulk sand samples collected on the beach, at 6 km, 18 km and

24 km inland are very similar, with a major component of fine sand (Fig. 4.11). The exception is the sample from 12 km, which is composed of significantly finer grained carbonate sand than the other active plume samples. The older radiocarbon ages of the sample from 12 km are therefore at least in part attributed to its finer grain size with a greater amount of 180-150 μm carbonate fraction.

Along Sixteen Mile Beach, the transition zone from fine to medium sand occurs from 9 to 12 km north of Gabbro Point with a northward increase in the amount of medium sand (from 57 to 65 wt%) and a decrease in the amount of fine sand (from 41 to 34 wt%, Table 2). Offshore, this transitional area is marked by a rapid steepening of the shoreface (Fig. 4.2). Along the backshore of the beach, this area is marked by the highest pioneer dunes (Fig. 4.7). Coast-parallel dunes are not well developed in this central transitional part compared to other areas along the beach.

The northern part of the Sixteen Mile Beach extends from 13 to 26 km north of Gabbro Point. Behind the beach, this area is composed of a pioneer dune 2 m high, and active foredune and coast-parallel dunes. The largest and highest dunes inside the complex are in this section, where long term accumulations of sand and successive generations of dunes become superimposed onto the pre-existing topography. The grain size of the beach sand is marked by an increase in medium sand (up to 90 wt%) and in coarse sand (up to 6 wt%, Table 2). The northern beach has a narrow and steep shoreface and the foreshore is very steep as an indication of the high-energy received. The sediment forming this large coast-parallel dune complex is composed of medium sand from the beach to 250 m inland (Fig. 4.9). On the shell deflated surface of the foredune from 250 m to 2 km inland there is an increase in fine sand (Fig. 4.9). However, the amount of fine sand is less than in the Yzerfontein-Geelbek dune plume (Tables 3, 4, 5) because the fine sand of the southern end of Sixteen Mile Beach is quickly moved inland to form the 24 km long active plume. In the northern part of the Sixteen Mile Beach complex, the present-day foredunes are also migrating inland, but not for long distances because they are composed of significantly more medium sand. Local winds are not strong enough to move this medium sand to form an active plume and vegetation stabilises this area more easily. The orientation of the Yzerfontein-Geelbek dunefield suggests that the prevailing wind direction since the Holocene has been from the south-south west. Similar conclusions based on the orientation of Holocene dunefields were suggested for the southern part of Namibia (Corbett, 1989).

The calcium carbonate weight percent along Sixteen Mile Beach (Fig. 4.5) increases from 47 wt% at Black Rock to 55 wt% at Tsaarbank, where a rocky shoreline results in very high biological fragmentation of *D. serra*, *C. meridionalis* and gastropods. The greatest abundance of *D. serra* and *C. meridionalis* occurs along the rocky outcrops of Sixteen Mile Beach and on the wind-deflated face of the foredune. Adult *D. serra* do not migrate with the tides, but occupy a more or less fixed position on the beach that is usually subtidal on the Atlantic coast (Branch and Branch, 1981; Branch et al., 1994). Similar to studies of gull scavenging of the black mussel *C. meridionalis* (Siegfried, 1977), gulls probably scavenged larger, adult *D. serra* stranded on the beach after

Sizes	Beach	6 km	12 km	18 km	24 km
>250	2.4	0.56	0.58	0.98	0.31
250-212	5.12	4.11	5.58	5.45	6.28
212-180	28.78	27.07	16.68	27.70	27.50
180-150	46.65	45.23	52.24	43.08	43.01
150-125	17.00	21.39	22.56	21.25	20.48
<125	0.06	1.64	2.36	1.56	2.42

Table 4. Grain-size distribution of the bulk samples for the active dune plume using the settling column.

Sizes	Beach	6 km	12 km	18 km	24 km
>250	0.4	0.17	0.12	0.05	0.02
250-212	2.22	1.86	1.45	1.525	1.12
212-180	24.07	22.07	23.12	22.57	23.91
180-150	49.5	48.02	46.08	45.27	45.10
150-125	22.09	24.38	25.3	25.6	25.23
<125	1.67	3.642	3.968	4.973	4.64

Table 4. Grain-size distribution of the carbonate-free samples for the active dune plume using the settling column.

Sizes	6 km	12 km	18 km	24 km
>250	1.567	1.564	1.983	1.423
250-212	14.001	14.382	13.923	12.093
212-180	15.077	16.994	19.932	18.013
180-150	47.525	44.675	44.61	48.759
150-125	21.38	21.642	19.099	18.93
<125	0.45	0.743	0.453	0.782

Table 5. Grain-size distribution of the bulk samples for the vegetated plume using the settling column.

Sizes	6 km	12 km	18 km	24 km
>250	1.1	1.092	0.95	0.626
250-212	10.01	11.011	10.01	10.01
212-180	15.027	16.5	17.04	15.01
180-150	47.716	46.2	46.01	46.343
150-125	26.003	25.051	25.97	28.01
<125	0.144	0.146	0.02	0.001

Table 5. Grain-size distribution of the carbonate-free samples for the vegetated dune plume using the settling column.

major winter storms and fractured the shells by dropping them from a 2-10 m height onto the wind-deflated face of the foredune that was hardened by deflation to a wet surface or by a previously accumulated shell layer. Gull-dropped shells are sparse on the crest and lee of the foredune. The abundance of gull-dropped *C. meridionalis* on the foredune decreases rapidly south of their rocky habitat at the northern end of Sixteen Mile Beach consistent with the observation that gulls rarely drop shells more than 500 m from their source (Siegfried, 1977). The presence of the dune snails *T. globulus* and *T. pisana* (up to 30 mm in size) indicates that the deflated face was previously vegetated.

4.6 INTERPRETATION OF RADIOCARBON AGES IN THE SIXTEEN MILE BEACH COMPLEX

Interpretation of radiocarbon ages of bulk sand samples is complicated by the different sources of carbonate grains, the mean grain size and any diagenetic recrystallisation of carbonate. In this thesis, bulk radiocarbon ages were determined because they provide average ages, that may be used to speculate on evolution of the complex. Ideally, carbonate grain of different size and texture should be dated by AMS but the number of analyses and cost required were prohibitive. Radiocarbon dating was performed on samples collected from Sixteen Mile Beach, Yzerfontein-Geelbek dune plume and coast-parallel dunes.

4.6.1 RADIOCARBON AGES ALONG SIXTEEN MILE BEACH

The known sources of biogenic carbonate (shell fragments) in the beach sand are the breakdown of modern shell in the surf zone, the onshore migration

In addition to migrated beach sand, the strandline would have reworked aeolian sand from coastal dunes deposited during the marine regression between 80 and 18 ka. The carbonate grains from these dune deposits would contain very little, if any, ^{14}C

Erosional reworking of variably cemented Late Pleistocene dunes (Langebaan Formation) is observed along the coast, for example, south of Gabbro Point (Fig. 4.2). Most of the dunes undergoing erosion along the coast are at least 80 kyr old, by analogy with the dunes of the Langebaan Formation on the western shore of the Langebaan Lagoon dated at between 120 and 79 ka (Roberts and Berger, 1997). Minor Holocene oscillations of sea-level since 7 ka (Compton, 2001) would have reworked these Pleistocene dunes. Carbonate reworked from Pleistocene dunes no longer contains ^{14}C and would dilute more recent carbonate resulting in an older, apparent bulk sand age.

The carbonate fraction of the bulk sand samples collected along the Sixteen Mile Beach consists of modern shell fragments derived from the fragmentation of fresh, Holocene shells and older, reworked shell fragments derived from beach and dune sand deposits that have migrated with the strandline during the Flandrian transgression or eroded from Pleistocene dunes deposited during the previous inter-glacial. The radiocarbon ages of the bulk sand samples, therefore must represent a maximum age of the carbonate grains because all reworked sources of carbonate sand will make the apparent age older. The maximum age of the carbonate grains for the southern part of the beach is 18.4 ka, and 10.9 ka for the northern part (Table 1, Fig. 4.13). To correct these ages for the amount of reworked, essentially dead (no ^{14}C), carbonate grains that would have increased the apparent age of the sample, the texture of various carbonate grains was analysed in order to distinguish between fresh carbonate and reworked dead carbonate. The route of differentiating carbonate grains in order to understand the provenance and the apparent age of the beach sand has been undertaken because we have no access to AMS dating. Texturally the carbonate grains for the beach and the dunes in the Sixteen Mile Beach complex are very different. Several shells of *C. meridionalis* and *D. serra* were collected from the beach grained to sand size and observed under a microscope in order to compare to modern beach sand. These grains are fresh in appearance and retain the original colour. The edges of the grains are very angular indicative of recent breaking. In opposition, the carbonate material from older dunes in the Sixteen Mile beach complex is yellow in colour and opaque. Analysed under the microscope these grains are milky-opaque and the edges are well rounded. The Pleistocne dune sand has no coloured carbonate grains. The carbonate sand on Sixteen Mile Beach is composed of three types of grains: coloured grains, translucent grains and white-opaque grains. The methods proposed here consists of counting the percentage of 300 different grains in selected samples and distinguishing among the three grain types (Table 6). Coloured grains range from pink, purple and orange and they largely originate from the break down of *C. meridionalis* and *D. serra*. Translucent grains are white or light-grey in colour. These carbonate grains are composed of fragments of *C. meridionalis, D. serra,* echinoderm spines and barnacles. Both the coloured and translucent grains are elongate and are interpreted to be fresh carbonate grains. White-opaque grains

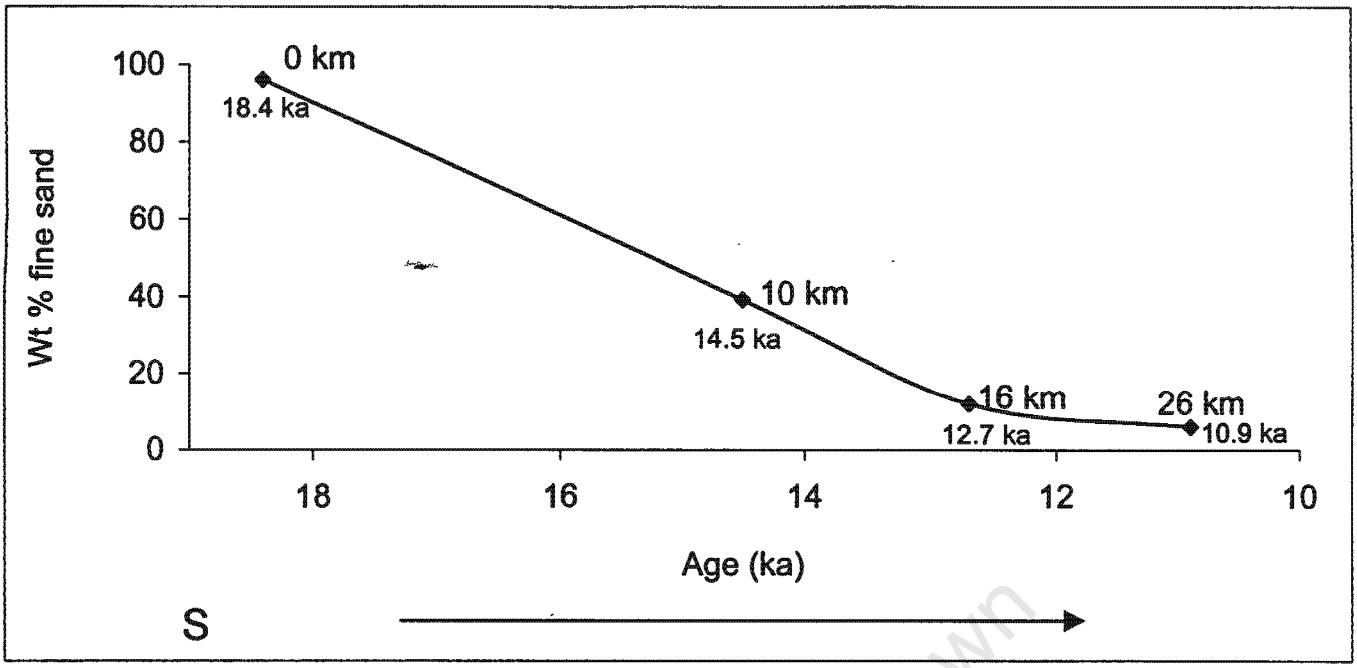


Fig. 4.13. Age-grain size correlation along Sixteen Mile Beach.

	Coloured %	Clear %	Opaque %	Notes
Gabbro Point	5	20	75	
Active foredune	2	5	93	
6 km	2	18	80	Phosphorite grains
12 km	0	10	90	
18 km	2	15	83	
24 km	0	10	90	
Tsaarbank	5	55	40	
Active foredune	15	50	40	
Pleistocene dunes	0	3	97	Phosphorite grains

Table 6. Distribution of different grain types along the Sixteen Mile Beach complex.

are white to yellow in colour. White-opaque grains are well rounded and they are abraded, with surfaces having a frosted appearance. White-opaque grains are interpreted to be predominantly dead carbonate grains derived mostly from reworked Pleistocene dunes.

In the southern end of Sixteen Mile Beach, 5% of the grains are coloured, 20% are translucent and 75% are white-opaque grains (Table 6). The mean average age for the carbonate sand of the southern part of Sixteen Mile Beach is 18.4 ka (Table 1), an age that is equivalent to 10% of modern ^{14}C. Considering that 25% are fresh carbonate grains and if all the remaining 75% of carbonate grains contain no ^{14}C (for the purpose of these calculations it is assumed that the amount of reworked carbonate sand such as migrated sand from the Flandrian Trangression is negligible), then it follows that:

$10\% = x\ (25\%)$

$x = 40\%$

This implies that the fresh carbonate (coloured and translucent) has an average of 40% modern ^{14}C which corresponds to an age of 7.3 ka. Similar calculations can be done for the beach sand sample collected 26 km northward of Gabbro Point (Tsaarbank) where the age of the carbonate fraction is 10.9 ka, an age that is equivalent to 24% modern ^{14}C, and the fresh carbonate grains constitute 60% of the sample.

$$\text{measured \% modern } ^{14}C = x\% \text{ (fresh carbonate sand)}$$

$24\% = x\ (60\%)$

$x = 60\%$

This implies that coloured and translucent, fresh carbonate grains that make up 60% of the bulk beach sand have an average of 60% modern ^{14}C, which corresponds to an age of 7.3 ka.

The minimum age of the fresh carbonate fraction on Sixteen Mile Beach is 7.3 ka. Reworking of carbonate grains younger than around 40 ka (for example migrated sand from the Flandrian Trangression) will make this age older since it has been assumed that all the white opaque grains have no ^{14}C. The age of 7.3 ka is the mean age of the "parent shells" from which the fine sand was derived (the southern part of the beach is composed of 97 wt% of fine sand; Table 2) and the medium to coarse sand (the northern part is composed of 95 wt% of medium to coarse sand, Table 2). This surprising result provide information on how shells break down. In fact, during initial fragmentation of parent shells, some fragments are small enough to contribute to the fine fraction. The remaining coarse and medium fragments will degrade further in time and form fine sand grains at a later stage. This, in effect, results in some of the fine sand having the same age as medium to coarse sand fragments and not necessarily older as previously suggested (Illenberger and Verhagen, 1990). The northward increase in the amount of fresh carbonate from 25 to 60% correlates with the increase in grain size and the direction of transport by longshore drift (Table 6). This northward increase in grain size can be attributed to the greater biofragmentation in the northern part of Sixteen Mile Beach, because of the presence of rocky outcrops and the rocky headland (Fig. 4.2) and the removal of fine sand from the southern part of Sixteen Mile Beach by wind to the Yzerfontein-Geelbek dune plume. However, the removal of fine sand from the beach is a secondary factor acting along the beach, otherwise a sharp contact between fine and coarse sand would have been detected along Sixteen Mile Beach (refer to Fig. 4.6).

4.6.2 YZERFONTEIN-GEELBEK DUNE PLUME

Active dune plumes have always been extremely difficult to date because their rapid downwind migration turnover makes the use of thermoluminescence dating techniques impossible. For the dune plume in the southern part of the Sixteen Mile Beach complex, the average landward migration rate deduced from aerial photographs for the last 55 years, is 3.6 m/y. However, aerial photographs show that migration of dunefields is complex (Fig. 4.14). For example, the Geelbek dunefield has contracted between 1938 and 1999 as a result of planting of the northern end of the dunefield (Fig. 4.14). Active sand retreated at its northern end by up to several hundred metres and advanced at its southern end by between 100 and 700 metres. A similar situation was recorded in the central part of the active dune plume, where decreases in size of the non-vegetated area can be seen from aerial photos (Fig. 4.14). Variations in rainfall and the frequency of fires would have an impact on the extent of active dunefields. Smaller dunes may break away or coalesce with larger dunes. Additional sand can be taken up by erosion of older, underlying sand and sand can be stabilised, at least temporarily, in vegetated trailing parabolic ridges. These complexities may account for the variable distribution of active dunefields among west coast plumes. The Swartlintjies River dune plume, located 350 km north of Yzerfontein (Fig. 4.1) has a similar inland reach of 24-

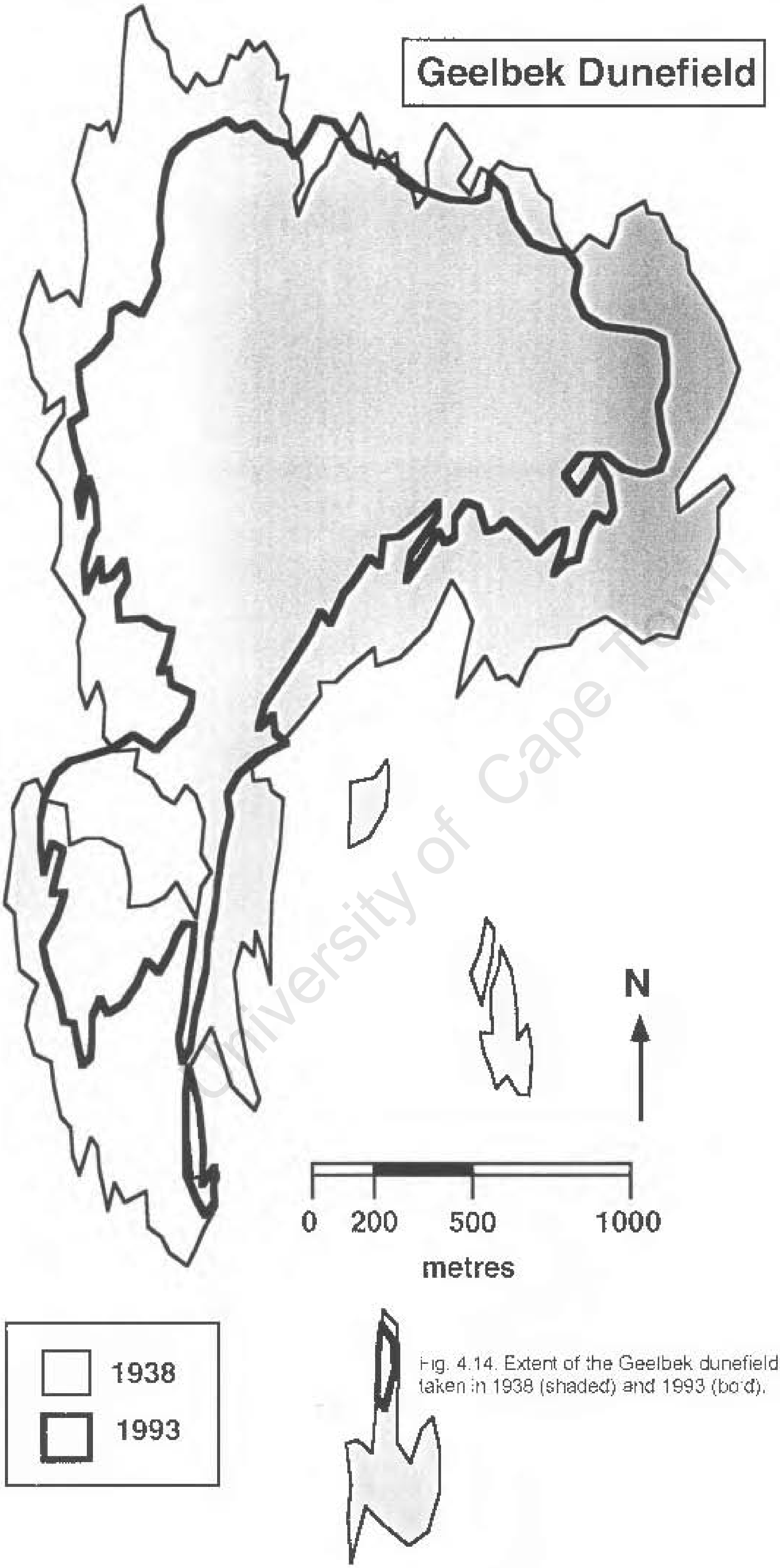


Fig. 4.14. Extent of the Geelbek dunefield from aerial photographs taken in 1938 (shaded) and 1993 (bold).

27 km, with active dunefields located at 0-7 km, 11-14 km and 21-25 km from the coast (Tankard and Rogers, 1978).

The age of the plume can be estimated by assuming that the carbonate fraction of the dune plume is composed of shell fragments from the beach. Once fine enough to be removed by the local winds, these carbonate fragments can be blown inland to form dune plumes. For example, the Cape Recife and Cape St. Francis headland bypass dunefields, located in the Eastern Cape, are inferred to date back to about 5,000 years ago (Illenberger, 1988).

Taking 18.4 ka as '0 age' of carbonate from the southern part of Sixteen Mile Beach, the age of the active plume is 1 ka at 6 km inland, 3.7 ka at 12 km inland, 3.8 ka at 18 km inland (Geelbek dunefield) and 4.5 ka at 24 km inland (Fig. 4.15 and red and green ages in Fig. 4.2 obtained by difference between 18.4 ka and the respective ^{14}C age). The apparent old age of the sample collected at 12 km inland can be attributed to reworking of old dunes. In fact, the sample collected at 12 km inland contains a large amount of fine sand concentrated in the carbonate fraction (Fig. 4.11). Another suggestion of the reworking of Pleistocene dunes in the sample collected at 12 km inland is offered by the low content in coloured and clear carbonate grains (Table 6) that form only 10% of the carbonate fraction. At 6 km inland and at 18 km inland the coloured and clear carbonate grains compose 20% of the carbonate fraction (Table 6).

The complex dynamics of the evolution of the Yzerfontein-Geelbek dune plume can be explained by viewing the plume as a series of discrete cells, which are open to sediment transfers amongst them. In recent years, a proliferation of possible non-linear models have been proposed ranging from deterministic to chaotic, and it is not difficult to envisage coastal phenomena developing under turbulent flow, that may impact differently over the cells. For example, Roy and Thom (1991) and Roy and Keene (1993), describe the sediment budget of the south-eastern margin of Australia involving the net transfer of sand from south to north throughout and the growth of offshore bars and transgressive dunes in the northern region and an area starved of sediment in the southern region. These changes are initiated at physical discontinuities such as drowned valleys and different coastal alignments (Ferland, 1990; Swift and Thorne, 1991; Roy et al., 1992). The interpretation of the Yzerfontein-Geelbek dune plume may be considered as an example of non-linear behaviour over time and erratic migration because of the non-linearity of the radiocarbon dating results. The downwind end of the active dune plume, using the correction factor of 18.4 ka, has an age that implies a mean velocity of the dune plume of 5.3 m/y, similar to the present-day yearly migration rate of 5 m/y.

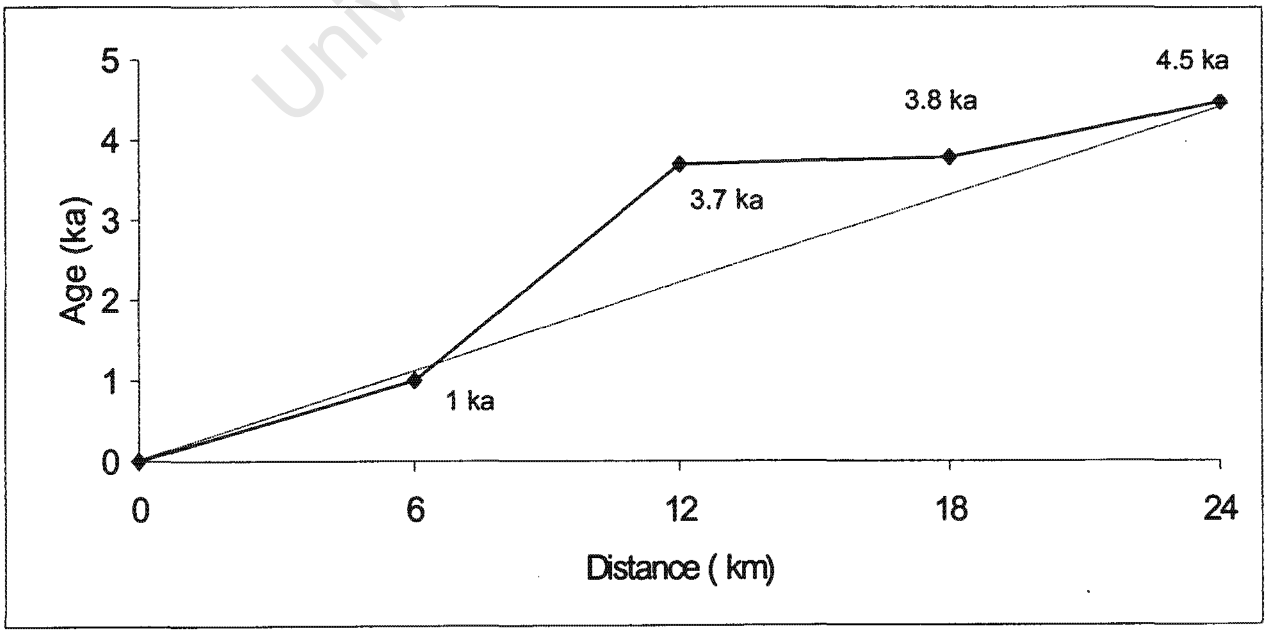


Fig. 4.15. Age-distance correlation along the Yzerfontein-Geelbek active dune

The age of the landward limit of the active dune plume implies that this plume started to form 4,500 years ago. Holocene sea-level reached its present-day position around 7.5 ka (Fig. 4.16). However, from 7.5 to 4-5 ka, the sea-level reached a maximum elevation of 3 m above msl (Compton, 2001). The sea level returned to its present-day position about 4-5 ka ago with minor (± 1m) oscillations of sea-level since 5 ka. The relatively stable sea-level since 5 ka would have allowed the dune plume to develop uninterruptedly.

Textural changes in microbenthos provide a way of tracking the transport of the sediment along Sixteen Mile Beach and the plume. Along the beach (Plate I) the foraminifera tests are abraded, but the overall microfossil structure is still recognisable. The foraminiferal assemblages collected at Gabbro Point are the only non-abraded and well-preserved foraminifera found along the beach. All the other tests found along Sixteen Mile Beach are abraded due to *post mortem* transport in the high-energy beach environment (Plates II, III, IV). Six km inland along the plume, the *Ammonia* and *Elphidium* tests show incipient signs of abrasion, in particular around the edges of the test. At 12 km and 18 km inland, recrystallisation occurs in the interior of the structure, whereas the external surface is marked by several abrasions (Plate III). At 24 km inland, no microbenthos were found, and this implies that calcium carbonate dissolution has completely leached out the foraminifera and echinoderm spines. The 2-3% calcium carbonate found 24 km inland is composed of elongate fragments that are robust and their flake-like shape allows them to be transported by wind over long distances.

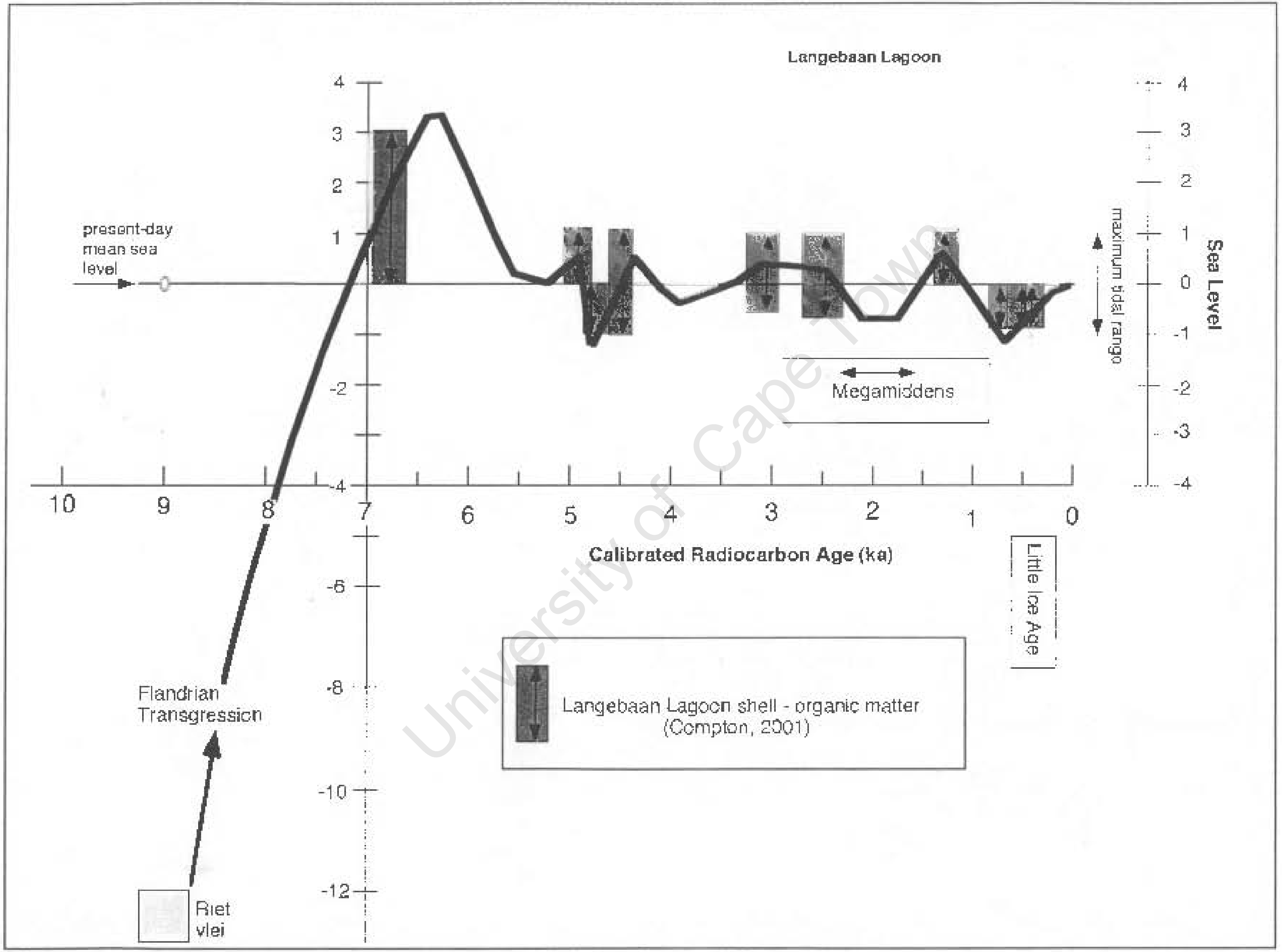


Fig. 4.16. Holocene sea-level changes inferred from the calibrated radiocarbon ages and estimated sea-level position of organic matter and shell material recovered from Langebaan Lagoon. Width of boxes indicates analytical uncertainty of calibrated ages and height indicates uncertainty in estimated sea-level (after Compton, 2001).

The radiocarbon results of the vegetated dunes are even more complex to interpret and this can be related to soil processes such as fungus re-growing on the sand and to the different moisture contents of the soil that play an important role in carbonate recrystallisation prior to laboratory analysis. Young carbon could have occurred by *in situ* cementation with calcite or calcitization of aragonite in association with evaporation, growth of roots or fungus (Geyh and Schleicher, 1990; Grootes, 1983). At 6 km inland the sediment of the vegetated dunes is 1.4 ka old, at 12 km inland 3.4 ka and only 0.2 ka at Geelbek dunefield, where recrystallization has played an important role.

Changes in climate, particularly rainfall, will have an impact on vegetation and on the stability of dunes with variable development of active and vegetated dunes. In the Yzerfontein-Geelbek dune plume, the active dunefield located 13 to 14 km from the coast became entirely vegetated between 1938 and 1993 and the Geelbek dunefield contracted (Fig. 4.14). The area is located in a semi-arid environment and cattle farming has always been limited (Saldanha Municipality, pers. comm., 2001). The increase in vegetation and contraction of active dunefields in the Yzerfontein-Geelbek dune plume between 1938 and 1993 corresponds to an increase in the recorded average annual rainfall at Langebaanweg (Fig. 4.17). Rainfall was generally below the mean from 1926 to 1951 and from 1960 to 1981, and above the mean from 1952 to 1962 and from 1982 to 1996. Some of the increase in vegetation is a result of planting of the dunes with indigenous species by the Forestry Department, but a significant amount of the increase in vegetation occurs beyond planted areas.

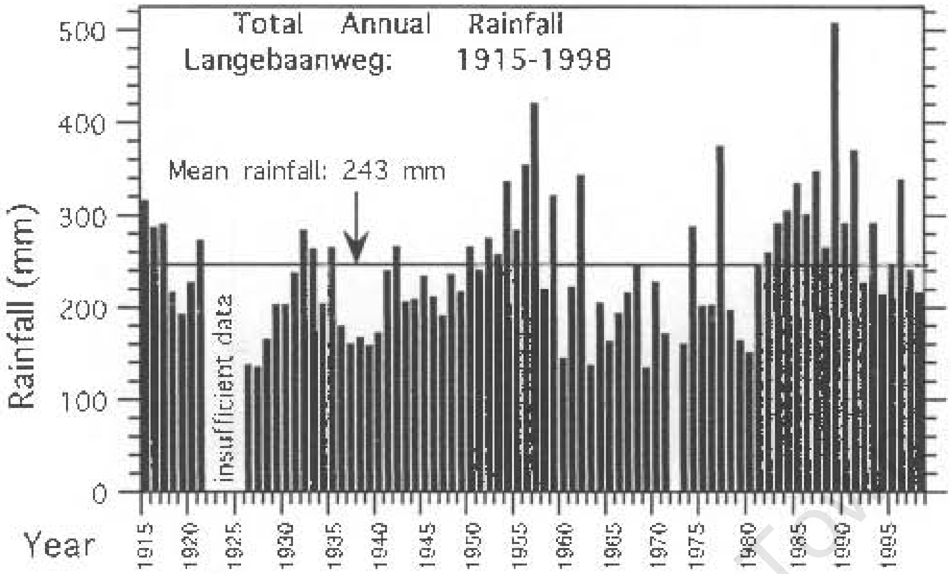


Fig. 4.17. Average annual rainfall from Langebaanweg for the years 1915 to 1998 (SA Weather Bureau, pers. comm.). Insufficient data are available for the years 1922-1925 and 1972.

Insufficient evidence is presently available to be certain about the number and causes of aeolian episodes in the active and vegetated dune plume, but all the data available for now underline the fact that active barchanoid dunefields indicate periods of increased sand supply and mobility along the coast, similar to the sand pulses proposed for the Algoa dunefields on the south coast (Illenberger, 1988). The increased volume of sand will result in a pulse of wind-blown sand onshore, assuming that most of the sand is not lost permanently to the offshore (Swart and Flemming, 1980). In coastal areas having a strong onshore wind, the majority of eroded dune sand appears to be recycled via the beach and offshore sandbars back into newly formed inland advancing dunes (Cooper, 1958, p. 131). Gaps between active dunefields in the plume may develop during marine regressions. As sea level drops, the beach migrates out to the relatively sand-starved offshore and while a new coastal foredune is established farther seaward by sand delivered by longshore drift, the previous foredune together with other active dunefields continues to migrate inland. In southern Namibia, Corbett (1989) based on present-day coastline morphology as well computer modelling, argues that marine transgressions may help to initiate aeolian transport corridor generations. In his model, in a case of marine transgression, the coastal high-energy area shifts across areas which were formerly influenced by the low to intermediate energy wind regime. Coastal dunes developed under the influence of this regime are then modified by the new higher-energy conditions, and a series of new dunes develop. If there is a significant amount of sand available, than an aeolian transport corridor may develop (Corbett, 1989). In the Sixteen Mile Beach complex coast-parallel dunes, the volume and migration rate are apparently too great to allow vegetation to permanently stabilise these active dunefields in the dune plume. The well developed active dune plume is restricted to the southern end of Sixteen Mile Beach, because the wind diverts a supply of finer, faster-migrating sand from the beach to the dune plume.

4.6.3 COAST-PARALLEL DUNES

Several authors have suggested that either a rise or fall in sea-level may impact the initiation or changes of coastal dunes (e.g., Bird, 1993; Hesp, 2002; Pye and Bowman, 1984; Thom, 1984; Thom et al., 1992). The position of the sea-level has a fundamental impact on the coastal dunes. The possible impacts on coastal dunes are briefly summarised here:

1- In the case of a sea-level fall, the beach width increases at a rate depending on the beach slope and the amount of sea-level fall. Once the sea-level has fallen to a lower level, new incipient dunes develop and eventually became established and vegetated (Saunders and Davidson-Arnott, 1990). The old dunes left behind become stabilised and with time calcrete develops (Rust, 1990). In the situation where sand is delivered from the new formed beach at a rate higher than vegetation growth can accommodate, it may result in dune instability and the sediment may bypass the original dune (Saunders and Davidson-Arnott, 1990; Hesp, 2002).

2- In the case of a sea-level rise, the beach width decreases depending on the amount of sea-level rise. In this scenario, either erosion takes place and the dunes gradually retreat landwards (e.g., Ritchie and Penland, 1990; Saunders and Davidson-Arnott, 1990; Psuty, 1992) or there is an increase in sand supply to the beach allowing the beach/aeolian system to maintain its integrity and dynamic interaction, thereby sweeping the entire coastal dunes landwards.

Regional wind velocities also play a very important role in dune evolution. In fact, reduced wind regimes in the case of a sea-level fall (scenario 1) due to highly irregular topography of the exposed continental shelf, may not be strong enough to impact dune movement. For these reasons, Pye (1984) proposed that pre-Holocene dune units in Cape Bedford-Cape Flattery area (northeastern Australia) are associated with earlier inter-glacial or inter-stadial high sea level. A model for a separate sediment budget for the foredunes and the beach has been developed by Psuty (1992). He argues that the optimum conditions for dune development occur when the beach budget is negative (erosion) and therefore there is a continuous opportunity for the sediment to be transferred from the beach to the foredune (Psuty, 1992). However, if the negative budget of the beach continues to grow, the foredunes may undergo morphological modifications through a sequence of attenuation stages that will lead to loss of a coherence. Despite many studies of coastal environmental changes and sediment interaction with sea-level changes, the topic of how sea level change impacts coastal dunes is still controversial and open to further research (Hesp, 2002).

In the Sixteen Mile Beach complex, the coastal dunes represent a sand wedge that was initiated 6 kyr ago, based on radiocarbon ages of oysters from Langebaan Lagoon (Compton, 2001) and estuarine fossils from Knysna (Marker and Miller, 1993) and Keurbooms (Reddering, 1988) on the south coast. During this maximum Holocene transgression, dunes up to 15 m high migrated over the Late Pleistocene dune cordon at the north end of Sixteen Mile Beach reaching Langebaan Lagoon at Kraalbaai (Figs. 4.2 and 4.8), where cemented aeolianites have bulk radiocarbon ages of 10 ka and U-series ages of 5 ka (Roberts and Berger, 1997) and an infrared stimulated luminescence (IRSL) age of 5 ka (N. Conard, unpublished report SANParks, 2000). The aeolianite sample of this study (Fig. 4.8, E-F transect) has yielded a bulk radiocarbon age of 11.9 ka, whereas the bulk radiocarbon age of the sample collected adjacent to the aeolianite has a bulk radiocarbon age of 18.6 ka. The aeolianite is well consolidated and orange-yellow in colour and the age is consistent with the radiocarbon age of other aeolianites collected in the Langebaan Lagoon area (Roberts and Berger, 1997).

Radiocarbon dating was performed on large shell fragments and on bulk calcareous sand from coast-parallel dunes at the northern end of Sixteen Mile Beach. *Donax serra* shells recovered from landward troughs are interpreted as dating the time of accumulation of gull-dropped shells onto an erosional, wind-deflated foredune face. The paucity of *D. serra* shell from middens on the west coast indicates that humans did not collect them for food, but rather used an occasional *D. serra* as a scraping tool (Robertshaw, 1978; Parkington, 1981). Therefore, *D. serra* shell ages are interpreted to date their accumulation on the deflated face of landward-migrating foredunes reworked during marine transgressions. Shell layers that develop on deflated foredune faces during sea-level highstands are preserved and are highly diluted by accumulating dune sand. As a new foredune builds, the abandoned secondary coast-parallel dune and associated blowout structures are stabilised by sandveld vegetation and develop an increasingly organic-rich, bioturbated and calcite-poor soil. The stabilised, landward coast-parallel dune is preserved as long as it escapes erosion by subsequent sea-level highstands or destabilisation by fire or drought. The radiocarbon dates from *D. serra* shells from relict blowouts are, therefore, interpreted to indicate Holocene highstands. The amplitude of sea-level fluctuations is difficult to estimate, but highstands may be suggested at around 6.2-5.9, 4.5 and 2.4 ka (Fig. 4.8). A +3 m Holocene highstand is indicated on the west and south coasts at around 6.3 ka. A sea-level rise during the final stage of the postglacial marine transgression has been described in the inner margin of Holocene coastal plains in Australia and New Zealand (Shepherd and Eliot, 1995). Indication of highstands at 4.5 and 2.4 ka is equivocal (Compton, 2001). At present there is no published evidence for a sea-level rise at 4.5 and 2.4 ka in southern Africa. *D. serra* shells, dated at 2.4 ka from immediately landward of the leeward edge of the northern active foredune, that has midden shells between 1.6 and 0.5 ka (Fig. 4.8), suggest that a significant drop in sea-level and progradation of the foredune seaward of its current position occurred between 2.4 and 1.6 ka. Sediment recovered from Langebaan Lagoon (Compton, 2001), Verlorenvlei (Baxter, 1997), and organic peat from the south coast (Deevey et al., 1959; Martin, 1968) indicate that sea level was approximately 1 m lower from 2.5 to 1.5 ka. The lowstand from 2.4 and 1.5 ka corresponds to the calibrated ages of megamiddens along the west coast (Buchanan, 1988; Jerardino and Yates, 1997) and supports the argument that shellfish (but not *D. serra*) were more easily exploited and made up a greater proportion of the diet of coastal inhabitants during this period of lowered sea level (Sealy and van der Merwe, 1988). The association of exhumed midden shells, dated at 1.6 to 0.5 ka, and modern *D. serra* shells indicates a rise in sea level and reworking of the foredune landward since 0.5 ka. A rise in sea level of approximately 1 m since 0.7 ka is indicated by the salt marsh sediments recovered from Langebaan Lagoon (Compton, 2001). The rise in sea level since 0.7 ka has reactivated coastal dunes and sent a recent pulse of sand inland which appears to have migrated over 500 m landward to its present position since 0.5 ka.

Donax serra shells found in vegetated, landward dune troughs probably indicate a relict wind-deflated foredune face, whereas *C. meridionalis* shells can be gull-dropped or manuported. Formation of an extensive shell-rich layer enhances preservation of *D. serra*, but the low density of shells in the landward troughs compared to the active deflated face of the foredune suggests that shells are later mixed and fragmented by mole-rat bioturbation. Pitted and etched surfaces indicate partial dissolution of the shells by organic-rich, acidic soil waters. *Patella* shells from dunes are interpreted to be manuported, because limpets live in intertidal rocky shores, are common in coastal shell middens and are not dropped by gulls. Radiocarbon ages of *Patella* shells provide a minimum age of the dune surface when humans occupied it. *Patella* shells are most abundant on the surfaces of deflated parabolic hollows of the active foredune located within 1 km south of their rocky shore habitat at the northern end of Sixteen Mile Beach. Scattering of originally stacked firestones and midden shells resulted from deflation of the dune surface by 2 to 8 m based on the height of parabolic dune ridges and terminal walls that surround deflation hollows. Whole and fragmented *Patella* shells are common, but not abundant, in relict parabolic hollows of landward vegetated dunes, where *Patella* shells are found associated with *D. serra*, as well as with variable amounts of *C. meridionalis* and, in places, the dune snail *T. globulus*. The association of *D. serra* with *Patella* spp. indicates that these were coastal middens as opposed to more landward middens, such as those found on the border of Langebaan Lagoon, where *Patella* spp. or *C. meridionalis* are abundant, but *D. serra* and *T. globulus* are rare (Robertshaw, 1978; Smith et al., 1991). Although not found associated with firestones, *Patella* shells from relict blowouts are interpreted to be bioturbated middens, rather than beach deposits, because of the absence of other intertidal rocky shore shells or pebbles. Limpets collected from the intertidal zone of rocky shorelines were carried to firestone sites that were probably leeward of the foredune for protection from the wind and for a source of firewood from more vegetated, landward dunes. Firesites may become buried by landward-advancing foredunes and eventually exhumed onto the foredune face if the foredune continues to migrate inland. Older, exhumed midden shells accumulate together with younger, gull-dropped *D. serra* and *C. meridionalis* shells to form a deflation lag deposit on the face of the landward migrating foredune. For example, the 6.0 ka *Patella* shells recovered from the relict blowout 2 km landward of Black Rock and at 3 m above sea level are 1.5 ky older than the 4.5 ka *D. serra* shells from the same sample (profile C-D; Fig. 4.8). The difference in age of 1.5 ky falls within the range in age of shell middens on the modern foredune of 1.6 to 0.5 ka.

In addition to large manuported and gull dropped shells, the bulk carbonate of dune sand was radiocarbon dated. The northern part of the Sixteen Mile Beach complex is composed of active and vegetated coast-parallel dunes. The active foredune is currently migrating upward and landward as beach and dune sand is blown up the windward face, across the crest and down the lee slope. Carbonate sand from pioneer dunes has an age of 20.6 ka in the southern part of Sixteen Mile Beach, 1.9 ky older than adjacent carbonate beach sand which has an age of 18.7 ka. In the northern part of Sixteen Mile Beach the carbonate fraction of the pioneer dune (11.8 ka) is 0.9 ky older than the adjacent beach sand (10.9 ka) with younger, coarse sand concentrated in the beach sand (Fig. 4.2). In the case of the northern part of Sixteen Mile Beach, the age difference of 900 yrs probably mostly reflects a change in grain size. This is supported by the comparable amount of coloured and clear shell fragments (60 wt% in the beach sand and pioneer dune sand at Tsaarbank, Table 6). In the southern part of Sixteen Mile Beach, the larger age difference of 1,900 yrs appears to have resulted from reworking of older carbonate as the coloured and clear grains are surprisingly less in the pioneer dune than they are in the beach sand (Table 6).

Along Sixteen Mile Beach between Black Rock and Tsaarbank, the calcium carbonate weight percent rapidly increases with a notable increase in sand coarse-size carbonate than in the samples collected between Gabbro Point and Black Rock (Fig. 4.5), resulting in a younger age for the sample collected at Tsaarbank. Correcting for the younger coarse carbonate component, the age of the predominantly medium sand of the sample collected at Tsaarbank is 11.8 ka which is consistent with the value of 11.8 ka obtained from a sample collected on the wind deflated surface on the pioneer dune (Fig. 4.8). An age of the active foredune of 2.1 to 2.3 ka is suggested by the age difference between the pioneer dune at 11.8 ka and the active foredune carbonate sand that ranges in age from 13.9-14.1 ka. An age of 2.1 to 2.3 ka for the active foredune is consistent with the 2.4 ka age of *D. serra* shell recovered from the trough immediately landward of the active foredune.

Stable secondary dunes have bulk radiocarbon ages of 13.4 to 18.9 ka (Table 1). If the reference age for the northern part of Sixteen Mile Beach is

11.8 ka, the difference between the secondary dunes and the beach sand ranges from 1.6 to 7.1 ka (Fig. 4.8). The large range in ages for the stable coast-parallel dunes was not expected, because the bulk of these dunes formed during the mid-Holocene highstand between 7 and 5 ka (Fig. 4.16). Ages of vegetated coast-parallel dunes younger than 5 ka do not reflect the time of deposition, but have been altered either by soil processes or by reworking that occurred with sea-level fluctuations of the order of ±1 m since 5.2 ka (Fig. 4.16). Vegetation, in particular, is believed to have played an important role in the alteration of ages of the coast-parallel dunes. Soil processes such as fungus re-growing and different moisture in the soil may have recrystallised the carbonate fraction resulting in an apparently younger carbonate age for three samples collected in the stable vegetated coast-parallel dunes (dated 13.4 ka, 15.7 ka and 16.7 ka; transect E-F; Fig. 4.8). The first sample on the western side of the transect in the stable vegetated coast-parallel dunes is dated at 13.4 ka; an age similar to the active foredune (13.9 ka). The sample collected in the stable vegetated coast-parallel dunes has probably a younger age due to soil processes that have recrystallised the carbonate. The second sample collected on the western side of the E-F transect (Fig. 4.8) has a bulk radiocarbon age of 15.7 ka and possibly has been recrystallised. The fifth sample collected in the western side of the E-F transect (Fig. 4.8) dated 16.7 ka has a high content of coloured and translucent grains. In this sample, mixing with younger carbonate from *D. serra* shells, has probably occurred. For all the other samples of the E-F transect, the radiocarbon ages obtained by differences with the reference value of 11.8 ka ranges from 5.2 ka to 7.1 ka. All these ages postdate the mid-Holocene highstand of 2 or 3 m (Fig. 4.16).

In contrast to the active dune plume, in which the use of radiocarbon analyses have proved successful, it is not advisable to use bulk radiocarbon dating for interpretation of the time of deposition of in the stable, vegetated coast-parallel dunes. Vegetation in particular is suspected to be related to recrystallisation that results in a younger age for the sample. Luminescence dating of quartz allows dating the last-exposure to sun light before deposition and may help to elucidate, in a more conclusive way, the evolution of the stable coast-parallel dunes in the northern part of the Sixteen Mile Beach complex.

4.7 HUMAN UTILISATION OF THE COAST

The age of *Patella* shells from relict parabolic blowouts of the landward coastal dunes indicates human utilisation of the area by 6.2 ka, significantly earlier than surrounding archaeological sites on the peninsula that date from 1.6 to 0.5 ka (Table 1) (Robertshaw, 1978; Smith et al., 1991). Human occupation at 6.2 ka also falls within the gap in the age of archaeological material noted regionally along the west coast and documented at the Elands Bay and Tortoise Cave sites to the north at Verlorenvlei (Fig. 4.1) from 8.6 to 4.9 ka (Parkington, pers. com., 1998; Jerardino, 1995). However, recently dated material from Steenbokfontein Cave, located 1.5 km from the coast and 20 km north of the Elands Bay Cave, indicates human occupation at 6.9 and 5.3 ka (Jerardino and Yates, 1996). Sea-level only rose to present-day levels by around 7.5 ka and coastal archaeological sites older than 7.5 ka would now be submerged. One possible explanation for why there are few archaeological sites that yield radiocarbon ages between 7.5 and 4.9 ka is a low coastal population density suggested by the fact that only 3 of 49 dated skeletons from coastal areas of the western Cape are older than 5 ka and include a 6.4 ka skeleton from Yzerfontein (Sealy and van der Merwe, 1988). Poor preservation from bioturbation and weathering, as well as burial of coastal sites by landward-migrating dunes would also contribute to the paucity of archaeological material older than 5 ka.

Archaeological sites on the western edge of the lagoon and on the granite headland at the northern end of the peninsula date from 1.5 to 0.5 ka and are contemporary with firestone sites located on the foredune from 1.6 to 0.5 ka (Fig. 4.2). Coastal firestone sites were advantageous in their proximity to marine resources, but their small size compared to inland sites suggests that they were used for shorter periods. Firestones were probably collected, along with shellfish, from rocky intertidal shores, and wood would have been available from vegetated dunes landward of the foredune. The low-density scrub of present-day vegetated dunes suggests that scrub wood would have been used to heat the firestones on which the shellfish were cooked. Larger and more diverse middens, located several kilometres to the east and northeast of the coastal sites (Fig. 4.2), are farther from predominantly rocky shore resources, but were probably more hospitable than the dunes, being protected from the wind, closer to fresh water and also closer to resources of the protected waters of the Langebaan Lagoon (Robertshaw, 1978; Smith et al., 1991). The absence of oysters and clams from inland middens suggests that these shellfish were too inaccessible for humans to collect (Robertshaw, 1978). In addition, significant fossil oyster beds are all older than archaeological sites located on the lagoon margin (Flemming, 1977; Compton, 2001). The young age of 1.2 ka for *Patella* shells collected from older, 6 ka landward dunes may represent shells dropped in transit along the most direct pathway between the exposed rocky shore at Kreeftebaai and the principal midden site at Stofbergsfontein, where the base of a 0.5 m thick shell midden has a date of 1.5 ka. Intertidal rocky marine resources were utilised at least as far south as Schrywershoek, 8 km southeast of Kreeftebaai (Fig. 4.2).

The abundance of *Patella* shells recovered from the coast-parallel dunes immediately landward of the active foredune, suggests that a rocky coastline extended as far south as Black Rock at 6 ka. Progradation of the coastal parallel dunes seaward since 4.5 ka and particularly since 2.4 ka would have covered rocky exposures near Black Rock and restricted rocky shoreline marine resources to the Kreeftebaai area. Why are these earlier coastal middens at 6 ka not associated with significant midden accumulations on the lagoon margin? Perhaps earlier sites were destroyed by cliff erosion or were buried by landward-migrating dunes. Another possibility is that these coastal areas were only sparsely or briefly occupied from 6.2 to 1.6 ka and became more permanently or regularly settled by a larger number of individuals with the establishment of pastoralism in the western Cape by around 1.5 ka (Sealy and Yates, 1994). Charcoal and blackened roots on some of the exposed lateral ridges of parabolic dunes suggest that fire was important in destabilising the foredunes. Along with fire, increased grazing pressure from domesticated herds since 1.5 ka may have decreased dune stability.

4.8 SUMMARY AND CONCLUSIONS

Much of the development of the southern African coastline can be related to changes in sea level and its effect on the coastal sediment budget (Tinley, 1985). This chapter provides several results that allow for some speculation on understanding the development of the beach/aeolian system in the Sixteen Mile Beach complex. In this section, firstly a summary of the most important information collected from the Sixteen Mile Beach complex is presented and secondly, provides some conclusions for specific topics studied in relation to the morphology, age and grain size distribution inside the complex itself.

4.8.1 SUMMARY

The Sixteen Mile Beach complex is comprised of a beach, coast-parallel dunes and a dune plume of vegetated and non-vegetated dunes (Fig. 4.2). Sixteen Mile Beach is a 26 km long beach composed of quartz and shell fragments (Fig. 4.5). Grain-size analysis of bulk sand shows a northward coarsening from fine to medium sand (Fig. 4.6). In the southern part of the beach, the wave energy of the predominant S-SW swell is largely absorbed by Dassen Island (Fig. 4.1) and the fine sand fraction is deposited on the low-energy, wave refracted beach. Subsequently, strong summer winds move the sand inland to form the Yzerfontein-Geelbek dune plume. The mean radiocarbon age of Sixteen Mile Beach is 14.1 ka (Table 1), similar to the age of 14 ka for the fine beach sand that is the source of the Alexandria dunefield in the Eastern Cape (Illenberger and Verhagen, 1990). Radiocarbon ages of bulk carbonate shell samples collected along Sixteen Mile Beach young in the direction of longshore transport. The fine sand of the southern part has a mean age of 18.4 ka, whereas the medium sand of the northern part has an age of 10.9 ka. In order to correct these ages for the amount of reworked, non radioactive carbonate grains, the percentage of coloured and translucent grains was determined. The mean age of the fresh carbonate fraction is 7.3 ka, both in the northern and southern part of the beach. This result allows some speculation on how shell break down, and suggests that the break down of shells proceeds by the production of fine sand sized material.

The Yzerfontein-Geelbek dune plume extends 24 km inland and consists of vegetated parabolic ridges and active barchanoid dunefields. The active plume is form of fine sand sized quartz and shell fragments. The calcium carbonate wt% decreases inland (Fig. 4.10). Grain size analyses of the bulk dune samples show that these dunes are composed of a very well sorted fine sand with a modal size of 180 µm. Radiocarbon ages of the bulk carbonate fraction of sand samples have shown that the active plume is 4.5 ka old. Different rates of sand movement along the active plume are indicated by radiocarbon results (Fig. 4.15). Change in climate, particularly rainfall, will have an impact on vegetation and on the stability of dunes.

Coast-parallel dunes are composed of fine to medium sand sized quartz and shell fragments (Fig. 4.9). Grain size analysis of the bulk sand shows a fining down-wind sequence (Fig. 4.9). Coast-parallel dunes are Holocene in age (Table 1). The age of the active foredunes are a reflection of the grain size and of the colour of the grains. In the southern part, the active foredunes have accumulated very fine sand while in the northern part of the complex, where very fine sand is not available, the apparent age of the foredune is younger. Variation in grain size, organic content and reworking of older dunes causes complexities in the understanding of the ages of these dunes. However, most of the coast-parallel dunes formed during the mid-Holocene highstand (Fig. 4.16).

Middens were identified on the deflated foredune faces by the presence of limpet shells (*Patella* spp.) with also minor amounts of ostrich egg shell fragments, black mussel and fire stones. Midden shell ages range from 0.5 to 6 ka. Sea-level rose to present-day levels by around 7.5 ka and coastal archaeological sites older than 7.5 ka are now submerged.

4.8.2 CONCLUSIONS

This study has indicated that the southern part of the West Coast of southern Africa has recorded a long and complex history of beach and dune evolution. Considering that few studies focusing on dune building and beach morphological changes have been undertaken in southern Africa (e.g., Tinley, 1985; Corbett, 1989; Illenberger, 1988; Illenberger and Verhagen, 1990), there is still some uncertainty surrounding the ages of the dunes and the beach forming the Sixteen Mile Beach complex. However, the extensive use of radiocarbon dating in conjunction with grain analyses of the sand may be used to speculate on the Holocene evolution of the cosatal area of the Sixteen Mile Beach complex.

The following conclusions are suggested:

Dynamic of the beach system

The northward coarsening from fine to medium sand along Sixteen Mile Beach is related to coastal morphology. The sand that is transported to the north by longshore drift is not deposited uniformly and the beach system consists of two distinct units in the south and north of Sixteen Mile Beach. Waves generated in the Southern Ocean, and local wind-generated surface waves, approach the Atlantic coastline obliquely, approximately from the south-west (Swart, 1993; Swart and Flemming, 1980). The rocky headland and the presence of Dassen Island (Fig. 4.2) in the south creates a shadow zone and protects the coast from direct wave approach. This low-energy enviroment results in the reduction of the beach slope and the average grain size of beach sediment. Small pioneer dunes develop in the backshore area of the southern part of Sixteen Mile Beach where high-energy winds from the S-SW deflate the beach. From the southern part of Sixteen Mile Beach, the fine sand is rapidly introduced to the Yzerfontein-Geelbek dune plume. In the northern part of the beach, the high-energy breakers maintain a steep beach profile along the exposed coastline and the beach sand is almost entirely composed of medium to coarse material. The northward coarsening of the beach sediment reduces the amount of material available for beach deflation, and the sandflow off the beach declines preventing the formation of dune plumes in the north. In the northern part of Sixteen Mile Beach, pioneer dunes (up to 3 m in height) run parallel to the coast and the leeward faces of the main foredunes rise steeply becoming increasingly irregular to the north (Fig. 4.2). Landward of the active foredune, stable dunes with coast-parallel troughs and ridges are present and are often cut by parabolic blowout features (Figs. 4.2 and 4.8).

Response of the Sixteen Mile Beach complex to sea-level changes

The coastal morphology as discussed above, governs the distribution of sand along Sixteen Mile Beach and therefore the location of dunefields and coast-parallel dunes. Consequently changes in the position of the coastline as a result of fluctuating sea-level will directly influence dune formation and evolution. Evidence presented in this chapter indicates that the development of the large aeolian sand bodies in the northern part of Sixteen Mile Beach complex probably occurred during marine transgressions. Compton (2002) recorded a 125 m lowstand offshore the Orange River mouth during the Last Glacial Maximum. During the rapid sea-level rise that occurred from 19 to 7 ka, the beach and the dune sand formed during the lowstand probably migrated landward. In addition to this additional volume of sand, the edge of pre-existing Pleistocene dunes were cut by marine erosion. In the northern part of the Sixteen Mile Beach complex, there is radiocarbon evidence that new dunes were initiated along, or very close to, eroding shorelines. These dunes are mostly mid-Holocene in age in accord with mid-Holocene dunes dated elsewhere (in Australia (Pye, 1993), Mexico (Murillo De Nava et al., 1999) and Argentina (Isla et al., 1996). The northern Sixteen Mile Beach mid-Holocene dunes migrated landwards climbing over older, non-carbonate stabilised dunes. During this process the underlying sediment was partially reworked and mixed, making it difficult to interpret conventional radiocarbon ages of dune sand.

However, radiocarbon analyses of *Donax serra* shells can distinguish between reworked old material and episodes of dune formation. The sea-level reached its present-day position by 7.5 ka (Fig. 4.16) and minor oscillations occurred since 5 ka. This relatively stable sea-level allowed the Yzerfontein-Geelbek dune plume in the southern part of the Sixteen Mile Beach complex to form.

Aeolian sediment dispersal and offshore sediment-starved environments

As Yzerfontein is located at about 100 km from major perennial sources of river sand, the sediment supply to the present beach/aeolian system is principally derived from the south with a longshore drift velocity of about 100 m/y (Swart and Flemming, 1980). The sand entering the log-spiral beaches or south-facing bays (e.g., False Bay, Fig. 4.2) located along the southern part of the Western Cape is deflated from the beach to form coast-parallel dunes as well as dune plumes. Once the sand has been depleted from the beach and transported inland to form coastal dune systems it appears remarkably resistant to destruction by erosion, especially after the dunes have made the transition from active dunefields to vegetated-stable dunes and after the unconsolidated dune sand has been transformed into aeolianites (discussed in Chapter 5). This implies that the river sand which passes through the beach system remains trapped inland creating offshore sediment-starved environments. This may well be one of the reasons of the thin Cainozoic sediment cover in Saldanha Bay (de la Cruz and Du Plessis, 1981).

Sand source

River sand transported along the coastline by longshore drift is the single most important source of sand which is delivered to the coastal dunes. In addition to this quartzose sand, sand grains are also derived from primary biogenic sources consisting of broken carbonate shells, invertebrate skeletal and fragments of other carbonate material. This part of sand population represents a renewable source of sand that is constantly added into the Sixteen Mile Beach dune system via the beach. The northward increase of calcium carbonate weight percent along Sixteen Mile Beach is related to the coastal morphology, with the northern part having a more aggressive wave and surf action on the highly shell-populated rocky headlands. The Holocene dunes are lighter in colour with 10 to 50 wt% of carbonate, while the surface of Pleistocene dunes are yellow-brown and primarily composed of quartz sand and organic matter with carbonate content < 1 wt%, except for some occasional surface float of calcrete. Two important facts of bioclastic fragmentation and erosion were also recorded. The first, concerns the breaking down of modern shell that results in a continual production of the fine fraction. The second, was that foraminiferal tests are transported along the active duneplume but become increasingly more abraded and no foraminiferal tests were found at a distance of 18 km inland onland.

Wind and palaeowind direction

Given a constant sand supply it is the strength of the wind more than any other external driving force which determines how coastal dunes will form and respond at any given location (Rust, 1990). Field evidence and dune morphology demonstrate that all the coastal dune systems were governed by a southerly-southwesterly quadrant wind regime. At present there is no evidence to support the suggestion that stronger winds were responsible for the building of older coarser coast-parallel dunes in the northern part of the complex. In agreement with Corbett (1989), the direction of the winds along the west coast since the Quaternary appear to have remained stable. At present it is uncertain what effect sea-level changes might have had on the wind velocity along the south west coast during the Pleistocene. However, since 5 ka the relatively stable sea-level would have allowed the Yzerfontein-Geelbek active plume to develop uninterruptedly with a mean velocity of the dune plume of 5.3 m/y, similar to the present-day yearly migration rate of 5 m/y. A factor that may have contributed to stabilisation of active dunes was an increase in vegetation mainly due to an increase of rainfall. Historically farming in the area has always been limited due to aridity and inaccessibility of water supply in the area.

Use of the radiocarbon dating inside the Sixteen Mile Beach complex

The use of radiocarbon dating of carbonate grains in order to understand the evolution of the Sixteen Mile Beach complex is complicated by several factors such as recrystallisation as well as grain size and grain characteristics. The use of radiocarbon dating on the beach sand material has proven to be successful if used in conjunction with grain size analyses and corrected for the presence of old reworked carbonate grains. This correction is determined by the percent of freshly coloured carbonate grains compared to the older translucent and white-opaque carbonate grains that no longer contain any ^{14}C. The correction factor is obtained by distinguishing fresh pink, purple and orange grains that originate from the break down of modern shells. Once the percent of fresh carbonate is established then the corrected age for the carbonate sand is calculated for the percent of modern ^{14}C in a dated carbonate sand. Along Sixteen Mile Beach the calculated corrected ages of the beach sand is 7.3 ka both in the southern and northern part. This is independent of the grain size (fine sand in the south and medium to coarse sand in the north). This, in effect, implies that some of the fine sand has the same age as the medium to coarse sand and are not older as previously indicated by Illenberger and Verhagen (1990). However, when a shell breaks down some of the fragments are small enough to immediately be contributed to the fine sand fraction.

The conventional mean average radiocarbon age for the beach sand along Sixteen Mile Beach is 14.1 ka, similar to the age of 14 ka recorded in the Eastern Cape (Illenberger and Verhagen, 1990). Both the corrected and conventional mean average radiocarbon ages of beach sand indicate the potential use of the above method when AMS is not available or either the two techniques may be used together. The use of radiocarbon dating may also be considered successful in attempting to date active dunefields that are difficult to date otherwise because the rapid turnover of the sand makes this material not suitable for thermoluminescence techniques. A correction factor must be applied to understand the age of the dunefield. This correction factor is the radiocarbon age of the beach sand that is subtracted from the age of the dated dune sand material. The age obtained in this way for the sample furthest from the coast in the Geelbek-Yzerfontein active dunefield is 4.5 ka, which is in agreement with the age of dunefields located in the Eastern Cape (Illenberger, 1988). Less encouraging results for the use of radiocarbon dating on bulk sand samples was obtained on the coast-parallel dunes and the vegetated dunes in proximity of the active dunefield. Recrystallisation, as well as windblown fine sand material from the beach that is subsequently fixed by vegetation, alters the ages of these dune sands. However, in the case of the coast-parallel dunes, their age of formation may be unravelled by the use of radiocarbon on *Donax serra* and limpet shells. This is possible because *D. serra* were not exploited for food by early human habitants (Sealy and van der Merwe, 1988) and therefore are interpreted as being deposited during Holocene highstands on the wind delated foredunes. Limpets were used as a food source and the age of the limpets therefore indicate periods of sub aerial exposure and humans exploitation.

The geomorphology, grain size analysis and radiocarbon dating of the Sixteen Mile Beach complex have proved that this area is an active transition zone for sand which is sensitive to changes in the environment. The understanding and recording of the processes involved in modern beach/dune environments provides the framework for Chapters 5 and 6 in which older dunes and paleogeography of selected areas along the Western Cape coast are addressed.

SIXTEEN MILE BEACH

x700 x1150 x7200

Unabraded *Elphidium* sp. collected in a rocky pool at Gabbro Point.

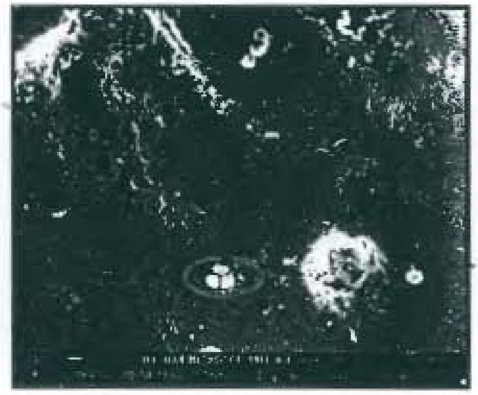
x750 x1150 x9250

Abraded *Elphidium* sp. collected along Sixteen Mile Beach.

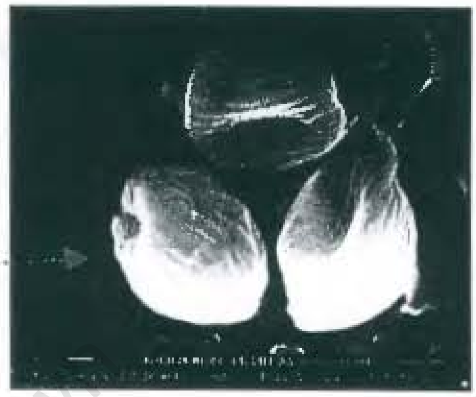
PLATE I

6 KM

Ammonia sp.



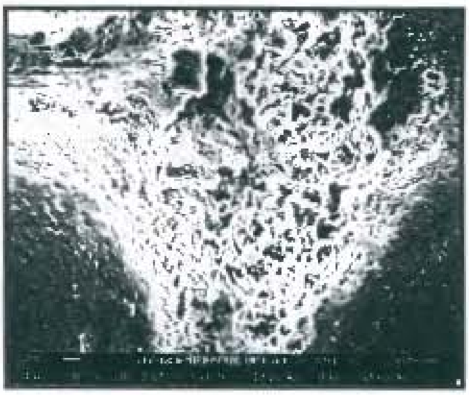
detail of fungus spores on the test



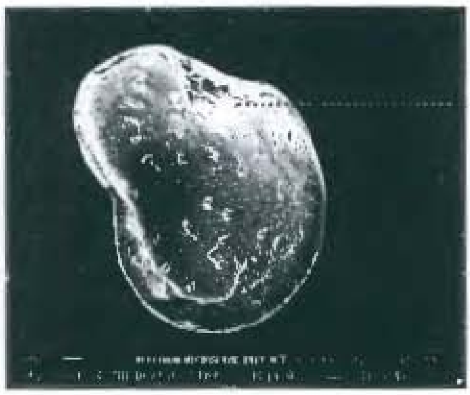
fungus spores

Ephidium sp.

enlargement of the edge of the text



enlargement of a chamber



Elphidium ?cf articulatum

enlargement of the edge of the test

enlargement of the test surface

PLATE II

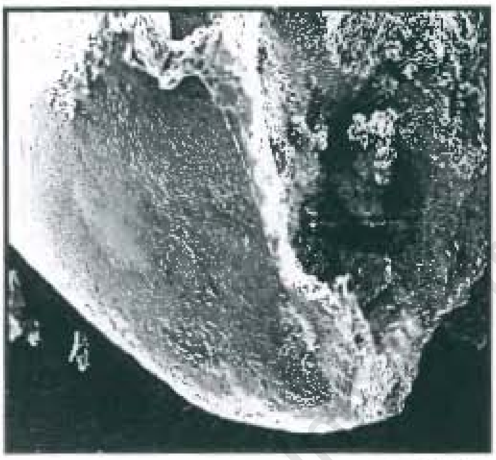
12 KM


x 3000

enlargment of a chamber


x6000

particular of the test surface
showing recrystallisation


x 3000

enlargment of the test surface


x6000

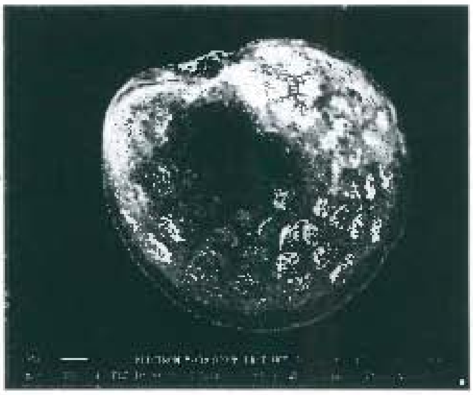
striations of the test


?*Ammonia* sp.

PLATE III

18 KM

?*Ammonia* sp.



?*Elphidium crispum*

?*Ammonia* sp.

enlargement of a detail of the test surface

PLATE IV

Chapter 5 -

Aeolian and marine deposits of the Tabakbaai Quarry area

5.1 INTRODUCTION AND AGE CONTROVERSY FOR THE DEPOSIT

Introduction

The evolution of Saldanha Bay area and of the southwestern African coastal plain is poorly understood. This is due to a number of factors including the lack of outcrops, paucity of fossil remains and mostly widespread reworking of older sand, which form an extensive blanket over most of the studied area. In Chapter 4, the Holocene evolution of the Sixteen Mile Beach complex has indicated that the coastal plain has undergone a complex geological evolution. The large coastal dune bodies that occur north of Saldanha (Fig. 5.1) provide an important window into the evolution of the area. These aeolianites are well exposed in the Tabakbaai Quarry, referred to in the literature also as Diazville Quarry or Prospect Hill Quarry. At the time of the writing on this work, much geological controversy is revolving around these aeolianites. In fact, the discovery of *Diamantornis wardii* eggshell fragments (Roberts, pers. comm., 2001) has led to a revision of the local stratigraphy. Previously all the aeolianites at Saldanha, were included in Quaternary undistinguished deposits (SACS, 1980). At the present it is not know if these aeolianites are Pleistocene, Pliocene or Middle Miocene in age. The main aim of this chapter is to describe the well-preserved coastal succession exposed in the Tabakbaai Quarry and to use detailed biostratigraphy and Sr isotope stratigraphy to assign an age to the deposit.

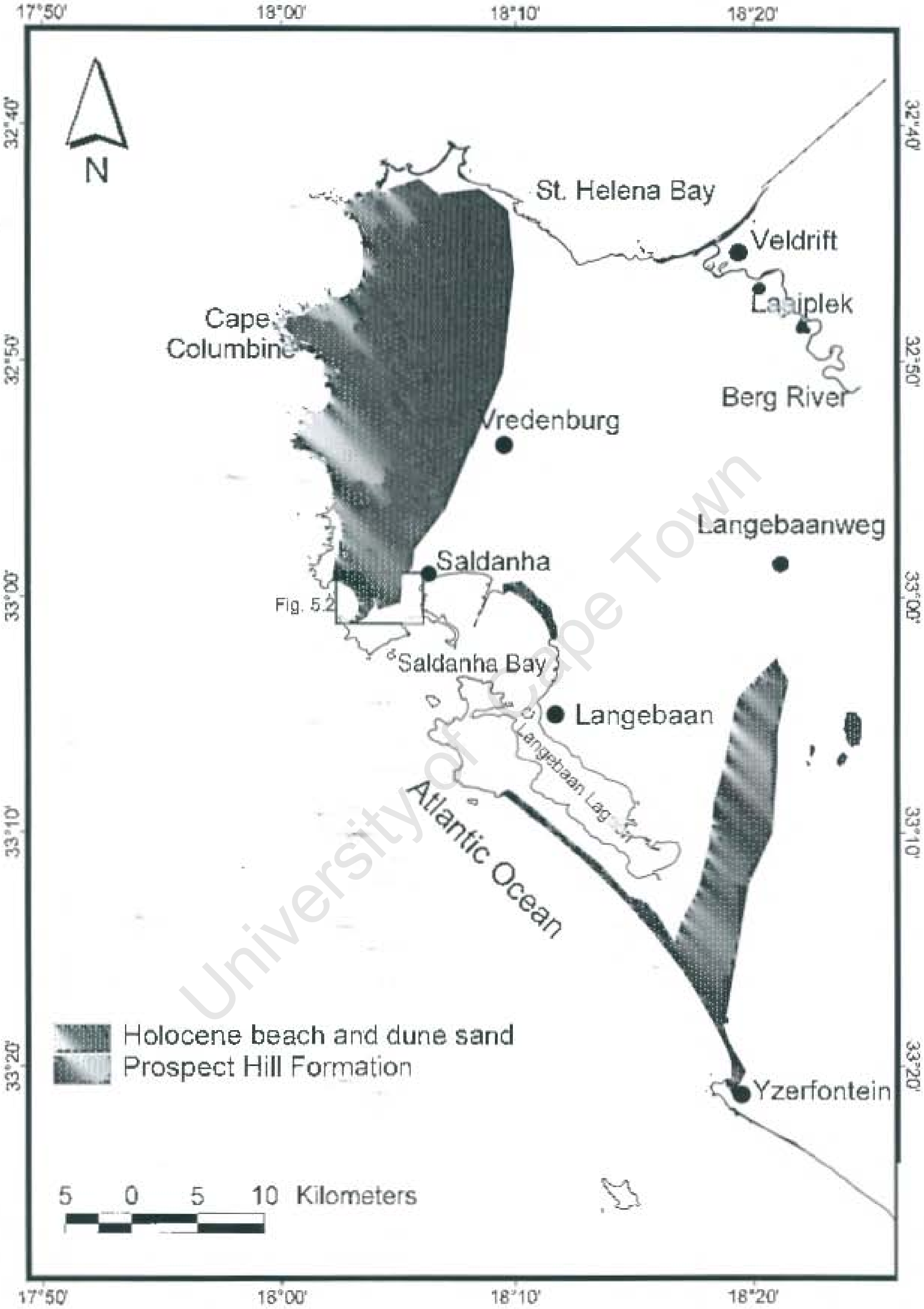


Fig. 5. 1. Location map of the Tabakbaal Quarry within the Cape Columbine area.

Although strontium dating has a wide range for Cainozoic deposits, it will be able to differentiate between Pliocene/Pleistocene and Miocene deposits. This Chapter provides information useful to the understanding of the long-term evolution of the Saldanha Bay region.

Age controversy around the Tabakbaai Quarry exposure

Dale and McMillan (1999) describe two marine packages of different ages and environments (refer to Chapter 2 and Fig. 2.2). In the lower quarry, (refer to Section A, Fig. 5.2) *Elphidium*, *Ammonia*, *Uvigerina* and *Pararotalia* are the dominant foraminiferal genera and indicate an Early Pleistocene age (Dale and McMillan, 1999) equivalent to the 30 m Package of Pether (1994). In the aeolianites of the upper quarry (refer to Section B, Fig. 5.2) the abundant presence of *Lobatula lobatula* and *Pararotalia nipponica* has led these authors to propose a Late Pliocene-Early Pleistocene age equivalent to the 50 m Package of Pether (1994). The work of Dale and McMillan (1999) has opened a scientific controversy on the age of Section B in the upper quarry. An eggshell of the giant struthious (ostrich-like) bird *Diamantornis wardii* found in the Section B, has led Roberts and Brink (2003) to propose that the aeolianites are 12-10 Ma based on the biostratigraphy of giant avians (Pickford and Senut, 1999; summarised in Table 1).

5.2 STUDY AREA AND METHODOLOGY

The Tabakbaai quarry is located 2 km west of Saldanha (Fig. 5.1). The present-day coastline of Tabakbaai west of the lower quarry (Section A) is 1 km

Million years	Species
0-2	*Struthio camelus*
2-5	*Struthio daberasensis*
5-8	*Struthio karingarabensis*
8-10	*Diamantornis laini*
10-12	*Diamantornis wardii*
12-14	*Diamantornis spaggiarii*
12-15	*Diamantornis corbetti*
12-16	*Namornis oshanai*
16-20	*Aepyornithoid*

Table 1. Biostratigraphy based on eggshells of ostriches in southern Namibia (after Pickford and Senut, 1999).

distant, and Tabakbaai beach is a sandy beach composed of 83 wt% calcium carbonate (R. Wigley, pers. comm., 2001). The coastline between Saldanha Bay and Cape Columbine (Fig. 5.1) is dominated by resistant headlands consisting of intrusive rocks belonging to the Late Precambrian to Cambrian Cape Granite Suite (Fig. 5.2). Holocene aeolian sand and sandy soils separate the quarry from the Atlantic Ocean to the west. The aeolianites cropping out in the quarry are the most exposed part of a 20 km long dune plume (Fig. 5.1).

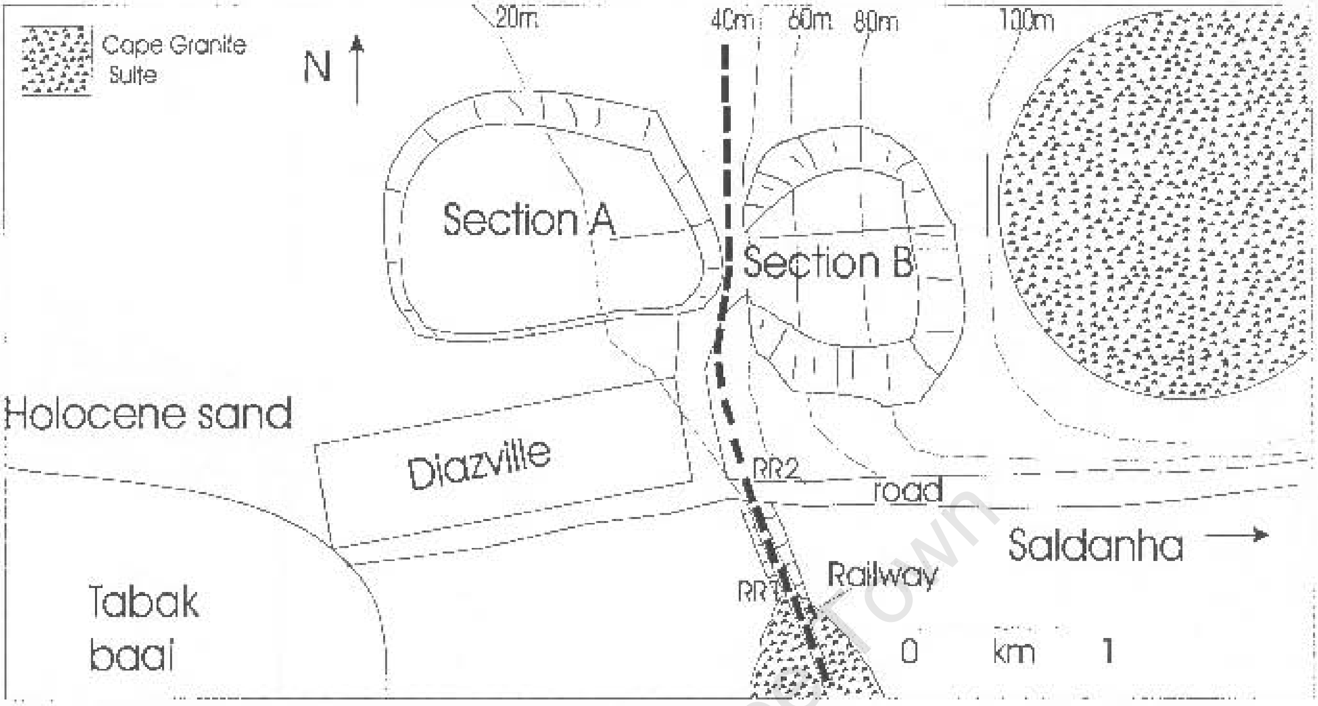


Fig. 5.2. Location of Section A and Section B of the Tabakbaai Quarry and of the railway cutting sections.

The elevation of the base of Section A is 25 metres, whereas the base of Section B is 45 metres above mean sea level – amsl (Fig. 5.2). Tabakbaai Quarry has been actively mined since 1982 for the production of agricultural and feed lime sands and the part of the studied stratigraphic section were recently opened (Van der Merwe, pers. comm., 2000).

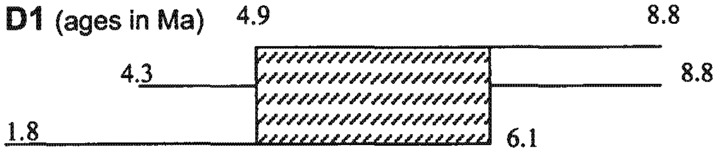
The contact between the underlying Cape Granite Suite and the section exposed at the Tabakbaai Quarry is not visible. This contact is exposed in a railway cutting 500 m to the south at 25 m amsl (sample RR1; Fig. 5.2). Another railway cutting at 45 m amsl exposes a section composed of fine sand with abundant terrestrial snails and a well developed calcrete (sample RR2, Fig. 5.2).

Fifteen samples for this study were taken from sections A and B of the Tabakbaai Quarry and from the railway cuttings south of the quarry. Calcium carbonate content was determined by HCl digestion. Foraminiferal assemblages were picked and illustrate using a scanning electron microscope at the University of Cape Town. Shell fragments, phosphorite grains, echinoderm spines and foraminifera were hand-picked for Sr analyses. Particular attention was paid to the hand-picked grains in term of recrystallisation. Sample preservation was evaluated from scanning electron microscopy studies and effects of diagenetic alteration were not observed. Biogenic grains did not appear recrystallised and so their Sr ratio is assumed to be unaltered and to represent the seawater in which they were living. Recrystallasation of the carbonatic material is expected to decrease the Sr content, but may not alter the $^{87}Sr/^{86}Sr$ ratio. In fact, the Sr isotopic composition of the precursor carbonate material contain much more Sr (1,000-10,000 ppm) than seawater (8 ppm) or ground water (0,2-50 ppm) (Bathurst, 1979). Sr isotope ratios were measured at University of Cape Town on a VG Instrument mass spectrometer with mass fractionation normalised to a ratio of 0.1194 and to a Standard Reference Material 987 ratio of 0.71022. Within-run precision on single measurements is $\pm 1\times10^{-5}$ (2σ error), whereas sample reproducibility is approximately $\pm 4.5\times10^{-5}$. The ages in Table 2 have been obtained by the use of the look-up table of Howarth and McArthur (1997). The age-range is based on the sample reproducibility of $\pm 4.5\times10^{-5}$.

Unit	Sample	Material	$^{87}Sr/^{86}Sr$	Age (Ma)[1]
0	D0	*Donax serra*	0.709125	0.5-2.2
1	D1f	*Lobatula lobatula*	0.708987	4.9-8.8
1	D1s	*Donax serra*	0.708945	4.3-8.8
1	D1e	echinoderm spines	0.708991	1.8-6.1
4	D9	echinoderm spines+forams	0.709074	1.2-5.6
10	D10	echinoderm spines+forams	0.708994	4.3-8.8
10	D10	*Diamantornis wardii*	0.709087	1.0-5.2

	RR1	phosphorite	0.709148	0-1.8
	RR1	echinoderm spines	0.709039	1.8-6.1
	RR2	phosphatic shell fragments	0.709033	2.2-6.3

[1] Ages from Howarth and McArthur (1997).



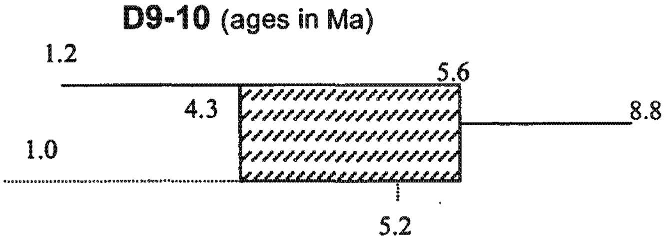


Table 2. Strontium isotope analyses with a schematic explanation of the overlapping ages (in Ma) for the Units 1, 9 and 10 (respectively samples D1 and D9-D10; dashed line for the *D. wardii* eggshell Sr-isotope result).

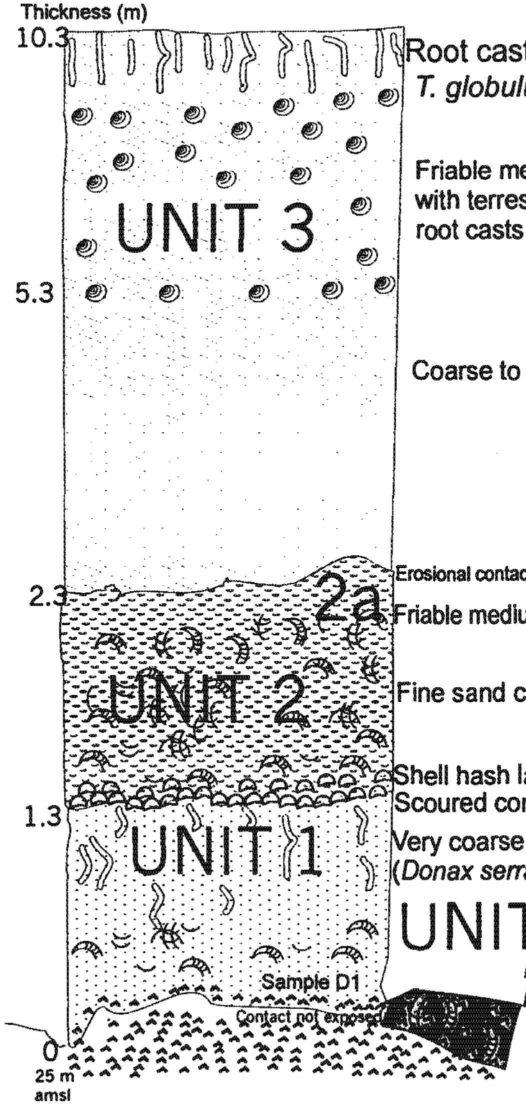
5.3 STRATIGRAPHY

The most complete vertical succession exposed in the lower Tabakbaai Quarry (Section A) contains four sedimentary units including a basal coquina bed (Fig. 5.3).

Unit 1 is a very coarse to coarse marine carbonate (85 wt % calcium carbonate) sand with iron oxidation and post-depositional root casts. The unit overlies the Cape Granite Suite, but the contact is not exposed. The unit has an average thickness of about 1.30 m. This unit contains shell fragments, echinoderm spines, barnacle plates, ostracods, foraminifera, quartz and granite pebbles. The foraminiferal assemblage (Appendix 3) includes *Ammonia* spp., *Elphidium* cf. *crispum*, *Elphidium* spp., *Glabratella 'australensis'*, *Lobatula lobatula*, *Pararotalia nipponica*, *Quinqueloculina* sp., *Uvigerina* sp., *Rosalina* sp. (Plate I). Strontium dating yielded ages ranging from 1.8 to 6.1 Ma for the echinoderm spines, from 4.9 to 8.8 Ma for the benthic foraminifera *Lobatula lobatula* and from 4.3 to 8.8 Ma for the white mussel *Donax serra* (Table 2). The contact between Unit 1 and Unit 2 has been directly observed and it consists of a coarse shelly layer mostly composed of *D. rogersi* (Pether, pers. comm., 2001).

Unit 2 is a medium to coarse carbonate sand with scattered shell fragments. Barnacle plates, echinoderm spines, phosphorite grains, foraminifera and sub-angular quartz also form this unit. Shell fragments are mostly *Donax serra*. Calcium carbonate makes up 87 wt% of Unit 2.

Section A



	Description	Composition	Foraminifera	Depositional Environment
UNIT 3	Root casts *T. globulus* Friable medium to fine aeolian sand with with terrestrial snails and in the top meter root casts Coarse to medium sand	Shell fragments, ostracods, echinoderm spines, barnacle plates, foraminifera, quartz, terrestrial dune snail	Abraded *Ammonia* spp., *Elphidium* spp., *Haynesina* sp., *Pararotalia nipponica*, *Lobatula lobatula*	Coastal dune
2a	Erosional contact Friable medium coarse sand without large shell fragments	Shell fragments, echinoderm spines, barnacle plates, foraminifera, phosphorite grains, angular quartz	*Ammonia* sp., *Haynesina* sp., *Pararotalia nipponica*, *Oolina* sp., *Siphonaperta* sp., *Rosalina* sp., *Uvigerina* sp., *Quinqueloqulina* sp., *Lobatula lobatula*	Coastal dune
UNIT 2	Fine sand coarsening upward into very coarse sand Shell hash layer with *D. rogersi*			Sandy beach
UNIT 1	Scoured contact Very coarse to coarse sand with shell fragments (*Donax serra*) iron oxidation and root casts	Shell fragments,ostracods, echinoderm spines, barnacle plates,foraminifera, granite fragments	*Ammonia* sp., *Elphidium* cf. *crispum*, *Elphidium* sp., *Glabratella* '*australensis*', *Lobatula lobatula*, *Pararotalia nipponica*, *Quinqueloqulina* sp., *Uvigerina* sp., *Rosalina* sp.	Subaerial exposure
UNIT 0	*D. Serra*, *limpets (Patella* spp.*)* Shelly horizon Sample D0 Cape Granite Suite	Shell fragments, echinoderm spines, barnacle plates, reworked foraminifera, granite fragments	Reworked *Ammonia* spp., *Elphidium* spp.	Sandy beach/ rocky shore

Fig. 5.3 Biostratigraphy of the lower Tabakbaai Quarry.

The foraminiferal assemblage is made up of *Ammonia* spp., *Hayasina* spp., *Lobatula lobatula, Pararotalia nipponica*, *Oolina* sp., *Quinqueloculina* sp., *Rosalina* sp., *Siphonaperta* sp. and *Uvigerina* sp. (Plate II). The depositional environment is a sandy beach as indicated by the presence of *Donax serra*. The thickness of this unit is 1 m. At the top of Unit 2 is a friable carbonate medium sand with shell fragments, rounded quartz, barnacle plates, phosphorite grains, ostracods and foraminifera (Unit 2a). Unit 2a is lacking in large shell fragments. Between Unit 2a and Unit 3 there is an erosional contact.

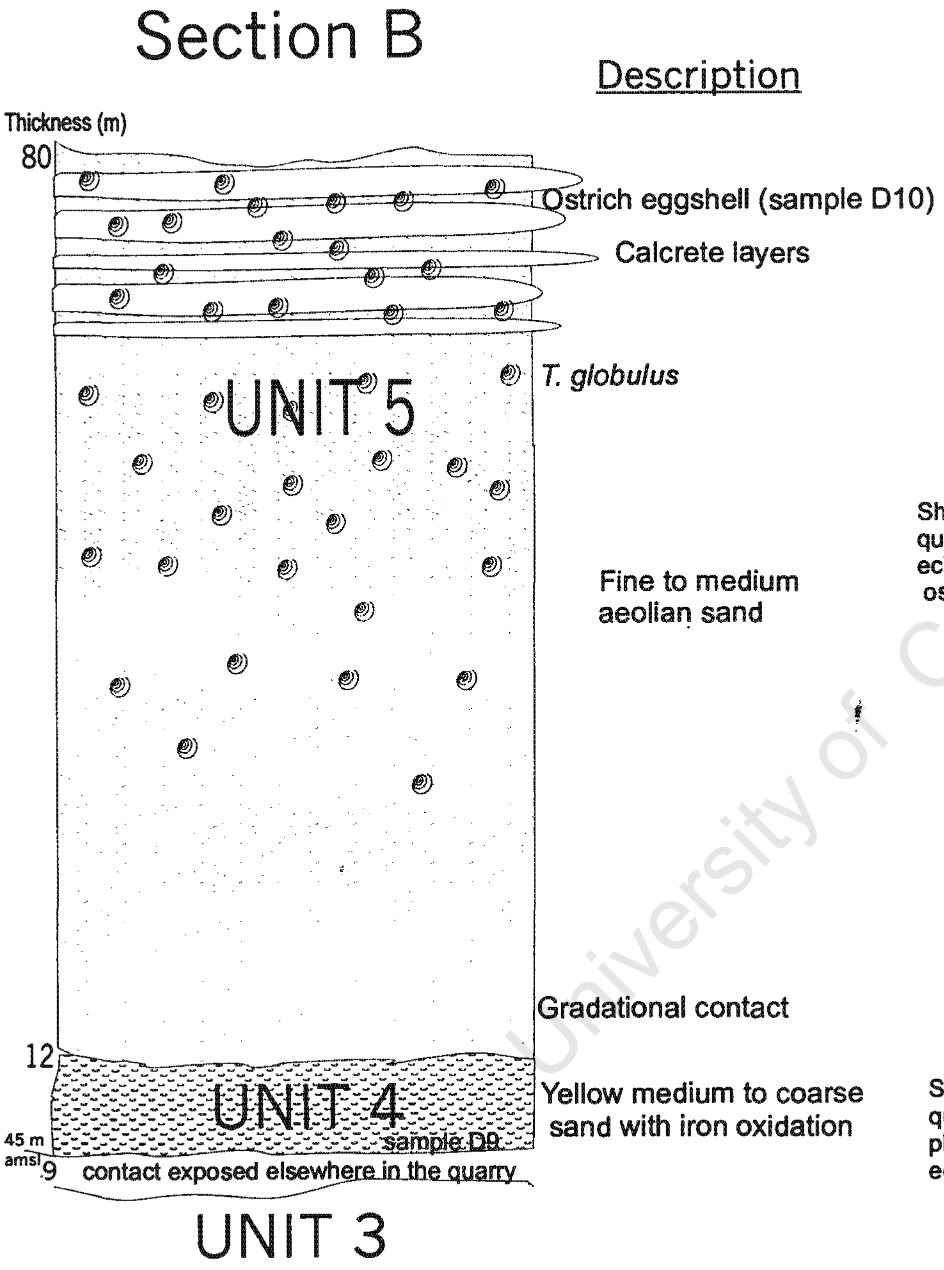
Unit 3 is a brown cross-bedded friable aeolianite consisting of weakly cemented fine sand with a maximum exposed thickness of 6 m. Numerous shells of the terrestrial snail *Trigonephrus globulus* and root casts are present in the uppermost three metres of the unit. Calcium carbonate comprises 80 wt% of this unit in the form of shell fragments, ostracods, echinoderm spines, barnacle plates and foraminifera tests. The foraminiferal assemblage is composed of *Ammonia* sp., *Elphidium* sp., *Haynesina* sp., *Pararotalia nipponica* and *Lobatula lobatula* (Plate III). Based on the lack of large marine shells, and to the presence of terrestrial snail *T. globulus* this unit is interpreted to be a coastal sand dune deposit.

At the base of the cliff of section A a coquina bed (Unit 0) crops out in depositional contact with the Cape Granite Suite (Fig. 5.3). The unit is almost completely formed of shells, shell fragments and reworked granite pebbles. The macrobenthos is composed mostly of *Donax serra*, and limpets (*Patella* spp.). Echinoderm spines, barnacle plates and angular granite fragments are also present in this unit. Rare phosphatised shell fragments have also been found.

Calcium carbonate makes up 90 wt% of the layer. The thickness is about 20 cm. The abundant presence of *Donax serra* suggests a sandy shore environment, whereas the presence of *Patella* shell fragments indicates that rocky outcrops were present in the area. The few benthic foraminifera found (*Ammonia* spp., *Elphidium* spp.) show signs of physical abrasion that suggest that they have been reworked in a high-energy environment. Strontium dating performed on a *Donax serra* fragment yielded an age ranging from 0.5 to 2.2 Ma (Table 2).

The contact between sections A and B is not directly exposed, but extensive field work in the area confirmed that section B directly overlies section A (Roberts, pers. comm., 2001). The aeolianites of Section B in the upper Tabakbaai Quarry have been divided into two units (Fig. 5.4):

Unit 4 is a medium to coarse, calcareous friable sandstone. It is composed of shell fragments, echinoderm spines, bryozoans, foraminifera, quartz and phosphorite grains (Fig. 5.4). The foraminiferal assemblage is composed of *Cibicidoides* sp., *Elphidium crispum*, *Elphidium* sp., *Eponides* spp., *Pararotalia nipponica*, *Rosalina 'diazvillea'* (Plate IV). Unit 4 contains 95 wt% calcium carbonate and the quartz grains are very well rounded (Fig. 5.5). Iron-oxide staining of the grains confers a yellow-orange colour to the unit. The unit is 2 to 3 metres thick. The contact between Unit 4 and Unit 5 is marked by a fining upward from medium sand to fine sand. Strontium dating performed on a mixture of echinoderm spines and foraminifera yielded an age ranging from 1.2 to 5.6 Ma (Table 2).



	Description	Composition	Foraminifera	Depositional Environment
UNIT 5	Fine to medium aeolian sand	Shell fragments, rounded quartz grains, barnacle plates, echinoderm spines, foraminifera, ostracods	Abraded *Pararotalia nipponica, Haynesina* sp., *Globigerina bulloides, Elphidium* sp., *Rosalina* sp., *Lobatula lobatula, Glabratella 'australensis'*.	Coastal dune
UNIT 4	Yellow medium to coarse sand with iron oxidation	Shell fragments, rounded quartz grains foraminifera (few), phosphorite grains, bryozoans, echinoderm spines	Abraded *Rosalina 'diazvillea', Pararotalia nipponica, Elphidium* sp., *Eponoides* sp.	Coastal dune

Fig.5.4 Biostratigraphy of the upper Tabakbaai Quarry.

Unit 5 is a fine to medium, moderately cemented calcareous sand (85 wt% $CaCO_3$). The unit is composed of shell fragments, barnacle plates, echinoderm spines, ostracods, foraminifera, well rounded quartz grains and the terrestrial snail *T. globulus* (Fig. 5.4). The foraminiferal assemblage (benthonic and planktonic) is composed of *Discorbis sp., Elphidium* sp., *Glabratella 'australensis', Globigerina bulloides, Haynesina* sp., *Lobatula lobatula, Pararotalia nipponica* (Plate V). Unit 6 is up to 70 m thick. Five calcrete layers are present in the upper 20 m of the unit. Fragments of the ostrich eggshell of *Diamantornis wardii* were found on the surface between the uppermost two calcrete layers (Fig. 5.4). The reddish-orange colour of this unit is a consequence of iron-staining of the sand. Tabular cross bedding in a north-northwesterly direction is also visible in Unit 5. The direction of the bedding suggests that the prevalent paleo-wind direction was as it is today from the south-southwest (Pether et al., 2000). Strontium dating performed on a mixture of echinoderm spines and foraminifera yielded an age ranging from 4.3 to 8.8 Ma and between 1.0 and 5.2 for a fragment of an eggshell of *Diamantornis wardii* (Table 2).

The section exposed at the railway cutting south of the Tabakbaai Quarry at 25 m amsl is composed of a carbonate sand with shells, shell fragments and large granite boulders (Fig. 5.6). The macrobenthos assemblage is composed mostly of *Donax serra* and *Patella* spp. that indicate a sandy beach with rocky outcrops. In the basal part of this succession, the Cape Granite is exposed (Fig. 5.6). Strontium dating yielded an age range between 1.8 to 6.1 Ma for the echinoderm spines and between 0 to 1.8 Ma for the phosphorite (Table 2).

Fig. 5.5. Rare well rounded quartz (300X) in a carbonate matrix.

The section exposed at 45 m amsl is formed of three units (Fig. 5.6). The basal aeolian sand is brown to yellow in colour, with large shells of the terrestrial snail *T. globulus* (up to 8 cm in diameter). Strontium dating yielded an age range between 2.2 and 6.3 Ma for phosphorite shell fragments collected from this basal unit. On top of this basal sand, a 1 m thick calcrete is exposed. The calcrete is well cemented and yellow-white in colour. The upper part of the succession is composed of a aeolian sand with *T. globulus* shells considerably smaller (up to 6 cm in diameter) than the ones present in the basal sand (Fig. 5.6).

5.4 DEPOSITIONAL HISTORY AND AGE OF THE TABAAKBAII QUARRY DEPOSITS

Coastal depositional systems on the modern west coast comprise a mosaic of shoreline to inner-shelf environments including lagoons (mud-rich),

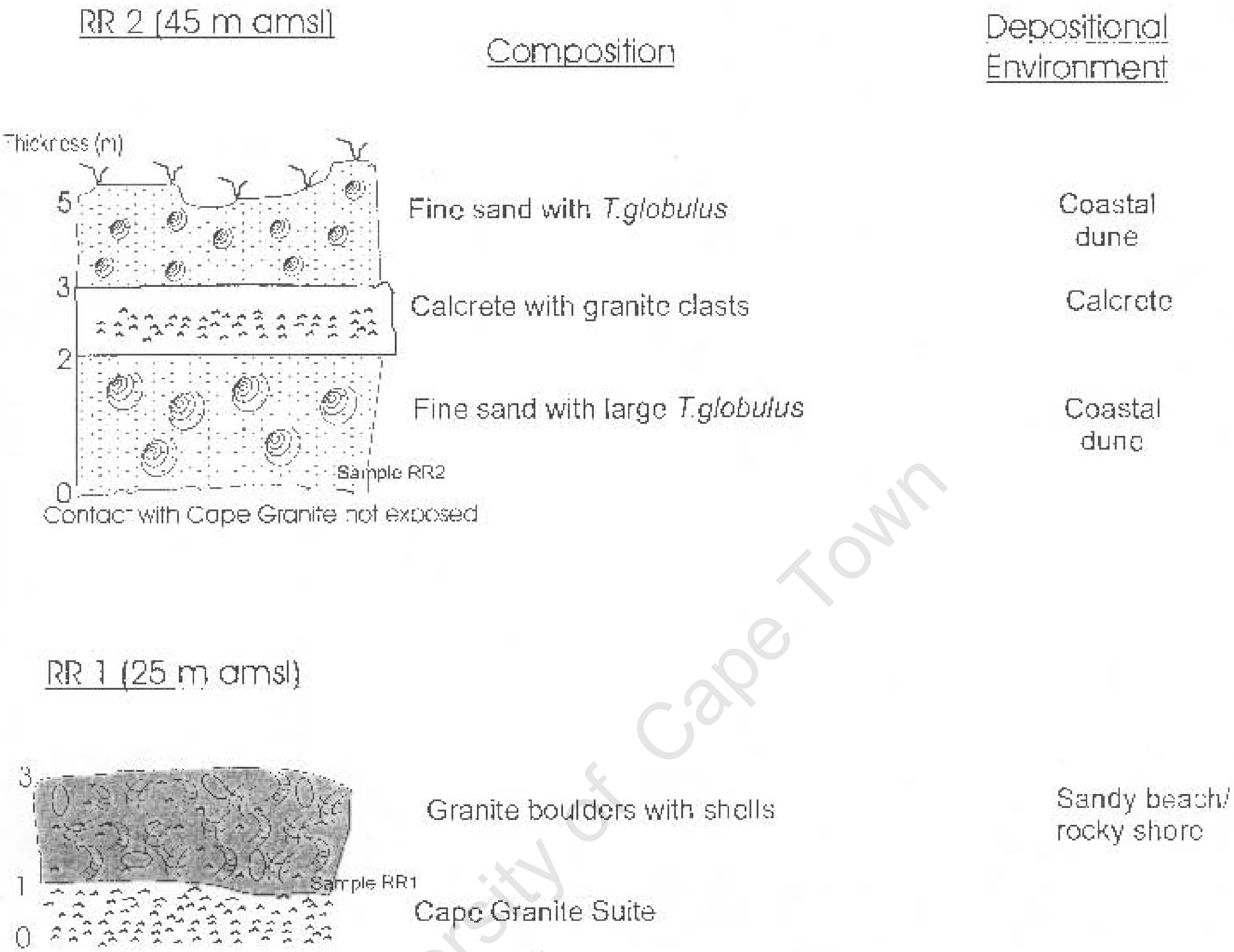


Fig. 5.6. Stratigraphical sections of the railway cut exposure, south of Tabakbaai Quarry.

beaches (sand-rich) and rocky shorelines (shell-rich), which commonly pass offshore into normally graded (sand rich to mud rich) inner-shelf sediments (Rogers, 1980; McMillan, 1987a). Bodies of sand accumulate in coastal areas in the Saldanha Bay region (Tankard, 1976a), and shell-rich gravel substrates occur in areas swept by tidal currents (Tankard, 1976a; Kensley, 1985). In the nearshore and inner shelf environments, the skeletal remains of benthic communities are dominated by mollusca, barnacles and foraminiferal components. Benthic foraminifera, in particular, are very sensitive to changes in the environment. The genus *Ammonia* has been regarded as a shallow water indicator (Dale and McMillan, 1999), and it is present today in the subtidal channels and low tidal flats of the Langebaan Lagoon (Chapter 3). *Elphidium* spp. and *Lobatula lobatula* have been found living in high-energy rocky pools of sandy beaches or attached to kelp (McMillan, pers. comm., 2001). The Tabakbaai Quarry deposits have micro and macro faunal assemblages that are closely analogous to several of these modern coastal and inner shelf environments.

The contact between Cambrian granites and Cainozoic strata presents a major erosional unconformity. Beach and coastal dune deposits indicate that the high-energy strandline has migrated repeatedly across this area. Unit 1 is interpreted to be a shallow-marine deposit because of its benthic foraminiferal assemblage and the presence of *Lobatula lobatula*, and several species of *Elphidium* spp. that have been reported to be found in South Africa in environments ranging from inner-shelf to high-energy rocky pools in sandy beaches (McMillan 1987a; Dale and McMillan, 1999; McMillan, pers. comm., 2001). The macrofaunal assemblage is mostly composed of shell fragments in which identification at the genus level is not always possible. However, *D. serra* hinges suggest a sandy beach environment. Sr-derived ages from phosphorite pebbles, as well as the foraminifera *Lobatula lobatula*, and echinoderm spines collected from Unit 1 (sample D 1) yield an overlapping age between 6.1 to 4.9 Ma (Late Miocene to Pliocene; Table 2). Analysis of different material from Unit

1 was undertaken for finding an overlapping age that may represent its depositional age. This overlapping age represents the minimum and maximum age of the Unit. Considering that, in a case of recrystallisation all the different grains would have been effected in the same way, and that the strontium coming from pore water is minimal in comparison to the strontium in the marine shells, the overlapping age represents a mean age for the strata (Table 2).

The basal part of Unit 2 is composed of scattered shell fragments of *D. serra* and it is interpreted as a beach deposit. Changes in grain size from very coarse (Unit 1) to coarse (Unit 2) to medium (Unit 2a) sand indicate a decrease in the energy regime of the area probably reflecting on an increase in water depth and, therefore, a marine transgression. The presence of barnacle plates suggests that rocky outcrops were present in the area at the time of deposition (Units 1 and 2).

On top of these basal marine horizons there are bioclastic aeolianites composed of a very homogeneous fine to medium sand with a trend of fining upwards. The mainly benthic foraminifera are abraded and not well preserved in these units and interpreted to be transported from the beach by the wind. The presence of well rounded quartz and the abundant *T. globulus* associated with root casts, suggests an aeolian origin for these deposits. These aeolianites are the southern tip of a 20 km long dune plume running in a northwesterly direction north of the Tabakbaai Quarry. This long plume of fine to medium sand, formed just downwind of a beach and it has a similar orientation to the present-day dunefield that runs from Yzerfontein to Geelbek (Fig. 5.1). The presence of well developed root casts suggests that these dunes were stabilised by vegetation.

In the uppermost part of the succession five calcrete layers are present. On the top of these calcretes several eggshell fragments of *D. wardii* have been recovered, associated with fossilised carapaces of terrestrial tortoises and micromammals, suggesting that the dune plume was vegetated. The *D. wardii* has been dated as middle Miocene by comparison to the East African faunal assemblage that are intercalated between volcanic rocks (Pickford and Senut, 1999).

The age of Tabaakbaai quarry is controversial with speculation on the time of deposition that ranges from Middle Miocene to Late Pliocene-Early Pleistocene (Pether et al., 2000; Dale and McMillan, 1999). For dating Upper Tertiary calcareous deposits in which luminescence dating can not be applied, the use of strontium isotope stratigraphy (SIS) may help to understand the time of deposition. SIS is based on the fact that the Sr-isotope composition of seawater has changed through time and it is controlled by different variations in the input of Sr from continental weathering, hydrothermal circulation and from carbonate dissolution (Bralower et al., 1997). Because the oceans are well mixed with respect to Sr and marine deposits record the oceanic Sr-isotope ratio at the time of deposition, the ratio $^{87}Sr/^{86}Sr$ provides an age control for sedimentary rocks (DePaolo and Ingram, 1985). However, some problems occurred using SIS for these Tertiary deposits:

1) the marine Sr isotope curve is well established but the steepness of the curve, and hence, the age resolution varies through time. The marine Sr isotope curve flattens out in the Pliocene, making it difficult to set narrow age limits since the Late Tertiary (refer to Chapter 1).

2) Sr ages are not well constrained, because the reproducibility of the Sr standard at UCT is ± 45x10^{-6}.

3) ages obtained via strontium isotope could have been affected by possible alteration since deposition by recrystallisation of the calcareous grains. However, shell fragments of *D. serra* (sample D0 and D1) were analysed using X-ray diffraction at the University of Cape Town. Neither of these shell fragments exhibited signs of diagenetic alteration of aragonite to calcite.

Nevertheless, the overlapping ranges of Sr-derived ages of different biogenic grains from the same sample, may be used to infer the age of deposition (Table 2). In the basal section (Unit 1) the overlapping range is between 6.1 and 4.9 Ma and at the top of the section (Units 4 and 5) between 5.6 and 4.3 Ma. Considering that these samples are in stratigraphical succession (as indicated by the overall younging upwards of the ages, Table 2) the overlap of the ages clearly indicates a latest Miocene-Early Pliocene age for the deposit. The middle Miocene age for the upper Tabakbaai Quarry deposits has been assigned using the biostratigraphy of giant avians found in southern Namibia and dated in East Africa (Pickford and Senut, 1999). Perhaps, the population of *D. wardii* is younger than it was previously thought to be or it represents a localized population that have persisted longer than its counterparts in southern Namibia. Foraminiferal biostratigraphy assigned a Late Pliocene/Early Pleistocene age for the deposit (Dale and McMillan, 1999). The foraminiferal assemblage and, in particular, the benthic foraminifer *Lobatula lobatula* are older than that previously proposed for the south Atlantic west coast deposits by Dale and McMillan (1999) and the result of the Sr isotope analyses may help to better constrain the age limits for the marine Packages (Pether, 1994) of the west coast.

The presence in the coquina bed (Unit 0, Fig. 5.3) exposed at the base of the Tabakbaai Quarry, of the shallow infaunal articulated *D. serra* associated with densely packed *Patella* shells indicates a high-energy environment at time of deposition, such as a sandy beach with adjacent rocky outcrops. The shell bed is characterised by layers, with most of the shell obliquely orientated in a massive carbonate sand matrix. Shell and shell fragments generally lack evidence of abrasion or bio-erosion. The basal coquina is interpreted to have been deposited later than the deposits that occur at higher elevations by an erosional wave-cut terrace at 25 m amsl during the Early Pleistocene (Table 2). The presence of younger layers overlying older deposits has been recorded elsewhere in the Namaqualand coastline (Pether, 1994). This is essentially because the erosion of terraces occurs during transgressive phases whereas deposition accompanies regression. Therefore, subsequently transgressions may re-occupy previously cut terraces, generally but not always reworking the deposits that lies upon them (Pether, 1994). The age during which the older deposits were cut may or may not correspond to the age of the subsequently deposited material. Highstands during the Early Pleistocene have been reported elsewhere in southern Africa (Pether et al, 2000). Modern shell gravels of similar faunal composition have been found in several localities along the west coast of South Africa, and Pleistocene shell-rich deposits have been described between Velddrif and Laaiplek in the Berg River Mouth (Tankard, 1976a), on the northern shore of Saldanha Bay and on the western shore of Langebaan

Lagoon, where they are overlain by the Langebaan Formation (Tankard, 1976a; Rogers, 1983, Roberts and Berger, 1997). These deposits belong to the Velddrif Formation and the age is Late Pleistocene when the sea level was at an elevation of 5 m amsl and a maximum height of 7 m amsl, defined on the basis of lithological, palaeontological and temporal criteria (Tankard, 1976a; Theron et al., 1992).

The succession exposed along the railway cutting at 25 m amsl south of the Tabakbaai Quarry is considered to be formed during the Early Pleistocene (overlapping age for the strontium isotope values of 1.8 Ma) and therefore equivalent to the basal shelly gravel of Section A. The presence of well rounded large granite boulders and of a shell assemblage mostly composed of *Patella* spp. and *Fissurina* spp. indicate a rocky shoreline at time of deposition. The section exposed by the railway cutting at 45 m amsl, is instead interpreted to be a coastal-dune deposit on the basis of the abundant presence of terrestrial snails and the lack of large shell fragments. The terrestrial gastropod *T. globulus* currently occupies arid to semi-arid Mediterrenean climatic zones (van Bruggen, 1982). The age of the lower part of the 45 m deposit is latest Miocene-Early Pliocene (Table 2) and therefore, equivalent to the aeolian deposits in the uppermost part of Section A and Section B of the Tabakbaai Quarry.

5.5 POSITION OF THE FORMER SEA LEVEL AND CHANGES IN COASTAL SEDIMENTATION

The evolution of the sedimentary units can be understood in terms of sea-level changes. The Tabakbaai area developed on the inner shelf during a marine transgression and a sea-level highstand when the palaeoshoreline was on the order of 25 m above its present-day position (Fig. 5.7). High sea-levels during the late Miocene-Early Pliocene have been recorded elsewhere in southern Africa (Pether, 1994). Marine fossils, including sharks' teeth and molluscs have accumulated in the Varswater Formation at Langebaanweg Quarry (refer to Chapter 2) probably during a +30 m highstand during the Late Miocene (Hendey 1981a, b; Dingle et al., 1983). Low terrigenous siliciclastic sediment accumulation resulted in the concentration of mainly molluscan shell remains on the inner-shelf. Facies evolution and grain size changes indicate decreasing water depth from Unit 1 to Unit 3. The grain size varies from a very coarse to coarse calcareous sand to a homogenous medium to fine sand. Foraminiferal tests also show signs of incipient abrasion in Unit 3 and indicate transport of the sand from the beach to form the dune plume. Changes in the global climate then led to coastal progradation as the sea level dropped at the Mio/Pliocene boundary causing the coastline to move seaward (Pether et al., 2000). Terrestrial aeolian sediments were then deposited (Units 3,4,5) on those which formed earlier in the marine settings. A rapid sea-level rise to 23-24 m during the Early Pleistocene induced marine re-deposition of the coquina layer and reworking of older deposits (shelly gravel, Fig. 5.3).

The palaeogeographic and stratigraphic record for the Late Tertiary to Pleistocene indicates major changes in coastal sedimentation in the Tabakbaai Quarry area. Coastal sedimentation alternated between sandy beaches with well-developed rocky shores and coastal dunes. Sedimentation in the area during the Mio-Pliocene mostly involved sandy beaches as indicated by the macrobenthos *D. serra*.

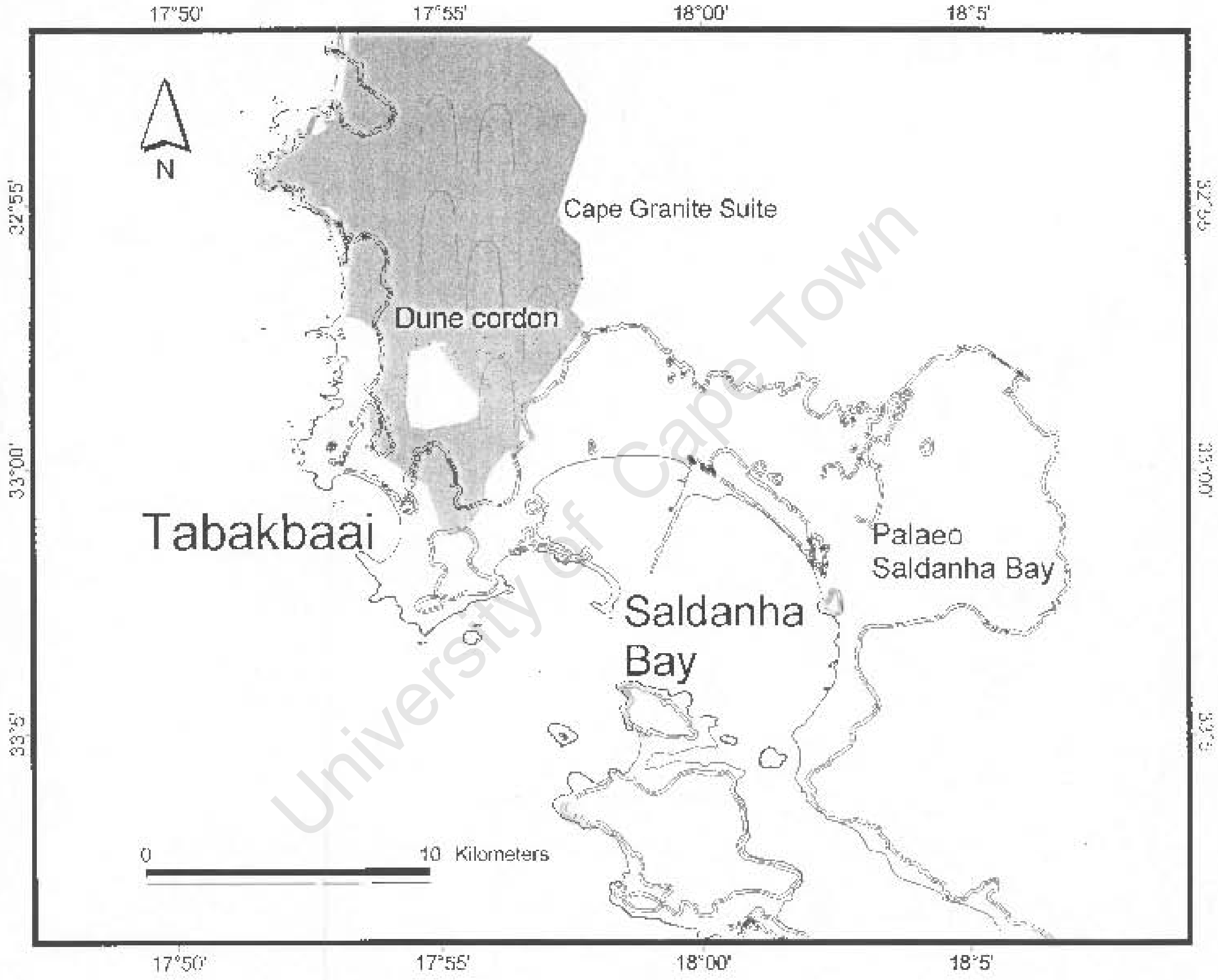


Fig. 5.7. Palaeogeography of the Saldanha Bay area in the case of a sea-level rise of 25 m.

In addition to sandy beaches, the presence of rocky shorelines is indicated by barnacle plates, echinoderms and benthic foraminifera such as *Elphidium* spp. and *Lobatula lobatula,* in an environment similar to modern coastal zones in the area of Cape Columbine (Fig. 5.1). The change from sandy and rocky shoreline to coastal dunes reflects a drop in sea-level, subaerial exposure and dune formation. The Tabakbaai dune plume formed immediately landward of the beach and extended for 20 km towards the north (Fig. 5.1). This dune plume is similar to the Geelbek-Yzerfontein dune plume in the Sixteen Mile Beach complex (Chapter 4, Fig. 5.1). One difference, however, can be highlighted between ancestral dune complexes and modern ones concerning the calcium carbonate content. The high calcium carbonate content (80-95 wt%) of the dunes exposed in the Tabakbaai Quarry is in contrast with the quartz-rich sand dunes of the Langebaan Lagoon area that contain 40-60 wt% calcium carbonate, just 10 km south of the quarry. Carbonate-rich sediments comprise most of the beaches north of Saldanha Bay with Diazville Beach having 83 wt% calcium carbonate and Paternoster Beach having 74 wt% calcium carbonate (Wigley, pers. comm., 2000). Quartz-rich sandy beaches are found in the south (45 wt% $CaCO_3$ along Sixteen Mile Beach, 40 wt% of $CaCO_3$ at Koeberg Beach). At the Berg River mouth today, (Fig. 5.1) the calcium carbonate content is very low (2 wt% at the mouth) because of the large supply of quartz sand by the Berg River to the coast.

The fluvial Elandsfontyn Formation and fluvial channels in the Varswater Formation (Hendey, 1974, 1981a; Coetzee and Rogers, 1982) indicate that a river, perhaps the proto-Berg River, discharged into a strait between the modern

Saldanha Bay and St. Helena Bay at Langebaanweg (Fig. 5.1) from the Late Miocene to the Mio-Pliocene (Hendey, 1981a,b). The proto-Berg River, in that case, would have contributed substantial siliciclastic material to the coastal dunes of the study area. Therefore, Pether et al. (2000) and Roberts and Brink (2003) conclude that it is likely that coastal dunes of the Tabakbaai Quarry are older than the Elandsfontyn and Mio-Pliocene fluvial deposit at Langebaanweg. The high carbonate content of the Tabakbaai dunes indicates that, similar to today the Berg River was most likely discharging its large siliciclastic content north of Saldanha Bay.

The greater carbonate content of modern beaches between Saldanha Bay and the Berg River mouth reflects the lack of river sand input as well as a lack of quartz sand derived by longshore drift from the south. The net annual longshore drift along the west coast is to the north and consequently the sediment comes from the southern part of the Western Cape (Swart and Flemming, 1980), where several perennial rivers discharge quartz and other terrigenous grains. These terrigenous grains are transported alongshore as far north as the mouth of Saldanha Bay, where they are presumably moved offshore creating low (<5 wt%) terrigenous beach sediments from the north side of the mouth of Saldanha Bay to the Berg River mouth. High shell fragmentation in rocky areas, mostly having high wave energy, is also important in the determination of the calcium carbonate content of the beach sand. North of Saldanha, the constant wave action and the numerous granite outcrops of the Cape Columbine peninsula have led to rapid fragmentation of shells. South of Saldanha Bay (Fig. 4.1) there are sandy beaches with less extensive rocky areas able to generate shell fragments. Mineralogical differences have been described in Australia, with calcareous sand beaches that dominate the southwestern coast, whereas quartz rich beach sands are characteristic of the southeastern coast (Bird, 1972). A similar situation has been described by Meldahl (1995) in Mexico for Pleistocene beach deposits. In the northern part of the Gulf of California the marine Pleistocene deposits are dominated by mature terrigenous sediments, while the deposits on the Vizcaino Peninsula (western Baja California) are dominated by biogenic sediments (Meldahl, 1995). The different lithological patterns reflect the local geological settings with terrigenous sediments originating from the Colorado River delta and biogenic sediments from fecund molluscs populations (Meldahl, 1995).

5.6 PALAEOGEOGRAPHY

Study of the outcrops in the Tabakbaai Quarry challenges the concepts put forward in earlier reports on the sedimentary units of this area. The succession is composed of Tertiary marine and aeolianite deposits. During the Late Miocene-Early Pliocene, as a result of a sea-level rise, a sandy shoreline with rocky shores occurred in the area (Units 1 and 2). During a highstand of 25 m above msl, the Tabaakbaai quarry area was located at the southern edge of a granitic headland, similar to that of the present-day Cape Columbine Peninsula (Fig. 5.7, reconstructed from the elevation data supplied by the Survey and Mapping office of Cape Town). Two large offshore islands created a tombolo setting that trapped the carbonate sand behind the islands (Fig. 5.7). A sea-level fall during the latest Miocene-Early Pliocene induced coastal dune development directly on top of the marine units. The area was subjected to strong wave action and the swell was coming from the south-south west. Strong south-southwesterly winds moved the carbonate-rich beach sand inland, forming the extensive south-north dune plume (Units 3, 4 and 5). The longshore drift was to the north and Saldanha Bay was significantly larger than today (Fig. 5.8). The log-spiral form of palaeo-Saldanha Bay was formed when headlands partially blocked longshore transport.

Coastal flooding occurred during the Early Pleistocene transgression that resulted in partial erosion of the basal shelly gravel and the formation of intertidal foreshore facies (Unit 0). During the Early Pleistocene a transgression positioned the sea level at 24 m above present msl. These sea level positions are relative, because it is not known by how much, if any, tectonism has moved the units since the Late Miocene. However, it would appear from evidence from the south-west Atlantic continental shelf that since the Tertiary the coastal region was not directly affected by faulting (Light et al., 1992; 1993). In southern Namibia/northern Namaqualand raised beaches were interpreted to reflect tilting of the land since the Tertiary (Stocken, 1978; Dingle et al., 1983). Recent studies have, however, shown that the appearance of tilting could be an artefact caused by erosion. In fact, in the case of deposits that slope seawards and their upper sections are eroded away and the lower part survived, this may give the erroneous impression of tilting (Pether, 1994; Light et al., 1992).

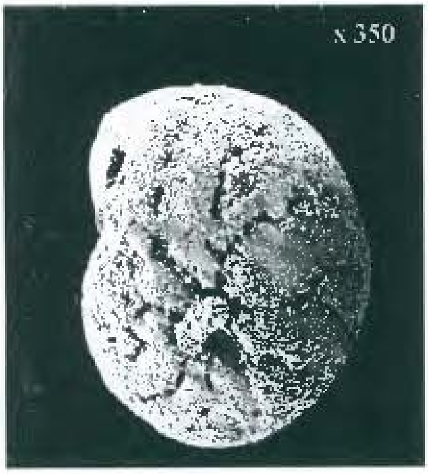
The section exposed at Tabaakbaai Quarry gives palaeogeographical information of complex coastal evolution ranging from the latest Miocene-Early Pliocene to the Early Pleistocene. Unfortunately, the paucity of deposits in the area does not allow interpretation of the Early to latest Pleistocene. During the latest Pleistocene the Velddrift Formation was deposited. It consists of fine to coarse shelly sands and shell coquina that is lacking in phosphorite grains similar to the shelly basal coquina bed found in the Tabakbaai Quarry (Unit 0). The major difference between these two deposits is however, that the Velddrift formation has been reported in the Saldanha Bay are outcropping at 5 to 10 m amsl (Tankard, 1976a). The other latest Pleistocene deposit found in the area, the Langebaan Formation, overlies directly the Velddrift Formation and mainly composed of calcareous sand, calcretes and limestones. The Langebaan Formation has been interpreted as the product of onshore sand deflation, during sea-level lowstand (Pether et al., 2000). This formation has not directly investigated, because its age was not controversial in the literature. The main difference between the coastal dunes bodies best exposed at Tabakbaai Quarry and the aeolianites of the Langebaan Formation is the content of calcareous material. In fact, while the aeolianites exposed at Tabakbaai Quarry are very rich in bioclastic material, the aeolianites of the Langebaan Formation are quartz rich.

5.7 CONCLUSIONS AND SUMMARY

This chapter provides useful information on the age and palaeogeography of the Saldanha Bay area since the Late Tertiary. The active Holocene Yzerfontein-Geelbek dune plume is used as an analogue of a stable, previously vegetated non-cemented 20 km long dune plume exposed at Tabakbaai Quarry. These two dune plumes have a similar orientation (Fig. 5.1), but a different mineralogical composition and ages. Strontium isotope stratigraphy has been used to infer the age of deposition of both marine and aeolian deposits in the quarry. The stratigraphy of the sedimentary sequence exposed at the Tabakbaai Quarry evolved over a considerable period. A latest Miocene-Early Pliocene age is proposed for this deposit making these dunes the oldest coastal dune system in South Africa (Table 2). A sandy beach related to a 25 m shoreline was deflated by strong southerly winds forming the elongate, coast-parallel dune system. Several minor sedimentation pulses occurred in the area, each accompanied by pedogenic development.

Fossil eggshell fragments of the giant struthious *D. wardii* were recovered from aeolianites exposed in the Tabaakbaai Quarry area (Unit 5). The Middle Miocene age suggested by the presence of eggshell fragments of *D. wardii*, is in apparent contradiction with the Strontium Isotope Stratigraphy results. Two possibilities may arise: the strontium dates were reset because of recrystallisation with older strontium or the age-range of the *D. wardii* is greater than previously defined in East Africa. However, recrystallisation is not likely to occur because observations were undertaken with the SEM and X-ray diffraction analysis of fragments of *D. serra* have shown that no diagenetic alteration has occurred. Therefore, it is possible that the age range of *D. wardii* extends to the Late Miocene/Pliocene. More dating of *D. wardii* eggshell fragments as well as carbonate material present in overlying or underlying strata may help to determine its age. Benthic foraminifera and Strontium Isotope Stratigraphy suggest that during the latest Miocene-Early Pliocene there was a stillstand at 25 m amsl that left a veneer of marine sediments in the base of the succession and that a fall in sea-level is responsible for the deposition of aeolian coastal sand deposited over the marine units.

Evidence of a highstand in the area during the Early Pleistocene is recorded in the coquina bed (Unit 0) found on the Cape Granite (Fig. 5.3), which left a highly fossiliferous deposit. This coquina bed has been deposited in a wave cut terrace. The relationships between the deposits exposed at the Tabakbaai Quarry and at Langebaanweg Quarry (25-30 m amsl) are investigated in Chapter 6.



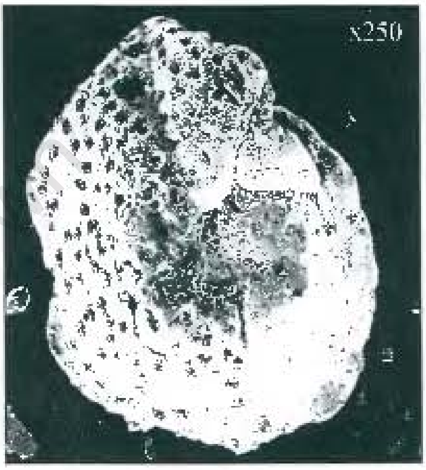
Ammonia sp.

Ammonia sp.

Elphidium crispum

Elphidium sp.

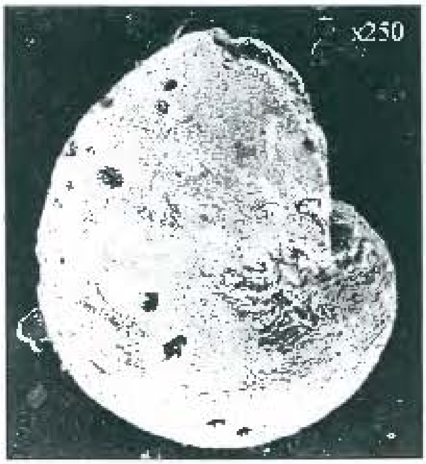
Glabratella 'australensis'



Lobatula lobatula

Pararotalia nipponica

Quinqueloculina sp.

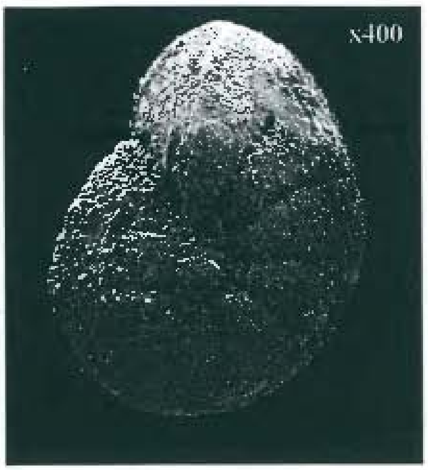


Rosalina sp.

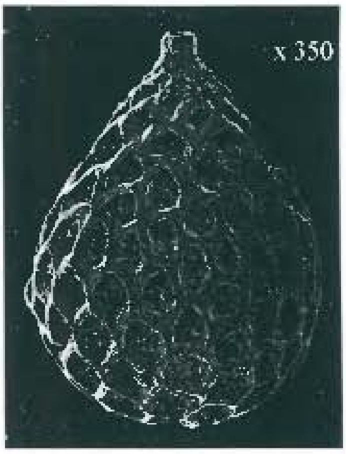
PLATE 1

Uvigerina sp.

Ammonia sp.

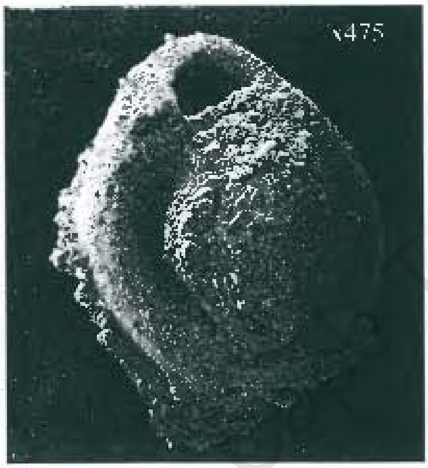


Haynesina sp.



Oolina sp.

Pararotalia nipponica



Quinqueloculina sp.

Siphonaperta sp.

Uvigerina sp

PLATE 2

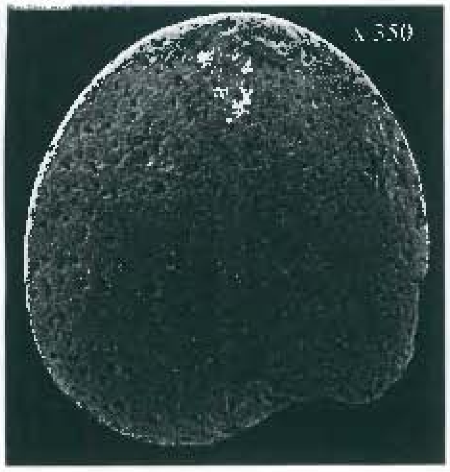
Ammonia sp.

Elphidium sp.

Lobatula lobatula

Pararotalia nipponica

PLATE 3

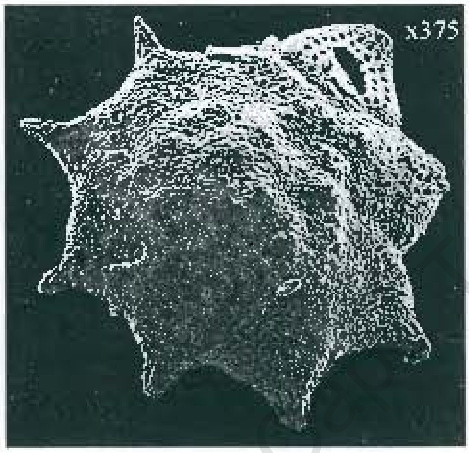


Cibicidoides sp.

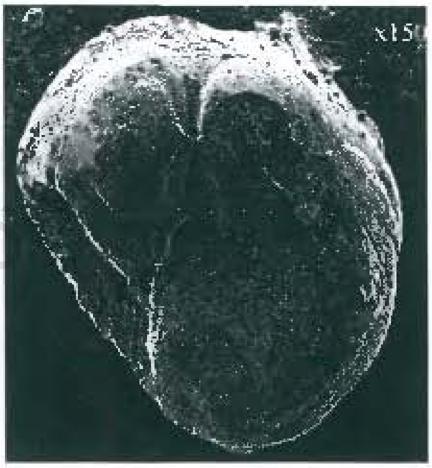
Elphidium cf *crispum*

Elphidium sp.

Eponides sp.



Pararotalia nipponica



Rosalina 'diazvillea"

PLATE 4

Discorbis sp.

Elphidium sp.

Glabratella 'australensis'

Globigerina bulloides

Haynesina sp.

Lobatula lobatula

Pararotalia nipponica

PLATE 5

Chapter 6 -

Onshore phosphorite from the Saldanha Bay area

6.1 INTRODUCTION

The coastal dunes and the marine strata exposed at the Tabaakbaai Quarry provide useful information regarding the age and palaeogeography of the Saldanha Bay area since the Late Tertiary. In order to verify the consistency of a latest Miocene-Early Pliocene highstand of 25 m amsl and of 24 m amsl during the Early Pleistocene, other Tertiary deposits in the area were studied. Few of these late Tertiary deposits have been preserved in the Saldanha Bay area, except for sections exposed at the Bomgat Cave in the Hoedjiespunt Peninsula and at the Langebaanweg Quarry (Fig. 6.1). These deposits are both characterised by the presence of phosphorites. In the Langebaanweg Quarry, the concentration of pelletal phosphorite has been described by Hendey (1974, 1976, 1981a, b), Tankard (1974a, b), Dingle et al. (1983) and Rogers (1980, 1982, 1983). Tankard (1974a, b) has described the petrology of onshore phosphorites and phosphatic sandstones from the Saldanha area concluding that they have formed in shallow marine environments during the Miocene.

Phosphorites are sedimentary rocks in which carbonate-fluorapatite (CFA) is a major component. Minor amounts of Sr (<2700 ppm) also occur in the structure of the mineral CFA (McArthur et al., 1990). CFA forms by precipitation from pore waters, as a cement often in the interior of bivalve or gastropod shells, or by replacement of precursor minerals, usually calcite (Birch, 1980).

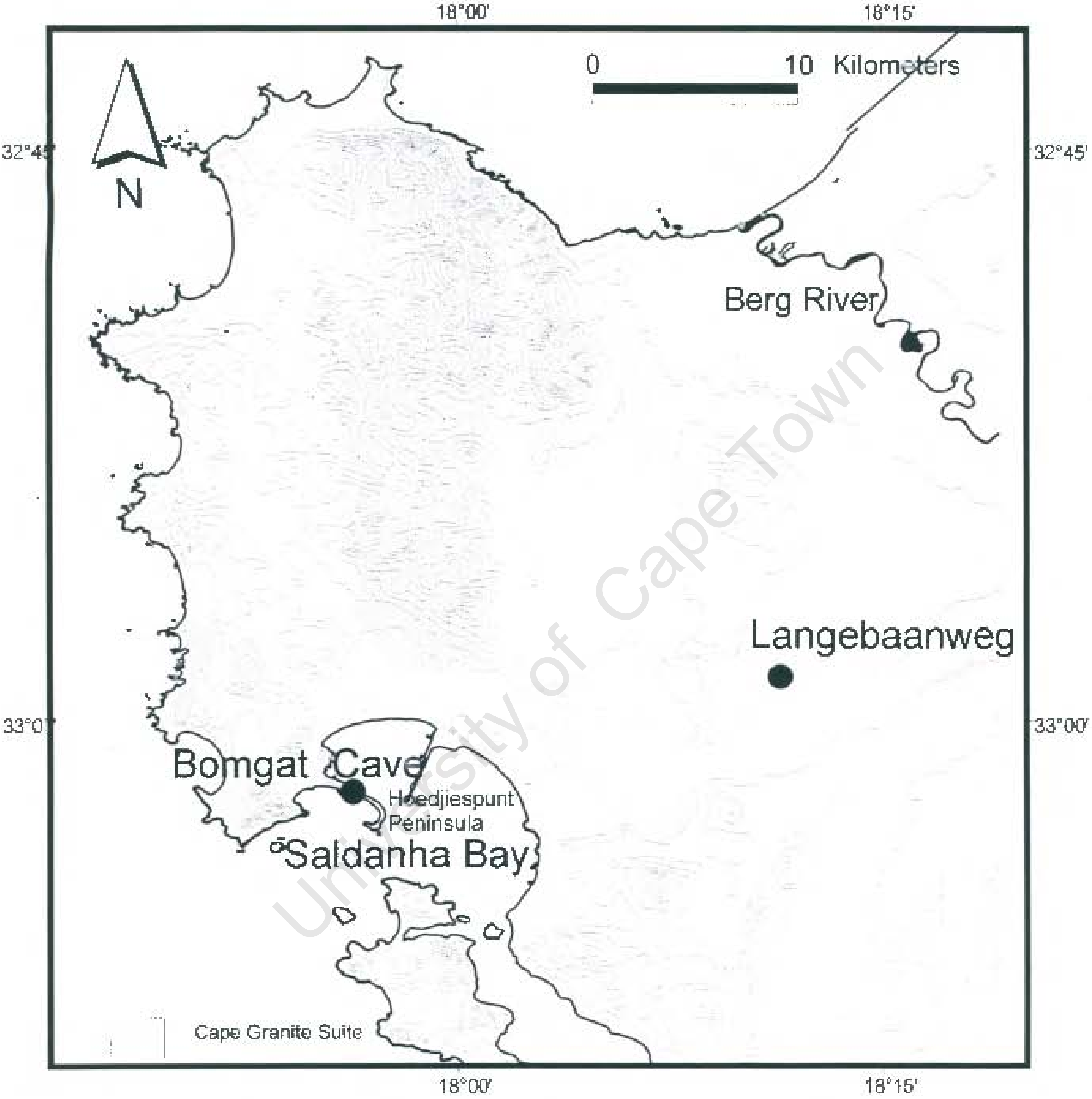


Fig. 6.1. Location of the Bomgat Cave and the Langebaanweg Quarry within the Saldanha Bay-Cape Columbine area (contour interval every 20 m).

The South Atlantic African continental shelf is one of two areas where phosphorite is presently being formed (Baturin et al., 1972; Veeh et al., 1974). Microfossil identification has proved to be difficult in phosphorites and, therefore, fossil age dating techniques can seldom be used for these rocks (Tankard, 1976; Siesser 1978; Burns 1984; Dale and McMillan, 1999). Microfossil ages may also not correspond to the age of the phosphogenesis if the fossils are reworked. The ages of the phosphorites can be determined from well established strontium isotope stratigraphy (e.g. Hodell et al., 1991; Farell et al., 1995) and this can provide a suitable method for understanding sea-level changes linked to marine transgression and increased upwelling productivity.

The present work provides additional information regarding sea-level highstands using strontium-derived ages for phosphorites, phosphatic shells and calcareous shells recovered from the Saldanha-Langebaanweg area.

6.2 PREVIOUS WORK

Over much of the coastal plain of the Western Cape, the deeply weathered, late Precambrian-lower Cambrian bedrock is overlain by the fluvial Elandsfontyn Formation (Rogers, 1980). The Elandsfontyn Formation attains its greatest thickness in bedrock topographic lows and it is never exposed. It is distinguished from overlying paralic and marine sediments by the angularity of its sands and the lack of carbonate and phosphate (Rogers, 1980, 1982). A number of fining-upward cycles terminating in muddy and peaty layers is usually present, and the depositional environments are interpreted to be those of meandering rivers under humid climatic conditions (Rogers, 1980, 1982).

The overlying Varswater Formation, best exposed in the Langebaanweg Quarry, 110 km north-north west of Cape Town (Fig. 6.1), was informally divided (Fig. 6.2) into a basal Gravel Member, overlain by a Quartzose Sand Member, a Pelletal Phosphorite Member and an upper Calcareous Sand Member (Rogers, 1980, 1983; Hendey 1978, 1981a, Hendey and Dingle, 1983; Dingle et al., 1983; Theron et al., 1992).

The Gravel Member is composed of 1 m thick phosphatic gravel rock (Rogers, 1980, 1983; Hendey 1981b; Dingle et al., 1983) that was eroded and reduced to a gravel by wave action (Hendey, 1982). In the Gravel Member, rare marine fossils, such as shark teeth and molluscs are present (Hendey 1981a, 1981b, 1982; Hendey and Dingle, 1983). The Gravel Member formed in a regressive environment during the Late Miocene (Hendey, 1981a, b, 1982).

The Quartzose Sand Member (QSM) at the Langebaan Quarry has been regarded as an estuarine deposit covered by forest and grassland (Hendey 1981a,b; Dingle et al., 1983; Rogers et al., 1990). The age of this deposit is Pliocene based on its vertebrate fossil remains (Hendey, 1981a, b; Dingle et al., 1983). The Pelletal Phosphorite Member and the Quartzose Sand Member are exposed in different parts of the Langebaanweg Quarry (Fig. 6.2) and the stratigraphical or age relation has not been proved. The Pelletal Phosphorite Member (PPM) is interpreted to be a Pliocene shallow marine environment associated with fluvial deposits (Dingle et al., 1983). Foraminiferal tests have been collected and studied by Dale and McMillan (1999) from the Pelletal Phosphorite Member. The presence of the benthic foraminifera *Zeaflorilus* sp. (originally described as ?*Pseudononion* cf. *chilensis*) has tentatively led these authors (Fig. 6.2) to propose an Early Pleistocene age (30 m Package of Pether, 1994). The depositional environment is inner shelf wave-dominated coastline and no river input is indicated (Dale and McMillan, 1999). Foraminifera are very abraded and encrusted in the Pelletal Phosphorite Member, and no other foraminiferal biostratigraphy could be performed on other members of the Varswater Formation (Dale and McMillan, 1999). The Calcareous Sand Member (CSM) is thought to be a coastal barrier complex deposited during the Pliocene (Hendey, 1981a). It consists of fine to medium sand with scattered phosphate grains, with numerous shells of the terrestrial snail *Trigonephrus globulus* (Pether et al., 2000). Texturally the CSM is similar to the aeolian Langebaan Formation and therefore has been assigned to the Late Pleistocene Langebaan Formation (Pether et al., 2000).

Phosphatic rocks are also exposed at the Bomgat Cave on Hoedjiespunt Peninsula (Fig. 6.1), which has been previously referred to as the Saldanha Formation (Tankard, 1975). The age of the Bomgat phosphatic deposit has been suggested to be Miocene (Tankard, 1975). Based on the presence of abundant echinoderm spines, Dale and McMillan (1999) suggest a Late Pliocene/Early Pleistocene age (the 50 m Package of Pether, 1994) for deposition of the basal layer of the phosphorites (Fig. 6.3). The overlying shelly limestone is marked by a basal unit with numerous shells and shell fragments that Pether (cited in Dale and McMillan, 1999) using molluscan biostratigraphy identified as well oxygenated turbulent depositional environment. Forammininferal biostratigraphy allocates this deposit to the 8-10 m Package of Pether (1994) and therefore a Late Pleistocene age (Dale and McMillan, 1999).

6.3 METHODS

Rock samples and shells were collected from the Varswater Formation in the Langebaanweg Quarry and in the Bomgat Cave. Rock composition was determined by XRD, petrography and optical microscopy work. Fossils were identified to species level by reference to the recent fauna (Dale and McMillan, 1999) as well as to work from Tankard (1976). Samples were dissolved at room temperature in twice-distilled 5 M glacial acetic acid for Sr isotope analyses. Sr isotope ratios were measured at UCT on a VG Instruments mass spectrometer with mass fractionation normalised to a $^{86}Sr/^{88}Sr$ ratio of 0.1194 and to a Standard Reference Material 987 $^{87}Sr/^{86}Sr$ ratio of 0.71022. Within-run precision on single measurements is $\pm 1 \times 10^{-5}$ (2σ error), whereas sample reproducibility is approximately $\pm 4.5 \times 10^{-5}$. The ages proposed in Table 1 have been obtained by the use of the look-up table proposed by Howarth and McArthur (1997) as described in Chapter 2 as well as Chapter 5.

6.4 STRATIGRAPHY OF THE VARSWATER FORMATION

The Varswater Formation is well developed in the Langebaan phosphatic quarry and based on field and subsequent laboratory work, three units may be distinguished:

Gravel Member

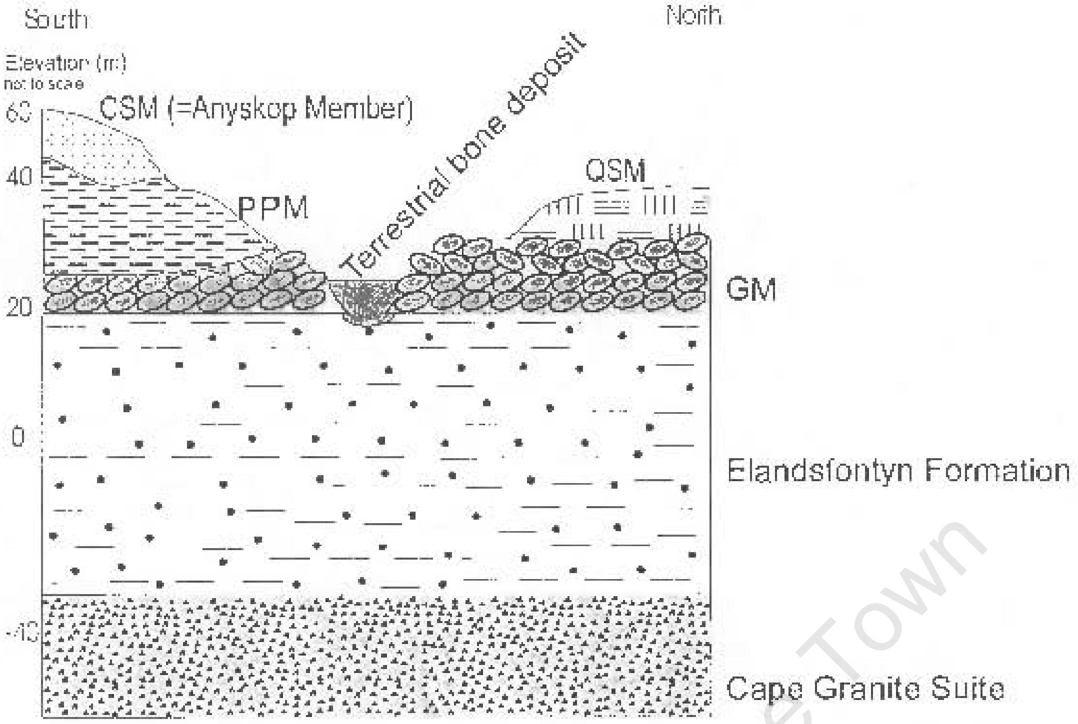
The Gravel Member is formed of well rounded pebble-size phosphorite, with rare mollusca shell casts. The presence of marine fossils such as shark's

Sample	Material	$^{87}Sr/^{86}Sr$	Age (Ma)[1]
Langebaanweg QTZ	*Ostrea* sp. fragment	0.708991	8.8-4.9
Langebaanweg PPM	seal fragment	0.709331	>sea water
Langebaanweg PPM	phosphorite	0.709133	2.5-0
Langebaanweg GM	phosphorite	no run (2)	
Bomgat	phosphorite	0.709123	3.6-0.0
Bomgat	phosphorite	0.709082	5.5-1.1
Bomgat	*Perna perna*	0.709083	5.5-1.1

[1] Ages from Howarth and McArthur (1997).

Table 1. Strontium isotope analyses.

teeth and sea shells (often broken and not well preserved) suggests a marine environment. No foraminifera were found in the Gravel Member. Two samples of phosphorite had insufficient strontium in the samples to be analysed with the VG Instrument.



CSM: Calcareous Sand Member (Langebaan Formation)
QSM: Quartzose Sand Member (Varswater Formation) Sr isotope 4.9-8.8 Ma
PPM: Pelletal Phosphorite Member (Varswater Formation) Sr isotope 0-2.5 Ma
GM: Gravel Member (Varswater Formation) no Sr

Fig. 6.2 Idealised stratigraphical column at Langebaanweg with the age of the sediments proposed by the Sr isotope.

Pelletal Phosphorite Member

The Pelletal Phosphorite Member is composed of fine to medium phosphatic quartzose sand with occasionally clay and lignite clumps (Dingle et al., 1983). A shallow marine environment with upwelling and phosphorite production has been proposed (Tankard and Rogers, 1978; Dingle et al., 1983, Rogers and Bremner, 1991). Selected phosphatic shell fragments give a Sr derived age of latest Pliocene to present (Table 1; Fig. 6.2). A seal bone (Haarhoff, pers. comm., 2001) fragment has a Sr isotope ratio greater than sea water and suggests that the bone has been recrystallized in ground water (Table 1). Rare phosphatized foraminifera tests have been found in this member but species identification is impossible because phosphogenesis has heavily transformed the external structure of the foraminiferal test.

Quartzose Sand Member

The Quartzose Sand Member is composed of medium to coarse quartz sand with minor amounts of phosphorite. Occasionally lignitic clays are present (Rogers, 1980; Dingle et al., 1983) and several fossil remains have been found including tortoises (*Cheresina* spp.), rhinoceroses (*Ceratotherium praecos*), seals (*Homiphoca capensis*), giraffids (*Sivatherium hendeyi*) and pigs (*Nyanzachoerus* spp.). Foraminifera tests have not been found and this may be due to rainwater leaching out the calcite from the sand. Strontium age dating of an *Ostrea* sp. fragment collected from an excavation site in the Saldanha area (P. Harhoff, pers. comm., 2001) yields a Late Miocene-Pliocene age (Table 1; Fig. 6.2).

Bomgat Cave deposit

Further investigation into the age of the phospatic rock of the Saldanha Bay region was done, analysing samples collected in the basal part of the Bomgat Cave. The basal phosphatic rock at Bomgat Cave is composed of 3 cm of resinous brown CFA overlaid by 12 cm of carbonate shelly sand (Fig. 6.3). A fragment of the resinous CFA yields an age ranging from Early Pliocene to present (Table 1; Fig. 6.3). Above the carbonate sand there is a layer of shelly sand in which the shells are replaced by CFA (Fig. 6.2). A coquina bed 5 cm thick with *Patella* spp., *Balanus* sp., *Perna perna* indicative of intertidal conditions is found just above the shelly sand (Fig. 6.3). Phosphorite collected in this unit yields an age of latest Miocene-Early Pleistocene (Table 1; Fig. 6.3). An 80 cm thick layer, with several large granite boulders and large shells (*Perna perna*, *Patella* spp.), covers the section. A *Perna perna* shell yields an age of latest Miocene-Early Pleistocene (Table 1; Fig. 6.3).

6.5 AGE OF ONSHORE PHOSPHORITE DEPOSITS

The age of phosphatic rocks has always been considered problematic because phosphorite deposits are often non-fossiliferous or if they contain fossils these are very poorly preserved. In addition to these problems, often phosphorites are too well lithified to extract microfossils and species identification in thin section is recognised to be less accurate than identification of loose specimens. Therefore, biostratigraphy may not often be applied to these rocks, creating scientific controversy on the age and depositional environments of these phosphatic deposits. Onshore phosphorites of the Saldanha Bay area have been considered Miocene in age (Tankard, 1976) and phosphorite rocks from the South African continental margin have been suggested to be Miocene/Pliocene in age (Siesser, 1978). Therefore, deposits with phosphorites or phosphorite grains in the area have been previously attributed to the Miocene/Pliocene. All these age dates are based on the poorly preserved fossils preserved inside these deposits.

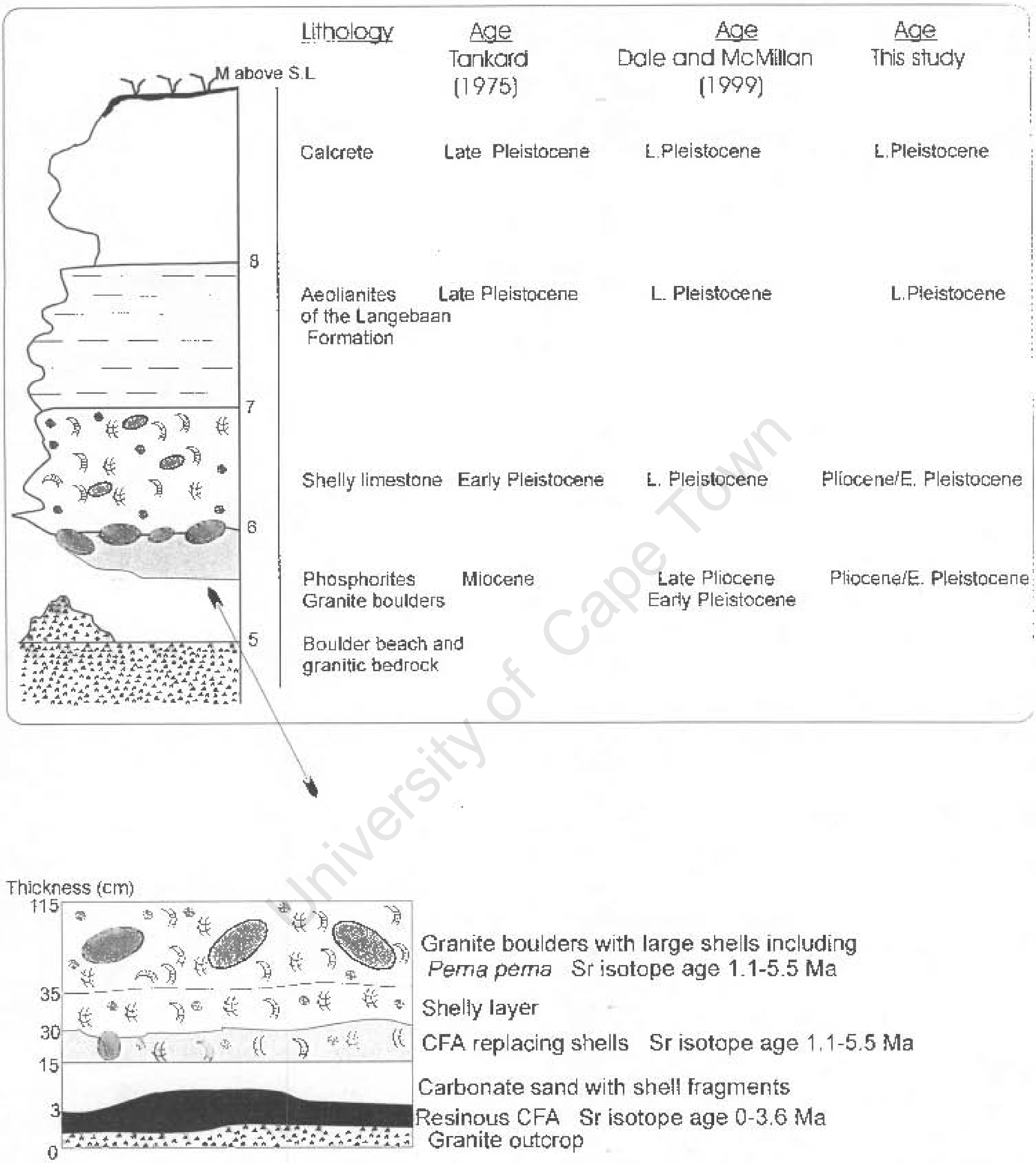


Fig. 6.3. Idealised stratigraphical column at Bomgat cave with the age of sediment proposed by Tankard (1975), Dale and McMilian (1999) and the $^{87}Sr/^{86}Sr$ data obtained for the Gravel Member (ex Saldanha Formation) at the Bomgat Cave.

Strontium derived ages have been provided by Lavelle (in Dale and McMillan, 1999) for two sites: a phosphatised mollusc fragment from the Pelletal Phosphorite Member from the Langebaan Quarry with an age of 1.2 Ma and a fragment of *Perna perna* from the Bomgat Cave yielding an age ranging from 5.2 to 2.4 Ma. Early Miocene to Quaternary phosphorite pebbles from the shelf off the Orange River have been dated using the ratio $^{87}Sr/^{86}Sr$ (Compton et al., 2002). These phosphorite grains show very complex formation histories and multiple phosphogenesis episodes (Compton et al., 2002). Offshore Cape Columbine phosphorites have Sr-derived ages that range from Miocene to Pleistocene (Compton, pers. comm., 2001).

The age of the Varswater Formation has been controversial and this initial study highlights that Sr isotope ages are only partly able to sort out the age of the deposit and that reworking of the fossiliferous deposit has occurred. Two samples have been run for the Gravel Member in the Langebaanweg Quarry but in both cases, the amount of strontium inside the phosphorite was insufficient to run on the mass spectrometer. The unusually low Sr content of the phosphorite may indicate that the Gravel Member has been recrystallised after deposition by groundwaters. This interpretation is consistent with the Gravel Member being cut by fluvial deposits containing terrestrial fossils of Miocene-Pliocene age (Hendey, 1981a; Dingle et al., 1983). The recovery of teeth of the horse *Hipporpion primigenium* from the Gravel Member in the Langebaanweg Quarry indicates a post-Middle Miocene age (Hendey, 1981a; Dingle et al., 1983). Although not directly dated with SIS, the age of this member may be inferred considering that the overlying Quartzose Sand

Member has been dated with Sr isotopes as Late Miocene - Early Pliocene. Therefore, the age of the Gravel Member is likely to be Middle to Late Miocene. The underlying Elandsfontyn Formation is also considered to be Middle to Late Miocene or older (Coetzee and Rogers, 1982; Dale and McMillan, 1999).

The rich Pliocene fauna found at the Langebaanweg Quarry (Hendey, 1980) has been mostly recovered from the Pelletal Phosphorite Member and the Quartzose Sand Member. The Quartzose Sand Member appears, on the basis of only one shell fragment, to be Late Miocene-Early Pliocene in age while the Pelletal Phosphorite Member appears to be latest Pliocene to Pleistocene in age (Table 1). The vertebrate fossils in the Quartzose Sand Member have been regarded as early Pliocene in age (Hendey, 1981a,b; Dingle et al., 1983) and this is confirmed by the age obtained with Sr isotope analysis (Table 1). The foraminiferal assemblages extracted from the Pelletal Phosphorite Member (Dale and McMillan, 1999) have been regarded as Early Pleistocene in age and this view is also confirmed by the SIS data (Table 1).

At the Bomgat Cave the shelly bed and the overlying layer contain wave-generated granite boulders that are associated with abundant shell debris and the mussel shell *Perna perna* (Fig. 6.3). The environment of deposition is a high-energy beach. The calcareous material in these deposits is 98 weight percent and the depositional environment was similar to present day coastlines near the cave with granitic outcrops and shell-rich beaches. The ages of the section exposed at the Bomgat cave suggest that deposition and phosphogenesis have occurred since the Pliocene-Early Pleistocene (overlapping range 3.6-1.1 Ma; Table 1). There are several differences between the phosphorite exposed at the Bomgat Cave and at the Langebaanweg Quarry that indicate that these two deposits have not been deposited under the some conditions:

1) The Bomgat Cave exposure is 5 to 6 m above msl, while the Gravel Member at the Langebaanweg Quarry is 20-25 m above msl;
2) The phosphorite at the Bomgat Cave is deposited directly on top of the Cape Granite Suite, while the Gravel Member at the Langebaanweg Quarry is deposited on the Elandsfontyn Formation;
3) The phosphorite at the Bomgat Cave is composed of a resinous CFA, brown to dark yellow in colour, while the Gravel Member of the Langebaanweg Quarry consists of phosphatic gravel, including casts of older phosphatic rock (Pether et al., 2000).
4) The phosphorites of the Gravel Member at the Langebaanweg quarry lack in strontium, while no signs of ricrystallisation were indicated by the phosphorites exposed at the Bomgat Cave.

At present, no evidence is available to support the hypothesis that the two deposits belong to the same member.

6.6 SEA-LEVEL CHANGES

Phosphorite is a common indicator of marine condensed sections, usually interpreted as a marker of slow deposition that forms during sea-level rise and highstands (Föllmi et al., 1992). The formation of phosphorites required elevated ion concentration of phosphorus that may result from degradation of organic matter in areas of upwelling (Bentor, 1980; Baturin, 2000). Therefore, phosphorites provide a good proxy for determination of organic-rich deposition on the stranded shoreline. The reconstruction of the evolution of the Hoedjiespunt Peninsula (Fig. 6.1) can be presented in 4 stages based on the Sr ages. During Stage 1 the area was a rocky shoreline with deposition of phosphorite directly on the granite outcrop. Strong waves and episodically high-energy events reworked and abraded the shelly bed (Stage 2). The water temperature was similar to the present day one as recorded by the shell assemblages (*Perna perna*, *Patella* spp.). During the latest Pliocene-Early Pleistocene a marine transgression covered the coastal area of the peninsula creating shallow protected environments in which phosphorite formed by replacing carbonate sand and shells (Stage 3). During Stage 4 (Late Pleistocene) a sea-level regression developed coastal dunes and calcrete formed during subaereal exposure.

In the Langebaanweg area the reconstruction of the palaeoshoreline can be done assuming that no tectonic uplift has occurred since the time of deposition. Langebaanweg (Fig. 6.1) lies in a flat area with two small hills just to the north-west and to the south-east of the Quarry. Hendey (1982) proposed a shoreline with a rise in sea-level of 20-25 m above the present (Fig. 6.4) in which the Pelletal Phosphorite Member and Quartzose Sand Member were laid down. In his reconstruction Langebaanweg was in a coastal area with a large offshore island in the Saldanha-Vredenburg area with the proto-Berg river discharging in a relatively shallow channel (Fig. 6.5). The same reconstruction has been done with the GIS system using Arcview 3.2 and the present-day elevation data supplied by the Survey and Mapping office in Cape Town.

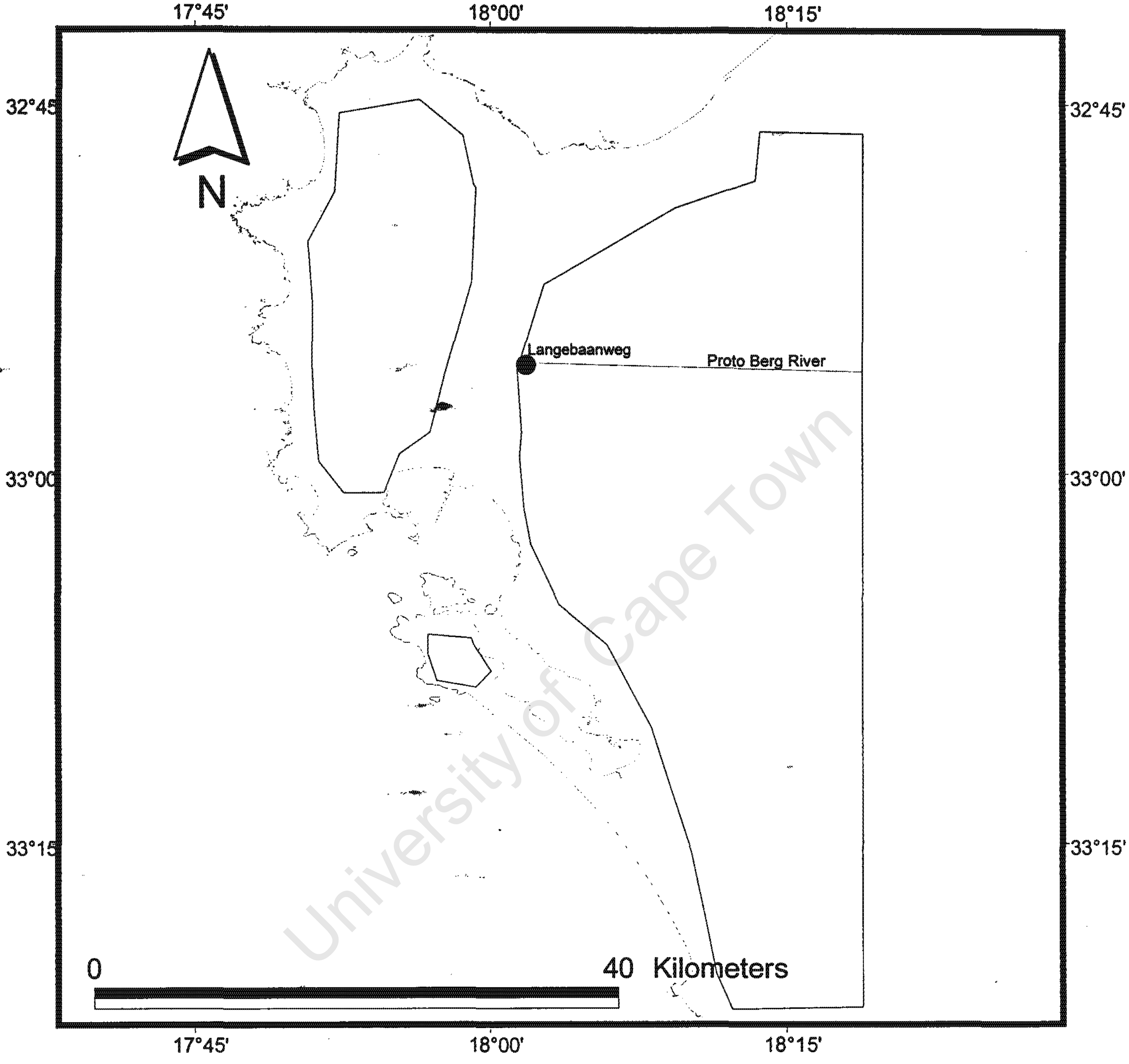


Fig. 6.4. Shoreline and course of the Proto Berg river proposed by Hendey (1982) at the time when the QSM and the PPM were laid down.

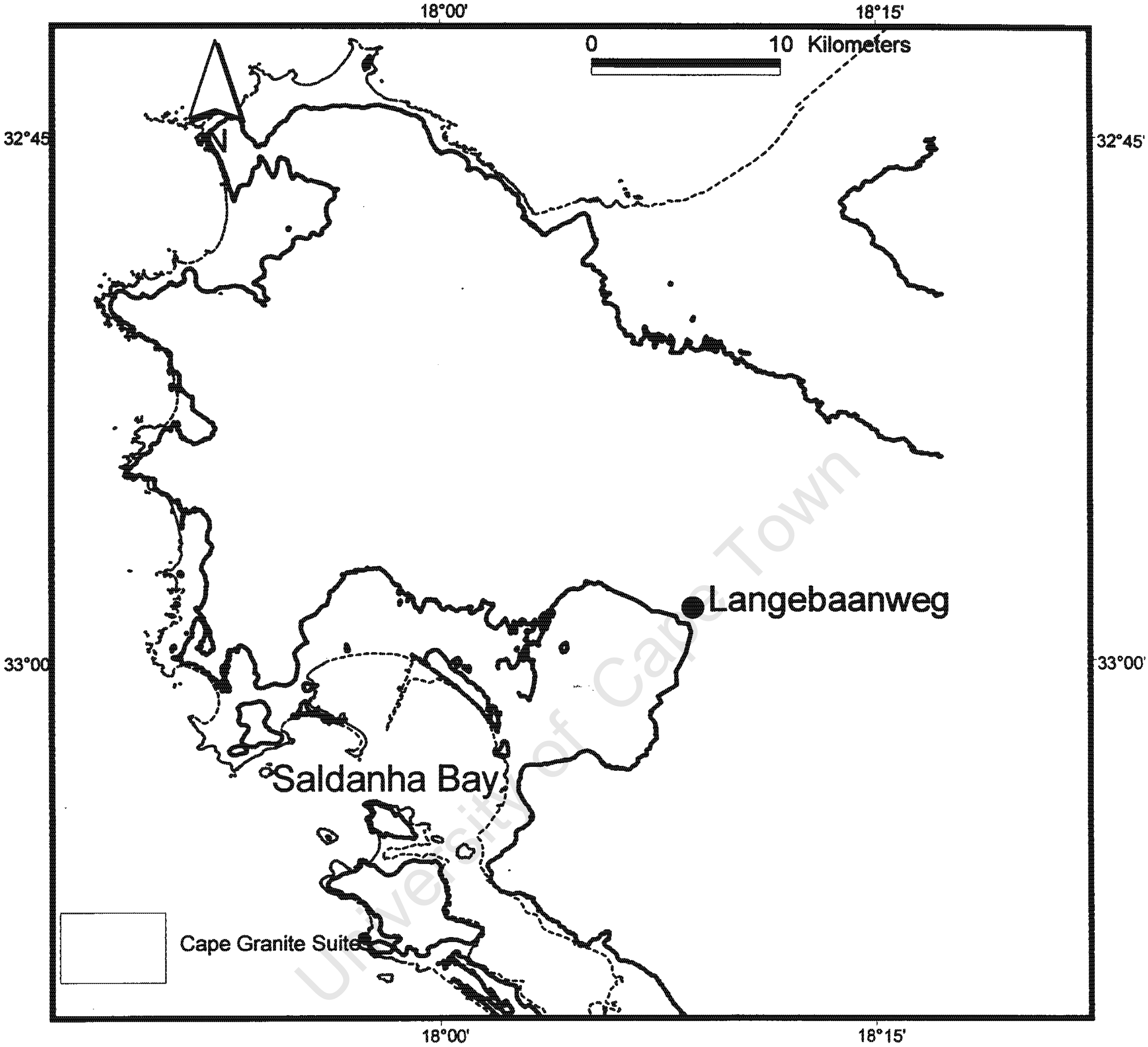


Fig. 6.5. Reconstruction of the palaeoshoreline in a case of sea-level rise of 20-25 m.

Accurate granite position has been recorded in several field trips using a manual GPS (Garmin). The position of the coastline in the case of a 20-25 m sea-level rise shows that Langebaanweg was situated on the coastline (Fig. 6.5). In the case of a 20-25 m sea-level rise the position of the coastline was similar to the present day except that Saldanha Bay was larger. In the case of a sea-level rise of 35-40 m, Langebaanweg was in a shallow marine channel (Fig. 6.6). On the basis of the palaeo sea-level reconstruction obtained from samples from the exposure at Langebaanweg Quarry, a sea-level highstand of 35-40 m is likely to have occurred during the Middle-Late Miocene, at the time of deposition of the Gravel Member and of the Quartzose Sand Member. A sea-level highstand of 20-25 m during the Early Pleistocene deposited the Pelletal Phosphorite Member and is confirmed by the +24 m highstand that deposited the gravel shelly layer in the basal part of Section A of the Tabakbaai Quarry (Chapter 5).

6.7 CONCLUSIONS

Several conclusions can be inferred from the study of the onshore phosphorite deposits of the Saldanha Bay area:

1) The lack of fossils and the lack of Sr in some of the phosphorites make age dating of these deposits extremely difficult and will require additional work. Strontium isotope stratigraphy can be used on deposits for understanding the age of phosphogenesis. In this study the use of Sr isotopes has been partially successful and in the case of the Gravel Member the low quantities of Sr present prevent any age determination.

2) The phosphatic rocks exposed at the Langebaanweg Quarry and at the Bomgat Cave are different in lithology, age and elevation above msl.

3) Two episodes of phosphogenesis have occurred at Langebaanweg Quarry: the first during the latest Pliocene and the second during the Early Pleistocene.

4) A sea level rise of 35-40 m was responsible of the deposition of the Gravel Member and the Quartzose Sand Member, best exposed in the Langebaanweg Quarry. This highstand occurred during the Middle-Late Miocene.

5) A sea level highstand of 20-25 m during the Early Pleistocene deposited the Pelletal Phosphorite Member.

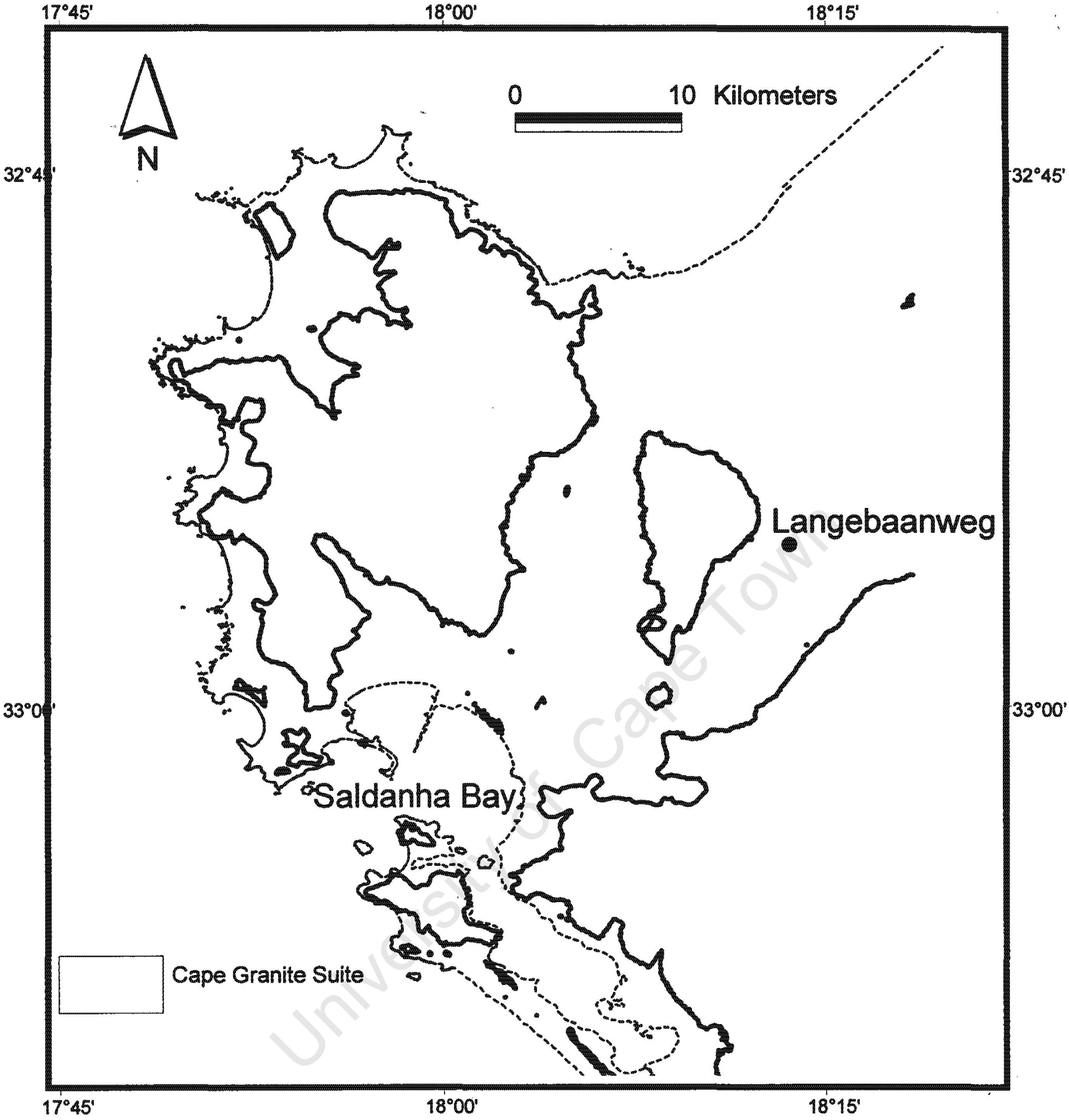


Fig. 6.6. Reconstruction of the palaeoshoreline in a case of sea-level rise of 40 m.

Chapter 7

Coastal evolution of the Western Cape

7.1 SUMMARY OF MODERN AND ANCIENT COASTAL ENVIRONMNETS OF THE WESTERN CAPE

The coastal area of the west coast of South Africa has preserved important Late Cainozoic deposits, and complex interaction between marine and non-marine processes has carved this area into its present-day shape. The understanding of sea-level fluctuations in the southern part of the west coast has been the focus of this work. Selected onshore localities ranging from lagoonal to aeolian marine have been analysed in detail and approached in a multidisciplinary way. The major conclusions of this multidisciplinary work are summarised here following the same order of the thesis.

7.1.1 LAGOONAL ENVIRONMENTS

Employing foraminiferal analysis to determine local sea-level changes requires an understanding of their contemporary distributions and relationships with environmental variables. Identification of the patterns of contemporary foraminiferal distribution in salt marshes or lagoonal areas in general, has not been previously studied in southern Africa. Microfossil assemblages were studied to determine the effect of sea-level change in the southern Langebaan Lagoon salt marshes and in fossilised lagoonal deposits in Monwabisi (Chapter 3). A transect sampled across the southwestern edge of the Langebaan Lagoon from the tidal channel to the high marsh (Fig. 3.2) shows interesting information on foraminiferal distribution. The high supratidal salt marsh is dominated by the agglutinated foraminifera *Trochammina inflata*; the middle salt marsh consists of a mixture of *Trochammina inflata* and *Jadammina macrescens* and the tidal channel-flat is dominated by the calcareous species *Ammonia japonica, Ammonia parkinsoniana, Ammonia* sp., *Elphidium articulatum*, *Elphidium* sp. A and *Quinqueloculina* sp. The foraminiferal zonation shows a strong relationship to elevation, which has important implications for establishing records of relative sea-level change. The studied area in the Langebaan Lagoon can be subdivided into three zones based on different foraminifera assemblages. Zone I is dominated by calcareous species, Zone II by agglutinated foraminifera, and Zone III by a monospecific agglutinated assemblage.

The Monwabisi section (Fig. 3.4) is characterised by a sandy cliff. Several stratigraphic layers were defined based on grain size, colour and fossil content (Chapter 3). The basal part of the succession is composed of three well developed calcrete layers with marine and non-marine deposits on top (Fig. 3.4).

7.1.2 AGE OF THE LAGOONAL ENVIRONMENTS

The age of the Monwabisi section has been inferred from Late Pleistocene foraminiferal biostratigraphy using as reference the work of McMillan (1987, 1990) and Dale and McMillan (1999). The presence of three well developed calcrete layers at the base of the succession may date back the deposit to OIS stage 11.

7.1.3 COASTAL DUNE ENVIRONMENTS

Reworking and reshaping of the pre-existing coastal dunes has taken place during the Late Cainozoic as a result of sea-level fluctuations. Some of the older dune deposits would have eroded and remobilised during subsequent changes in the shoreline position creating generations of dunes superimposed on one another. Interpretation of the evolution of the coastline is aided by the understanding of the factors that affect the present-day development of coastal dunes. In the following section the processes controlling the development of coastal dunes in the Saldanha Bay area will be considered.

Geology

Geological factors influencing the coastal landforms are related to the different lithologies that outcrop in the coast or nearshore zone. In the Saldanha Bay-Cape Columbine area (Fig. 1.2) the bedrock geology is composed partly of the metasediments of the Malmesbury Group and mostly of the intrusive rocks of the Cape Granite Suite (Theron et al., 1992). Along the coastline only the Cape Granite outcrops, and this is related to the easy erodibility of the shales of the Malmesbury Group. The outcropping of the granites along the coast influences the deposition of sand in the coastal area in two ways: creating a source of terrigenous and biogenic sediment, and producing headlands for log-spiral beaches and lagoons development.

Sand supply and longshore drift

Abundant sand supply is a necessity for dune development. The majority of the sand in the Western Cape is provided by longshore drift which moves sand northwards. The grain-size mineralogy of the beach sands along the Western Cape have shown that Saldanha Bay acts as a boundary to longshore drift of terrigenous material. Between Cape Town and Saldanha Bay the beaches are composed of a decreasing amount of quartz ranging from 65 to 45 wt% (Chapters 4, 5). North of Saldanha Bay until the Berg River mouth, the quartz fraction of the beaches is less than 10 wt% (Chapter 5). The carbonate-rich deposits have been, and remain actively mined as agricultural and feed lime.

Wind

Wind is of particular importance in the coastal evolution of the Western Cape. The west coast of southern Africa has been considered by Tinley (1985) as one of the windiest areas in the world and, therefore, susceptible to dune development. The prevailing winds in the study area are from the south-south west, and wind speeds of 20-40 km/h are attained for 25% of the year (Chapter 4). Seasonal variations in the wind direction (winter winds blow from the north-northeast) result in a different sand transport along the shore from south to north in summer and from north to south in winter. However, the summer winds are much stronger than the winter winds, and the general net transport is to the north (Swart and Flemming, 1980). The south-south west wind direction is parallel to the axes of the coastal dune plumes of the region (Chapters 4, 5). Since the axis of the latest Miocene-Pliocene dune plume is also parallel to the direction of the onshore winds, it is suggested that the winds creating the coastal dunes in the area have been fairly constant in direction since at least the latest Miocene (Chapter 5).

Morphology of the beach

Steepness of Sixteen Mile Beach increases to the north (Chapter 4). The position of the active Yzerfontein-Geelbek dunefield (Fig. 4.2), in the southern part of the Sixteen Mile beach complex is related to the position of Dassen Island that create a low-energy beach environment in the southern part characterised by fine sand size material. The medium to coarse sand found from 6 km north of Gabbro Point (Fig. 4. 6) is the reason for the lack of coastal active dune plumes behind the northern part of Sixteen Mile Beach (Chapter 4). In this area coast-parallel dunes are well developed (Fig. 1.5) and they have formed as a regressive sand wedge that has prograded seaward since sea-level peaked at an estimated +1 to +3 m above msl during the Mid-Holocene highstand (Chapter 4).

Climate and vegetation

The climate in the Western Cape is semi-arid with an increase in the aridity northwards. Change in climate, particularly in rainfall, has a direct impact on vegetation. In the Yzerfontain-Geelbek dune plume, the active dunefield which is located 13 to 14 km from the beach, became completely vegetated between 1938 and 1993, and the Geelbek dune field receded during the same period (Fig. 4.17). This increase in vegetation corresponds to an increase in annual rainfall in the area over the corresponding period, considering that because of the semi-aridity of the area, cattle farming has always been limited (Chapter 4).

7.1.4 AGE OF COASTAL DUNE DEPOSITS

In the Saldanha Bay area three formations are characterised by aeolian deposits: the Prospect Hill Formation, the Langebaan Formation and the Witzand Formation. The Prospect Hill Formation, which is best exposed in the Tabakbaai area (Fig. 5.1), is the oldest dune deposit in the area. It forms a 20 km long fossilised dune plume (Fig. 1.2). Carbonate shell fragments, foraminiferal tests, echinoderm spines, and barnacle plates make up the great majority of the sand. The rest (less then 10 %) is composed of well-rounded quartz (Fig. 5.6). The coastal dunes of the Prospect Hill Formation are up to 70 m in thickness, and are deposited directly on top of latest Miocene–Pliocene marine units. Foraminiferal biostratigraphy has been used to interpret the depositional environments of the marine units. The presence of species such as *Pararotalia nipponica*, *Glabratella australensis*, *Haynesina* sp., *Rosalina diazvillea* suggests a beach-inner shelf depositional environment. On top of these marine units, just behind the original beach, a 20 km long dune plume developed and post-deposition terrestrial weathering occurred extensively (Chapter 5).

The age of the Prospect Hill Formation was proposed to be Middle Miocene on the basis of the recovery of an extinct ostrich egg-shell (Pether et al., 2000; Roberts and Brink, 2003). Strontium isotope stratigraphy has been performed on samples from the Prospect Hill Formation (Table 2, Chapter 5) and yielded ages of latest Miocene to Pliocene. A reconstruction of the palaeoshoreline in the Saldanha Bay area (Fig. 5.6) has proved that coastal progradation was dominant in the area up until the latest Miocene, when sea-level was 25 m amsl. A progressive fall in the shoreline position since the latest Miocene has allowed terrestrial deposition of aeolian deposits. These dune deposits lie at an altitude ranging from 25 to 100 m (Fig. 5.2).

The Langebaan Formation and the Witzand Formation were deposited during the Late Pleistocene and Holocene, respectively. The Langebaan Formation has been regarded as the product of onshore sand deflation during oxygen isotope stage 5 (a-d). It has not been directly studied in this thesis, but reworking of old dunes has occurred in the southern part of the Sixteen Mile Beach complex (Chapter 4).

Active, partially vegetated Holocene dunes forming the Witzand Formation constitute excellent modern analogues of earlier formations. Holocene dune sands are white-beige in colour and composed of quartz and carbonate grains. Two major morphological Holocene dune types exist in the Western Cape.

a) The first category is formed by a transgressive dune plume, which develops adjacent to sandy beaches. The Yzerfontein-Geelbek dune plume, in the southern part of the Sixteen Mile Beach complex, is a 24 km long inland sand plume with mobile and immobile dunes. The dune plume is composed of very well sorted fine sand. The $CaCO_3$ content of the active dune plume decreases from 45% to 3% at 24 km inland. The age of the dune plume (Table 1, Chapter 4) was obtained by radiocarbon dating of sand-sized shell fragments. The active dune plume is 4,500 years old at 24 km inland, suggesting that the dune plume was initiated after sea-level returned to its present-day position.

b) The second dune category comprises a coast-parallel dune system. Dunes up to 15 m high migrated over the Late Pleistocene dune cordon at the northern end of Sixteen Mile Beach reaching Langebaan Lagoon at Kraalbaai (Figs. 4.2 and 4.8). Coast-parallel dunes are made up of a mixture of fine and medium sand, with an increase in the fine sand fraction downwind (Fig. 4.9). Coastal dunes consist of a non-vegetated, wind deflated shell layer (composed largely of *Donax serra* and *Choromytilus meridionalis*), vegetated dunes and parabolic ridges. Coast-parallel dunes are also primarily composed of quartz and shell fragments ($CaCO_3$ content ranges from 35 and 65 wt%, Table 3, Chapter 4). Coast-parallel dunes formed since the mid-Holocene 6 ka (Chapter 4).

7.1.5 MARINE AND ESTUARINE ENVIRONMENTS

Besides the basal section of the Tabakbaai Quarry (Chapter 5), marine and estuarine environments of the Varswater Formation characterised by phosphatic rocks have been studied in this thesis (Chapter 6). The Varswater Formation is divided into the Gravel Member, a Pelletal Phosphorite Member and a Quartzose Sand Member (Fig. 6.3). The Gravel Member is composed of phosphorite grains and shell casts. The Pelletal Phosphorite Member is formed of fine to medium phosphatic quartzose sand. The Quartzose Sand Member is composed of medium to coarse quartz sand with phophorite grains (Chapter 6). Phosphatic rocks are also present at the Bomgat Cave (Fig. 6.2).

7.1.6 AGE OF MARINE DEPOSITS

The age of the Varswater Formation is controversial in the literature. Onshore phosphorites of the Saldanha Bay area have been considered Miocene in age (Tankard, 1975 a, 1976b). Micropalaeontology work (Dale and McMillan, 1999) has suggested an Early Pleistocene age for this formation. Sr-isotope stratigraphy suggests that the Quartzose Sand Member was deposited during the latest Miocene-Pliocene. A sea level highstand of 20-25 m during the Early Pleistocene deposited the Pelletal Phosphorite Member. The exposure at the Bomgat Cave yields an overlapping Sr age of latest Pliocene-Early Pleistocene, and it is suggested that the Bomgat Cave deposit formed in a different environment as well as age than the Gravel Member of the Langebaanweg Quarry (Chapter 6).

7.2 A PROPOSED MODEL OF COASTAL EVOLUTION IN THE WESTERN CAPE

7.2.1 INTRODUCTION, OBJECTIVES AND APPROACH

Geological, morphological and palaeontological information concerning the coastal evolution of the Western Cape Province has been documented in this thesis and briefly summarised in the first part of this chapter. These data, collected in different locations, offer unique and detailed windows into the history of the development of high and low energy coastal areas. The sediments preserved in these windows date back to the Late Cainozoic and provide information on sea-level fluctuations, climate and vegetation changes and rate of sediment supply over time. Previous studies of the coastal evolution of the Western Cape and the geological information covering this area have yielded conflicting ages and depositional environments for deposits on the west coast (Chapter 2). An understanding of modern coastal processes will help to elucidate older depositional environments as well as future geological evolution of the area. For this reason the modern environments were monitored, dated, analysed for grain size and grain texture. A model of coastal geomorphological evolution for the Western Cape has important scientific implications and will allow for a better definition of the Late Cainozoic sea-level fluctuations. It will also allow for a description of past and present depositional environments in high and low energy areas. It also has important applications to mineral exploration and coastal engineering. Mineral exploration is currently active along the west coast of southern Africa (Corbett and Burell, 2001). Diamond mining concessions and exploration licenses extend as far south as Cape Columbine (Fig. 1.2). The understanding of the high-energy environments, specifically the surf zone and the coarse sand-pebble distribution along the coastline, is of vital importance for these commercial companies, as these environments include diamondiferous placer deposits. Environmental and engineering studies are also underway in the Saldanha-Langebaan area because of the severe beach erosion that takes place in Langebaan North, damaging private and public properties. Progressive erosion has occurred in the area and more than 100 m of beach has been lost since 1960 (Common Ground Consulting, 2001).

The objective of the proposed model is to reconstruct the coastal evolution of the Western Cape. This was done by revealing the driving forces of coastal evolution and their effects on sediment distribution and deposition. The great complexity of these environments has been well documented in the study of the Sixteen Mile Beach complex, in which the reworking of different generations of coastal dunes has been elucidated. The model also provides new insights regarding geological evolution of coastal environments in southern Africa and a framework for future research and mining.

7.2.2 MODERN AND HOLOCENE ENVIRONMENTS

The modern environments studied in the Western Cape comprise high to medium energy environments, such as coastline and coastal dunes (Sixteen Mile Beach complex) that are directly exposed to the forces of the Atlantic Ocean. Low-energy environments in the present study comprise the Langebaan Lagoon primarily influenced by tidal forces.

High-energy environments

Here sediment sources may be considered as inputs to the littoral system and can be provided by a number of mechanisms. Sediment sources are vital to the sustainability of sediment circulation and can be primarily derived form eroding cliffs, longshore and onshore transport, marine and dune erosion and fluvial input (Cooper et al., 2001). Terrigenous sand supply to the Western Cape coast is provided by the two perennial rivers namely the Diep River and the Berg River. The Diep River discharges in the greater Cape Town area (Fig. 4.2) and the Berg River discharges near Velddrif (Fig. 1.2). Along the Western Cape coastline annual precipitation is 600 mm in Cape Town and rarely exceeds 300 mm in Langebaanweg (SA Weather Bureau, pers. comm., 1998). Beach sediments in the Western Cape are therefore derived from sand delivered by longshore drift from the south. The sand transported northward has been estimated to be 0.2 million m3/y with a drift velocity of 100 m/y (Swart and Flemming, 1980). In general, sediment distribution is a function of the energy levels on the seabed, which in turn are directly related to the orbital velocities generated by the prevailing wave regime (Bird, 1972). Coarse sediments occur in areas of high energies whereas fine sediments will accumulate in areas of lower energy. From grain size analyses (Fig. 4.6) of the sediment distributed along Sixteen Mile Beach, the distribution trends of the size fraction outline the energy controlled sediment dispersal regime. Along Sixteen Mile Beach the lowest energies are found in the southern part where fine sand is dominant due to the protection created by the Dassen Island-Yzerfontein headland. The central and northern part of Sixteen Mile Beach experience the highest energies and are subsequently composed of medium to coarse material (Fig. 4.6). This relatively sharp transition between fine to coarse sediment marks a definite depth-controlled energy threshold that creates a size sorting mechanism as well as an increase in the steepness of the beach face and backshore, northwards (Fig. 4.4). The northward increase in grain size is not related to a substantial increase in shell material (Fig. 4.5), as recorded in the northwestern beaches of Nordemey Island (North Sea) (Eitner, 1996). Therefore, the existence of a size sorting mechanism is suggested. Corbett (1989) recorded a similar situation along log-spiral beaches in southern Namibia (Sperrgebiet -Diamond restricted area- located 700 km north of Saldanha Bay). Here, the protection from direct wave approach due to the shape of the log-spiral beaches, reduces the wave energy and wave heights allowing a flat beach profile in the southern part and, substantial deposition of fine sand (Corbett, 1989). The northward coarsening of sediment along spiral beaches is well known to the diamond divers that operate along the west cost of southern Africa. Although very few data have been published, the richest diamond deposits along beach/surf zone are located in the northern part of these beaches (Apollus et al., 2002; G. Davies, pers. comm., 2003).

The mineralogy of the fine, medium and coarse sand along Sixteen Mile Beach is almost sub-equally composed of a terrigenous quartz population and a biogenic carbonate population (Fig. 4.5). The carbonate component of the beach sand is slightly higher (up to 55 wt%) in the central and northern part, due to its proximity to rocky coastlines with a high production and fragmentation of shelly molluscs (Fig. 4.2). Studies have shown that Saldanha Bay may also be divided into two hydraulic energy zones, with the coarsest material found along the northern outer shores of the bay where the energy is highest. Fine sand material is found in protected areas in the southern part of the bay (Flemming, 1977; de la Cruz, 1978). The coarser material found in the northern outer shores of Saldanha Bay is mainly composed of large shell material. The rocky areas present are the main source of this biogenic component of the sediments (Flemming, 1977). Carbonate material is on average higher in Saldanha Bay than in the Langebaan Lagoon (Willis et al., 1977). Between Saldanha Bay and Velddrif the beach sand is carbonate-rich (up to 83 wt%) and in St. Helena Bay, just north of the Berg River mouth, the beaches are quartz-rich with up to 96 wt% quartz sand (R. Wigley, pers. comm., 2001). The difference in beach sand mineralogy is complex to explain. The following explanations are suggested:

1- The increase in $CaCO_3$ between Saldanha Bay and the Berg River mouth is related to a higher $CaCO_3$ biomass production. A comparative study of surface sediments has shown that the present-day biomass production of carbonate is much higher in mixed rocky-sandy areas of Saldanha Bay than in the Langebaan lagoon indicating that the carbonate material forming in the bay is then transported northwards (Flemming, 1977 and de La Cruz, 1978). Longshore transport is also responsible for the northward transport of terrigenous material discharged in Velddrif by the Berg River.

2- The terrigenous component of beach sediments decreases significantly north of Saldanha Bay. Information gathered during the dredging operation whilst building of the Saldanha Bay harbour, has provided information on the sediment thickness as well sediment composition of Saldanha Bay. In general the thickness of the sediment is very limited (<2 m) and composed of a mixture of fine to coarse quartzitic sand (Du Plessis and de La Cruz, 1977). This implies two hypotheses, that the terrigenous grains are moved offshore and transported northwards along the inner shelf by longshore drift bypassing Saldanha Bay, or sand depleted from the beach is transported inland to form coastal dunes that remain trapped inland. At present there are no cores available offshore the Western Cape coast to test these two hypotheses. Furthermore, the ratio of offshore removal to shore deposition between north and south of Saldanha Bay is unquantified. However, much of the western continental shelf of South Africa lacks Quaternary sediment cover, or has only a thin veneer of sediments (Rogers, 1977; Rogers and Bremner, 1991). In contrast, the largest coastal dune deposits are found in the Western Cape (Tinley, 1985; Theron et al., 1992) supporting the theory of shore deposition and sediment retention. In this study it has been documented that much of the sand transported by longshore drift is retained onshore as dune deposits (Chapter 4).

Once the quartzose material transported by longshore drift is deposited along the south Western Cape beaches and mixes with skeletal carbonate fragments, beach deflation from strong winds move these sands to form coastal dunes. The meteorological setting of the Western Cape is characterised by strong seasonal winds from the south-south east (Cape Town) and from the south-south west (Langebaanweg). The changes in wind direction (Fig. 4.3) as well as the diminishing terrigenous sand material input to the north is responsible for the decreasing size of the dune plumes (Fig. 4.1) located respectively on the Cape Flats (243 km2), west of Atlantis (88 km2) and north of Yzerfontein (43 km2). Changes in wind direction also create changes in the axis of these dune plumes as shown in Fig. 4.1. The Yzerfontein-Geelbek dune plume extends 24 km inland in a N/NEE direction (Figs. 4.1 and 4.2). The Yzerfontein-Geelbek dune plume consists of vegetated parabolic ridges and non-vegetated active barchanoid dune fields located approximately 0 to 8, 9, to 11, 13 to 14 and 17 to 19 km from the coast (Fig. 4.2). In the northern part of the Western Cape coast, the Swartlintjies River dune plume (located 350 km north of Yzerfontein) has a similar inland reach of 24-27 km, with active dune fields located at 0-7 km, 11-14 km and 21-25 km from the coast (Tankard and Rogers, 1978). The Swartlintjies dune plume differs from the Yzerfontein-Geelbek dune plume in terms of the mineralogy of the dune sand. This is due to a greater terrigenous input from the Swartlintjies River. Grain size analyses of the dune sand of the Yzerfontein-Geelbek dune plume have shown that the sediment is well sorted and almost completely composed of fine sand with a mean grain size of 180-150 μm (Figs. 4.11 and 4.12). The calcium carbonate content of the Yzerfontein-Geelbek dune plume is similar to the calcium carbonate weigh percent of the beach up until 12 km inland. Thereafter it decreases rapidly to 3 wt% at 24 km inland (Fig. 4.10). The skeletal composition along the dune plume is mainly composed of bivalve fragments, echinoid spines and foraminiferal tests. The foraminiferal tests show increased signs of abrasion with increasing distance from the beach source (Chapter 4, Plates I to IV). The downwind decrease in carbonate content reflects dissolution of carbonate by rain combined with reworking of older Late Pleistocene low-carbonate sands. Surficial sand colour changes from white in the Holocene dunes (10 to 50 wt% carbonate grains) to yellow-brown in the Pleistocene dunes (< 1wt% carbonate grains).

The size, composition and sorting of the Yzerfontein-Geelbek dune plume sand indicates that its location is related to the fine sand distribution along Sixteen Mile Beach. As discussed above the southern part of the beach is composed of fine sand. This fine sand is windblown to form the dune plume. In the Sperrgebiet area of southern Namibia, Corbett (1989) described several "aeolian transport corridors" that are aligned parallel to the wind direction, as is the case for dune plumes of the Western Cape. The "aeolian transport corridors" are fed by beach sand either from log-spiral beaches or south facing bays (Corbett, 1989, 1993). The southern Namibia dune plumes are composed of fine to medium sand (Corbett, 1989). The dune plumes of southern Namibia are composed of coarser material than the counterparts in the Western Cape. This is due in part, to stronger unimodal southerly winds experienced in southern Namibia (average wind velocities of 50-60 km/h versus average wind speeds of 20-40 km/h at Langebaanweg) (Corbett, 1989). The south facing bays of southern Namibia that act as an entrant point for the beach sand that feeds coastal transport corridors are modern analogs of what occurred in Saldanha Bay. In fact, the latest Miocene-Early Pliocene age aeolianites of the Prospect Hill Formation have as sand source, the beaches of the northern part of the south-facing Saldanha Bay.

Comparison of aerial photographs for the Yzerfontein-Geelbek dune plume indicates that the movement of the active barchanoid dune fields is highly erratic. Surveyed individual 15 m high barchanoid dunes at Geelbek have migrated 5 m/year (Conard, unpublished report, SANparks, 2000). In southern Namibia, where the wind is stronger and gale-force winds are experienced 10% of the year, 20 m high active dunes can migrate 50 to 60 m in one year (Corbett, 1989; Rothmann, 1999). In the Alexandria dune field (Eastern Cape) the landward movement is 0.25 m/year as determined by field observation over a 5 year period. This is due to less persistent southwesterly winds with average speeds of 10-20 km/h (Illenberger, 1986).

The age of active dune fields present along southern Africa are inferred to be mostly mid to late Holocene in age and have formed since sea-level returned to the present-day level from the last glacial (Tinley, 1985). In an attempt to verify the timing of coastal dune formation in the Western Cape, radiocarbon dating was performed on calcareous coastal dunes in the Sixteen Mile Beach complex. The method used consists of dating the calcareous dune sand material and subtracting the radiocarbon age obtained for the calcareous beach sand that is the sand source for the dunes. In this way, the age when the dune sand left the shore, assuming that the age of the beach sand does not vary too much, is determined. Along Sixteen Mile Beach, six bulk sand samples were radiocarbon dated with mean ages varying from 18.4 ka in the southern part to 10.8 ka in the northern part (Fig. 4.2) The overall mean beach sand age for Sixteen Mile Beach was calculated at 14.1 ka. Coastal sand, with an average radiocarbon age of about 18.4 ka is being blown into the southern dune plume at present. If this age is used as a correction factor and subtracted from the radiocarbon age of the sand of the dune plume, it yields the age of the dune since it left the beach. In the Yzerfontein-Geelbek dune plume at 24 km inland sand thus left the shore 4,500 years ago. This indicates that the dune field formed since the mid Holocene. In the Western Cape the sea-level reached its present-day position at approximately 7.5 ka. Between 7.5 and 4 to 5 ka, the sea-level reached a maximum elevation of 3 m above msl (Fig. 4.16; Compton, 2001). The stable sea-level since 5 ka, therefore, would have allowed the dune plume to develop.

The ages of the other dune plumes in the Western Cape (Fig. 4.2) are also suggested to be mid Holocene, although additional radiocarbon dating is needed to confirm their age. The Alexandria coastal dune field in the Eastern Cape has also been dated using radiocarbon on the bulk sand sample. The average age of the shore sand is 14 ka. The inland dune sands vary in age from

17 ka to 21 ka. This indicates that the inland sand left the shore 3000 to 7000 years ago (Illenberger and Verhagen, 1990). Additional analyses are required in the Alexandria coastal dune field, but from geomorphological considerations, an age of 6.5 ka has been assigned to this dune field (Illenberger, 1988; Illenberger and Verhagen, 1990). Coastal dune fields in New South Wales, Australia, have also been assigned a mid Holocene age. This was calculated using radiocarbon dating of the organic material within these dunes (Thom et al., 1981).

The use of radiocarbon dating has also proved that the Western Cape dune fields are mid-Holocene in age and have developed since 4.5 ka and that sea-level must have remained stable (oscillations less than 1 m), allowing for the development of active, dune plumes. The radiocarbon dating of the carbonate sand comprising the Yzerfontein-Geelbek dune plume has shown that this technique may be used to date active, fast moving dune plumes, which cannot be dated with thermoluminescence. However, because of the variable sources of beach sand as well as the complexity in the breakdown of carbonate sand grains, a correction factor must be determined separately for each beach zone's sand source. While for the southern part of the Sixteen Mile Beach complex the correction factor was the age of the beach sand, in the northern part, this correction factor must also consider the coarser grain size that youngs the radiocarbon ages (Chapter 4, Table 6). This is well shown in the northern part of Sixteen Mile Beach where the coarse beach sand yields a radiocarbon age of 10.9 ka while the age of the medium sand of the pioneer dune is 11.8 ka. The age difference of 900 years reflects the change in grain size and therefore the age of the pioneer dune has been used as the correction factor for the northern part of the Sixteen Mile Beach. The coarser grain size of the central and northern part of the Sixteen Mile Beach complex prevents the formation of dune plumes and instead coast-parallel dunes develop (Fig. 4.2). The largest and highest dunes inside the Sixteen Mile Beach complex are to be found in the northern section, where accumulation of sand and successive generation of dunes become superimposed onto the pre-existing topography. These dunes are often broadly parabolic shaped. Their margins are often defined by a partially vegetated ridge and they may resemble the 'long-walled transgressive ridge' dunes described by Thom et al. (1978) in New South Wales (Australia) or they may be considered similar to the 'precipitation ridges' described by Cooper (1958) in Oregon (U.S.A.).

The age of formation of coast-parallel dunes in the Western Cape has been suggested to be Holocene (Roberts and Berger, 1997), but the exact timing of their formation and evolution is unknown. Mixing with older dune material makes the dune evolution of the Western Cape difficult to unravel. To understand this complex evolution radiocarbon dating was performed separately not only on bulk dune sand, but also on the molluscs *Donax serra* and *Patella* spp. *Donax serra* occupy a fixed subtidal position on the beach (Branch and Branch, 1981; Branch et al., 1994). The ages of the radiocarbon dating on *D. serra* are interpreted as indicative of Holocene highstands. Large *D. serra* stranded on the beach after major storms are fractured by gull-dropping onto the wind-deflated face of foredunes or by the previously accumulated shell layer. *D. serra* shells recovered from landward troughs are, therefore, interpreted as dating the time of accumulation of gull-dropped shells onto the erosional, wind-deflated face of landward-migrating foredunes. Shell layers that develop on deflated foredune faces during marine transgressions are stabilised by vegetation and preserved as long as the dunes escape erosion by subsequent sea-level highstands or destabilisation by fire or drought. The paucity of *D. serra* from shell middens on the Western Cape indicates that early humans did not collect them for food (Parkington, 1981). Shells middens were identified by the presence of varying proportion of limpet shells (*Patella* spp.), black mussel (*Choromytilus meridionalis*) and perlemoen (*Haliotis midae*). *Patella* spp. shells from coast-parallel dunes are interpreted to be middens because gulls do not drop them. The radiocarbon dating of *Patella* spp., therefore, provides information on the human utilisation of the southern part of the west coast.

The gathering of all the radiocarbon dating on coast-parallel dunes suggests that the bulk of these coast-parallel dunes formed during the mid-Holocene highstand between 7 and 5 ka and indicates sea-level highstands at around 6.2-5.9, 4.5 and 2.4 ka (Figs. 4.8, 4.16). A 3 m sea-level highstand at around 6.3 ka is indicated by other studies from the west and south coast of southern Africa (Redding, 1988; Marker and Miller, 1993; Compton, 2001). During this time new dunes were initiated along, or very close to, eroding shorelines. A period of high sea-level between 6.7 and 6.0 ka has been described in the inner margin of Holocene coastal plains in Australia and New Zealand (Pye and Bowman, 1984; Pye, 1993; Shepherd and Eliot, 1995; Muckersie and Shepherd, 1995). After the erosion caused by the final stage of the postglacial marine transgression, a period of stabilising sea-level would then have occurred. It is, however, possible that those other minor oscillations occurred after sea-level stabilised. The indication of a sea-level highstand at 2.4 ka is equivocal and there is no published evidence for a rise in sea-level between 3 and 2 ka along the Western Cape coast. In contrast, sediment recovered from the west and south coast of South Africa indicates a 1 m sea-level lowstand between 3 and 2 ka (Deevey et al., 1959; Martin, 1968; Baxter, 1997; Compton, 2001). However, Playford (1988) in Australia suggests a sea-level rise of 1 m at above the present about 3 ka. Local tectonism variations between areas and the paucity of detailed Holocene data in the south western margin of South Africa makes comparison to other studies inconclusive.

Low-energy environments

In the Western Cape low-energy environments are present in the Langebaan Lagoon that is protected from the Atlantic Ocean by granite hills and a ridge of Pleistocene to Holocene dunes (Figs. 1.2 and 4.2). Contrary to the physiographic north/south division of the Sixteen Mile Beach, the lagoon can be subdivided texturally into an eastern and western unit. The eastern unit is characterised by fine sand, whereas the western half consists of medium sands (Flemming, 1977). The sediment distribution in the lagoon has been previously mapped by Flemming (1977) who demonstrates the complexity of the sediment distribution due to the two-directional tidal flow plus local wind influence. Considering that the grain size distribution of the Langebaan Lagoon has been previously studied, the composition, vegetation and foraminiferal assemblage of the tidal channel, tidal flat and salt marsh were recorded. The tidal channel and flat are composed of muddy sand (70% fine sand, 30% mud). From the low to the high marsh, the sand fraction decreases and the high-marsh sediment consist of 50% fine sand and 50% mud. The sand fraction is composed of reworked fine aeolian quartz and calcareous material (mostly foraminifera). The mud fraction consists primarily of quartz, plant debris, diatoms and clay minerals. The tidal flat and tidal channel are populated by Zostera capensis, the low marsh by *Chenolea diffusa*, *Salicornia meyeriana* and *Spartina maritima*, the middle marsh by *Chenolea diffusa*, *Pulcinella* sp., *Sarcornia pillansii*, *Salicornia meyeriana* and *Triglochin bulbosa*, the low marsh by *Chenolea diffusa* and *Salicornia meyeriana*. Foraminiferal analysis on a transect from the tidal channel to the high marsh allows separation of the area in three zones. The tidal channel and tidal flat area is composed of the calcareous species *Ammonia japonica*, *Ammonia parkinsoniana*, *Ammonia* sp., *Elphidium* sp. A and *Quinqueloculina* sp. The low to middle marsh areas are dominated by *Jadammina macrescens* and *Trochammina inflata*, with subordinate presence of *Ammonia japonica*, *Elphidium articulatum* and *Elphidium* sp. A. The high marsh areas are dominated by *Trochammina inflata* with scattered presence of *Jadammina macrescens*. Very little work has been published concerning foraminiferal distrubition around the south African coastline, resulting in a deprived database, in placing limitations on describing the taxonomy of the species and in comparing recent to fossil faunas. In addition, foraminiferal assemblages and distribution have not been previously studied in the Western Cape lagoonal areas. However, salt marsh foraminifera studies are well established elsewhere in recent literature. These studies have proven that salt marsh foraminifera are widely distributed, and many resident taxa have both long stratigraphic ranges and wide geographic distributions within these environments (Scott et al., 1990; Goldstein and Watkins, 1999). The distribution patterns of these foraminifera assemblages often reflect variation in elevation (Scott and Medioli, 1978, 1980, 1986; Horton, 1999) and also may be influenced by salinity (de Rijk, 1995b). The information on the foraminiferal distribution from the Langebaan Lagoon were used for the reconstruction of the past depositional environments that will lead to the description of the evolutionary coastal model for the Western Cape.

7.3.3 PALAEONVIRONMENTS

The Western Cape coastal area is almost completely covered by aeolian deposits, but often their age is uncertain. These aeolian deposits are the Langebaan Formation and the Prospect Hill Formation. The Langebaan Formation has been recently dated as latest Pleistocene and therefore its age of formation is known (Roberts and Berger, 1997). The Prospect Hill Formation is a 20 km long dune plume oriented N-NE (Fig. 5.1), composed of carbonate material (up to 90 wt%) and minor well rounded fine to medium quartzitic sand (Figs. 5.3 and 5.4). These aeolianites are rich in fossils of *Trigonephrus globulus* and few eggshell fragments of struthious birds (*Diamantornis wardii*). The Prospect Hill Formation is the oldest aeolian deposit of the Western Cape and has been dated in this thesis using Sr isotope stratigraphy as latest Miocene-Pliocene. In the geological literature coastal carbonate aeolianites have been seldom reported as pre-Quaternary in age (Marker, 1976; Fairbridge and Johnson, 1978; Gardner, 1983; McKee and Ward, 1983). The predominance of Quaternary aeolianite deposits may be related to the difficulty in the differentiation of aeolian units and shallow marine deposits, especially in drilled cores (McKee and Ward, 1983) or when, because of weathering, the distinct cross bedding of the aeolian deposits are altered (Marker, 1976). Large Pre-Quaternary aeolianites have been reported only in southern Africa (Malan, 1987; Brooke, 2001). Studies that focused on Late Tertiary-Early Pleistocene aeolianites that underlie Middle to Late Pleistocene dune deposits in south Australia (Belperio and Bluck, 1990; Belperio 1995; Belperio et al., 1996), western Australia (Collins and Baxter, 1984) and South Africa (Maud, 1968; Marker, 1976; Yallon, 1983) have shown that the carbonate content of the basal units is considerably lower than the Pleistocene deposits. The Prospect Hill aeolianites are an exception and their carbonate rich-nature suggests that carbonate production, carbonate accumulation and terrigenous sediments input has not substantially changed, at least in the Western Cape, since the latest Miocene-Early Pliocene. The scale and wide distribution of the Late Pleistocene aeolianite deposits in the Western Cape suggests that although coastal dunes were deposited before the Quaternary, it has become a more significant and distinctive coastal deposit during the Quaternary. The cyclical movement of the Quaternary sea-level fluctuations has been considered as the major factor in the formation and preservation of dune deposits creating pulses of shoreline sediment accretion and aeolian reworking (Playford et al., 1976; Garrett and Gould, 1984; Belperio, 1995).

The most extensive Quaternary coastal dune deposits occur along the southern and western coasts of Australia. The early chronological interpretation of these dune deposits were based on field studies and geomorphic interpretation. Later radiometric dating helped to refine the formation and evolution of these areas. The Coorong coastal plain (eastern part of south Australia) has shown that major phases of coastal dune deposition occurred during interglacials throughout the Late Quaternary. In this area, as a result of gentle uplift during the Quaternary, relict shoreline barriers (composed of dune and subordinately by beach and lagoonal deposits) form a series of coastal ranges that has been formed mostly during interglacials and interstadial sea-level highstands of the last 1 Myr (Belperio, 1995; Murray-Wallace et al., 2001).

Wave-dominated marine deposits have been preserved as coquina-bed deposits in two areas: the Bomgat Cave and the basal part of the Tabakbaai Quarry deposit both of a latest Pliocene/Early Pleistocene age. In both areas fecund mollusc populations are the source for the substantial amounts of carbonate material found in these deposits. In the Western Cape, also the Pleistocene Velddrif Formation is characterised by shell-rich assemblages. The main difference between these deposits is that the Bomgat Cave deposit has phosphatic grains while in the other two deposits have only rare, probably reworked phosphatic grains. The use of strontium isotope stratigraphy in phosphatic material has proven to be able to date the deposit as well as phosphogenic events in the Western Cape. In contrast to wave-dominated depositional environments, tide controlled environments were found in the Monwabisi deposits and interpreted as forming during the Eemain on the basis of biostratigraphy. These deposits, their relation to sea-level fluctuations and the palaeoevolution of the coastal deposits of the Western Cape is addressed in the following section.

7.2.4 EVOLUTION OF THE COASTAL DEPOSITS OF THE WESTERN CAPE

The relative age of the Gravel Member (Table 1) is based on stratigraphic relationships as attempts to measure the Sr isotope composition to derive a Sr age of the CFA cement were unsuccessful. The underlying Elandsfontyn Formation is considered to be Early to Middle Miocene or older (Coetzee and Rogers, 1982; Pether, 1994; Dale and McMillan, 1999, Pether et al., 2000) and the overlying Quartzose Sand Member, dated in this study by strontium isotope stratigraphy as latest Miocene/Pliocene. As a consequence, the Gravel Member must have been deposited during the Middle to Late Miocene. Pickford (1998) and Pickford and Senut (1999) describe, on the basis of faunal fossils, three transgressive events in southern Namibia (Fig. 1.3). The first event occurred during the Early to Middle Miocene (ca 20 to 17.5 Ma). The second event occurred during the Middle to Late Miocene (ca 11 to 10 Ma). The third transgressive event occurred during the Late Miocene/Pliocene (ca 7 to 5 Ma). The first event was a major trangressional episode (75 to 90 m msl) that formed the 90 m Package deposits. At the end of the second transgressive event a series of basal gravels were left behind. These diamondiferous basal gravels were described in Namaqualand by Pether (1994) and in southern Namibia by Pickford and Senut (1999). At Ryskop Bay in Namaqualand the 90 m Package is directly overlain by a large basal gravel deposit, while in the Western Cape the Gravel Member is overlain by the Elandsfontyn Formation. However, in the Namaqualand coast, gravel deposits were also found

Western Cape	Package	AGE (previous studies)	Age (this study)
Witzand Formation	2 m	Holocene	Holocene dated with ^{14}C
Langebaan Formation			Late Pleistocene (105-80 ka) dated with U/Th[a]
Velddrif Formation	4 m	Latest Pleistocene (Eemian)	Late Pleistocene (120 ka) dated with IRSL[a]
Bomgat Cave (3.6-1.1 Ma)	8-10 m	Late Pleistocene	latest Pliocene/Early Pleistocene dated with SIS
Pelletal Phosporite Member (2.5-0 Ma) of the Varswater Formation basal coquina bed (2.2-0.5 Ma) underlying the Prospect Hill Formation	30 m	Late Pliocene[1] OR Early Pleistocene [2]	latest Pliocene/Early Pleistocene dated with SIS
Prospect Hill (6.1-4.3 Ma) Quartzose Sand Member (8.8-4.9 Ma) of the Varswater Formation	50 m	Pliocene/Miocene[1] OR Late Miocene[3] latest Pliocene/Early Pleistocene[2]	Latest Miocene/Pliocene dated with SIS
Gravel Member			Middle to Late Miocene -not dated-
Elandsfontyn Formation	90 m	Early Miocene[1,3] OR Middle Miocene[4]	Early to Middle Miocene -not dated-

Table 1. Proposed ages of marine packages in the Western Cape.

1 Pether (1994), Pether et al., (2000)
2 Dale and McMillan (1999)
3 Pickford and Senut (1999)
4 Coetzee and Rogers (1982)

a Roberts and Berger (1997)

underlying older not well constrained Early Miocene deposits. The third transgressive event described by Pickford (1998) and Pickford and Senut (1999) formed the 50 m Package deposits.

The Gravel Member was deposited during a sea-level highstand that has been interpreted either to be equivalent to the 90 m Package of Namaqualand or deposited after a subsequent transgressional event. The 90 m Package was deposited during a marine transgression (75 to 95 m asl) that occurred during the early to middle Miocene (Pether, 1994; Pether et al., 2000) that is older than the transgressive event that must have formed the Gravel Member. This suggests a correlation between the Gravel Member and the middle to late Miocene second transgressive event suggested by Pickford (1998) and Pickford and Senut (1999) with a maximum sea-level highstand of at least 30 m in the Western Cape. High sea-levels during the Middle to Late Miocene have been recorded elsewhere (e.g., southeast Australia; Gallagher et al., 2001) as well as indicated in the global sea-level curve (Haq et al., 1987). Because the various facies which make up each of the transgressive packages and because the basal gravels tend to be similar, it is difficult to assign a correct age and event of deposition (Pickford and Senut, 1999). Therefore, additional Sr dating is required to clarify the age of formation of these older deposits.

The 50 m package of Namaqualand was considered to be laid down by shoreline progradation during the marine regression that occurred after a Middle Pliocene (ca 3 Ma) sea-level highstand (Pether, 1994). It has also been suggested that the 50 m package was formed by the third transgression recorded for southern Namibia at the end of the Late Miocene (ca 7-5 Ma) by

Pickford and Senut (1999). In the Western Cape the 50 m Package has been assigned to a marine transgression during the latest Pliocene/Pleistocene (Dale and McMillan, 1999). The use of strontium isotope stratigraphy indicates that the Quartzose Sand Member, as well as the aeolianites of the Prospect Hill Formation, formed during the latest Miocene/Pliocene (Table 1). Strontium isotope stratigraphy also shows that the Quartzose Sand Member is older (8.8-4.9 Ma; Table 1) than the Prospect Hill Formation (6.1-4.3 Ma; Table 1). As the Quartzose Sand Member outcrops at about 30 m above msl and is older than the Prospect Hill Formation, which outcrops at about 25 m above msl, it is suggested that the Quartzose Sand Member formed during the third transgressive event recorded in southern Namibia/northern Namaqualand at the end of the Late Miocene (Pickford 1998; Pickford and Senut, 1999). About 1 to 2 Myr after the transgressive maximum, with sea-level falling, the area of Tabakbaai Quarry would have been exposed and the coastal dune plume of the Prospect Hill Formation would have formed. The suggestion that the proto-Berg River discharged into Saldanha Bay from the Late Miocene to the Middle Pliocene (Hendey, 1974, 1981a) is not supported by the latest Miocene/Pliocene age of the Prospect Hill Formation. The high carbonate content of the Prospect Hill Formation (up to 95 wt%) indicates that the proto-Berg River did not discharge siliciclastic material into Saldanha Bay before the latest Miocene.

The 30 m Package has been considered to have formed during a marine transgression of the Late Pliocene (Pether, 1994; Pether et al., 2000) or Early Pleistocene (Dale and McMillan, 1999) (Table 1). In southern Namibia (Pickford and Senut, 1999), a marine transgression has been recorded at the Plio-Pleistocene boundary (ca 2.6 to 2.3 Ma). In the Namaqualand coastal plain, the 30 m Package extends to near the present-day shoreline, where it is overlain by regressive deposits of a possibly Early Pleistocene high sea-level that reached 10 m asl (Pether, 1994). In the Western Cape, a marine transgression during the latest Pliocene/Early Pleistocene has been responsible for the deposition of the Pelletal Phosphorite Member (2.5-0 Ma; Table 1) of the Varswater Formation, the coquina bed outcropping at the basal section of the Prospect Hill Formation (2.2-0.5 Ma; Table 1) and the basal part of the Bomgat Cave deposit (3.6-1.1 Ma; Table 1). This latest Pliocene/Early Pleistocene highstand of 20-24 m asl eroded the base of the coastal dunes of the Prospect Hill Formation and deposited the shell-rich layer that underlies the aeolianites. The latest Pliocene/Pleistocene age obtained for the Bomgat Cave deposit (8-10 m package of Dale and McMillan, 1999) indicates that both the Late Pleistocene age indicated by Dale and McMillan (1999) or the Miocene age of Tankard (1975a, b) differ significantly from the Sr isotope stratigraphy results. A Miocene age for the deposit is however, very improbable because the Bomgat Cave deposit is close to present-day sea level and it would have been reworked by subsequent marine transgressions. The Late Pleistocene age for the Bomgat Cave deposit (8 to 10 m Package) suggested by Dale and McMillan (1999) is also difficult to explain, particularly considering that a second Sr isotope derived age of Late Pliocene/Early Pleistocene age was obtained for this outcrop (M. Lavelle, as cited in Dale and McMillan, 1999). Possible reworking of the 8 to 10 m package is indicated by Dale and McMillan (1999), but not conclusively resolved.

Pether et al. (2000) describe younger marine packages 8-10, 4 and 2 m above msl as being deposited during a series of marine transgressions in Namaqualand. The age of these marine packages varies from Late Pleistocene to Early Holocene (Dale and McMillan, 1999; Pether et al. 2000). In southern Namibia raised beach deposits are commonly known as sub-10 m beaches and are found at 8, 5 and 2 m asl. These sub-10 m beaches are considered to be younger than Middle Pleistocene based on mammal faunal stratigraphy (Pickford and Senut, 1999). There is no indication from the present study that deposits between the latest Pliocene/Early Pleistocene and the Late Pleistocene (Eemian) are preserved in the coastal area of the Western Cape. Additional dates are required for the 8-10 m packages/sub beaches from Namaqualand/southern Namibia to assess the ages of these deposits. It is possible that they are older than what was previously suggested or that tectonic uplift occurred up the coast preserving them from subsequent erosion. The 4 m Package in the Western Cape (Veldrift Formation) has been described in several localities at elevations of 5 to 7 m above msl and has been dated as Eemian (~120 ka) using IRSL (Roberts and Berger, 1997). The Eemain coastline, which was elevated a few meters above the present-day sea level, is comprised of different depositional environments. In the Saldanha Bay area it is composed of shell coquina beds that directly overlie the Malmesbury Group bedrock. In the Monwabisi beach area, it is represented by a tidal environments. It is apparent that these deposits represent littoral sediments that were deposited during the Last Interglacial at around 120 ka (Fig. 1.3) Pleistocene shallow water marine sediments representing beach, tidal flat, tidal channel, marsh and near shore environments have been recorded both on the east and west coast of Gulf of California and along the Pacific coast of Baja California in Mexico (Meldahl, 1993, 1995; Medahl and Culter, 1992). These deposits are 0.5 to 5 m thick and formed as a result of one of several Pleistocene sea-level highstands, most commonly during marine oxygen isotope stage 5e (Eemian). These sediments, like those studied in the Western Cape, vary from shell-rich wave dominated beach to tide-dominated fine-grained deposits. Rocky-shore environments and associated biotas from over 50 localities around the world that are coeval to the Velddrif Formation are provided by Johnson and Libbey (1996) showing the importance of these and the wide spread distribution of the Last Interglacial coastal deposits. In the Western Cape, lithologically, the Eemian deposits are characterised by the absence or paucity of phosphorite grains that are well preserved in the older strata. The genesis of phosphorite along the Western Cape has been linked to the upwelling of cold-phosphate rich waters which precipitated phosphates in the littoral zone as the waters became warmer in the vicinity of the coast and the pH increase shoreward (Tankard, 1975 a; Tankard and Rogers, 1978). The onshore Western Cape phosphates, which started to form during the Middle to Late Miocene (age of the Gravel Member), indicate that the cold Benguella Current has upwelled in the area since then. By the Early Pleistocene however, the near shore coastal waters become cold and the precipitation of phosphorites decreased rapidly or stopped altogether.

At the end of the transgression recorded by the Eemian sea-level highstand, the well-developed aeolianites of the Langebaan Formation that crop out from False Bay to the Berg River formed. The Langebaan Formation is the product of onshore sand deflation and coastal dune formation when the western continental shelf was exposed during the lowstands of the last Glacial. The Langebaan Formation has been dated using IRSL and U/Th at about 107, 103 and 75 ka on the western flank of the Langebaan Lagoon (Robers and Berger, 1997) and 140 and 65 ka at 18 km inland of the Geelbek-Yzerfontein dune plume (Conard, unpublished report, SANParks, 2000). These ages imply that the bulk of the dunes of the Langebaan Formation formed since 140 ka with major pulses at around 100 ka and 75 to 65 ka, when sea-level was 20 to 80 m below present-day (Fig. 1.3). Additional dates for the Langebaan Formation may help to elucidate the complex evolution of the coastal dunes during the Late Pleistocene, and the reworking that occurred since then. After the Last Glacial Maxiumum lowstand of -125 m, the beach and dune sand of the Last Glacial Maximum coastline, rather then being abandoned offshore, migrated landwards to the present-day shoreline as suggested by the radiocarbon ages of the beach sand collected along Sixteen Mile Beach (Chapter 4, Table 1). During the mid Holocene as discussed earlier in this chapter, the bulk of the coastal dunes of the Witzand Formation accumulated.

The sea-level curve of Fig. 7.1 summarises the marine regressions and transgressions as recorded by Late Tertiary sediments in the Western Cape. The Early Miocene was a period of transgression during which the 90 m Package and the Elandsfontyn Formation were deposited. The Middle Miocene was a period of regression. This was followed by a Middle to Late Miocene

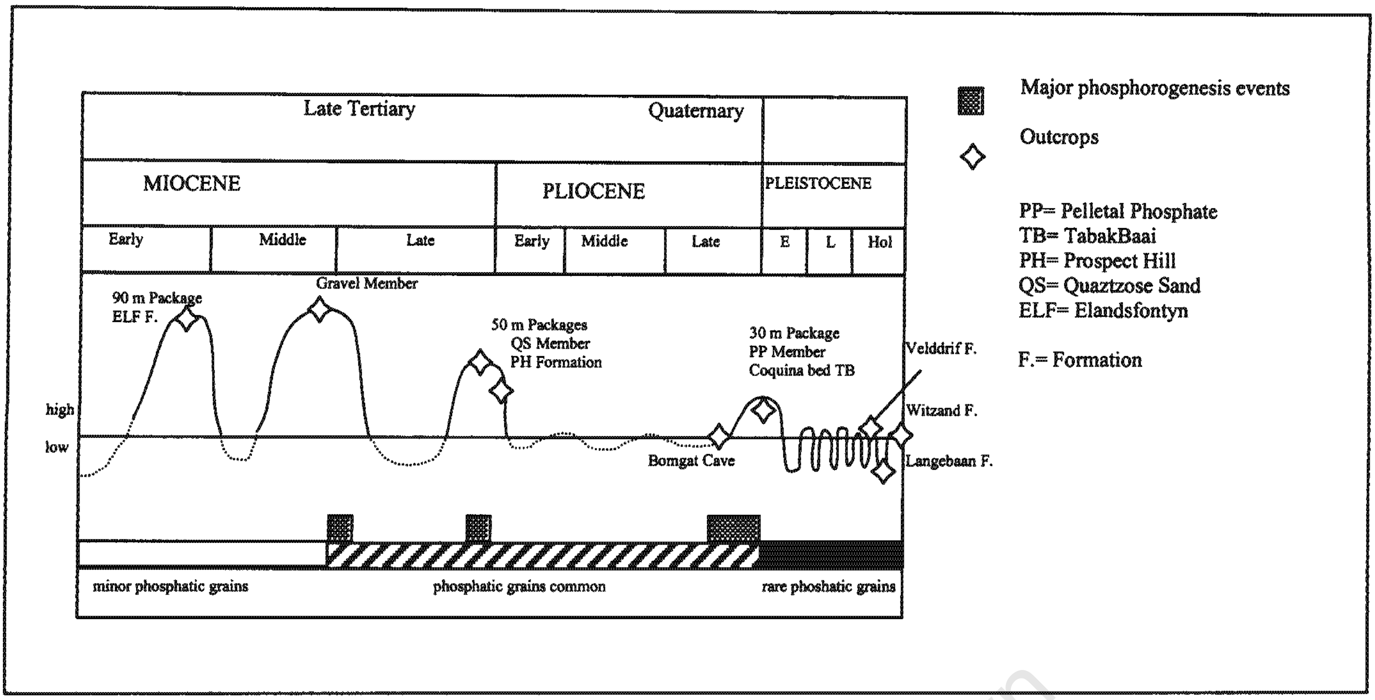


Fig. 7.1. Late Tertiary and Quaternary time-scale and diagrammatic representation of marine transgressions and regressions for the west coast of South Africa.

transgression during which the Gravel Member of the Varswater Formation was deposited. The Latest Miocene/Pliocene was a further period of transgression to 30 m above msl during which the Quartzose Sand Member of the Varswater Formation was deposited. In the subsequent regressive event, the coastal aeolianites of the Prospect Hill Formation formed. A further transgression of 24-25 m took place at the end of the Pliocene during which the Bomgat Cave deposit and the Pelletal Phosphorite Member of the Varswater Formation accumulated. Pleistocene sea-level fluctuations have then eroded most of the strata that formed during this epoch. Two deposits however, are well preserved in the Western Cape. The Eemian beach deposits found at 5 to 7 m above msl (Velddrif and Monwabisi) and the large coastal dune deposit, Langebaan Formation, of the Last Interglacial. Coast-parallel dunes as well as active dune plumes formed during the mid- Holocene and cover extensively the coastal plain area.

The decrease in altitude of marine transgressive deposits on the west coast may be either explained by eustatic rise and fall of sea-level, tectonic uplift or some combination of the two. When there is a marine transgression that reaches a higher level than the previous one, then it will tend to destroy evidence of the earlier one, and thus a series of raised complexes will tend to be oldest at the highest elevations and younger at successively lower elevations. This however, can be an artefact of epeirogenic uplift that would raise a marine complex beyond the influence of the later transgression of a similar altitude. On the east coast of South Africa, the Alexandria Formation composed of littoral deposits deposited during the Middle Miocene to Pliocene has been rised to an elevation of 300-400 m by severe uplift occurred during the Pliocene (Partridge and Maud, 1987). At present it is difficult to ascertain the involvement of tectonic uplift in the Western Cape, Namaqualand coastline or southern Namibia. However, the latest Miocene to latest Pliocene/Early Pleistocene marine packages (50 and 30 m packages) in Namaqualand tops out at about 50 m above msl, while the correspondent strata in Western Cape are found at 30 m above msl, suggesting differential uplift of at least 20 m between the northern and southern part of the Western Cape coastline. Dale and McMillan (2003) using microfossils assemblages tentatively correlate the west coast offshore marine units with the 90 m Package (Pether, 1994; Pether et al., 2000) suggesting a 90 m uplift along the west coast since the Pliocene. This is in agreement with the ~100 m uplift for the west coast suggested by Partridge and Maud (1997). In contrast, Roberts and Brink (2003) note that the stratigraphic equivalent Namaqualand deposits are ~50 m lower that those of the Western Cape. The correlation between these units is based on the elevation of the deposits dated by avian biostratigraphy (Pickford, 1988; Pickford and Senut 1999). Middle to Early Miocene deposits are not directly dated, either in the Western Cape or in the Namaqualand and therefore the correlation is based on stratigraphy. There is no evidence yet to solve the conundrum between tectonic uplift or eustatic sea-level (Pickford and Senut, 1999). Dating of apatite fission-tracks is presently underway along the western margin of southern Africa (G. Viola, pers. comm., 2002) and will help to elucidate the complex uplift evolution of this margin. This future research may help to reveal the relevant roles and will lead to a better appreciation of the timing and the processes involved in the deposition and reworking of marine and aeolian deposits in coastal areas of the southwestern African margin.

7.3 SUGGESTIONS FOR FUTURE WORK

The South African coastline extends for more than 3,000 km. Sandy beaches compose 80% of this coastline (Tinley, 1985) and enormous dune systems have been deposited both in the west and east coastal area of South Africa since the Late Tertiary (Tinley, 1985; Illenberger and Burkinshaw, 1996). The work of this thesis aims to highlight some of the geological processes that were, and remain, involved in the formation of the southern part of the west coast of South Africa. The study of different environments in the Saldanha Bay area has shown that, for a better understanding of the past, it is very important to document the present.

Future work along the south African coastline can be done in order to document the present-day living conditions of foraminifera of salt marshes and estuarine deposits. Comparison with other salt marsh deposits may add important information to the ecology of the most used biostratigraphical taxa. A foraminiferal-distribution study is presently underway at Knysna Lagoon, on the South Coast of South Africa. Agglutinated species (in particular *Trochammina inflata*) dominate the microbenthos in the salt marshes of the Knysna Lagoon, whereas calcareous species are rare or absent (Compton, pers. comm., 2001; Simpson, 2003).

Radiocarbon dating of bulk samples from beaches along the southwestern Cape may help to understand the longshore drift and the processes involved in the fragmentation of the sand. AMS dating of different shell-sizes can in particular elucidate the processes involved in the break down of shells. Radiocarbon dating may also be used to understand the development of other coastal dune complexes. Several dune plumes are present along the west coast and their age of formation or grain-size is still unknown.

Late Cainozoic sediments in South Africa have always been dated bioststratigraphically. The use of SIS, which is clearly able to distinguish between Pleistocene and Pliocene deposits, may solve the age of deposition not only of marine deposits but also of aeolianites. SIS dating of the marine Packages of the west coast (Pether, 1994) is presently underway (McMillan, pers. comm., 2003). Thermoluminescence dating may be applied to younger aeolian deposits. In particular, the basal calcrete exposed at Monwabisi beach can be dated with IRSL.

Proposals for further investigation on coastal environments in the Western and Eastern Cape have been submitted to several international and national foundations. The final aim of these studies as well as this thesis is to fill a gap in the knowledge of the evolution of coastal areas in southern Africa. Since changes are a continuous and constant factor in coastal evolution, understanding environmental and geological factors of the past is the key to more appropriate management of changes evidently occurring at present and likely to occur in the future.

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Units	Sample No.	% foraminifera species
Unit 8	12	Not identifiable - Abraded ?*Elphidium* spp.
Unit 7	11	*Ammonia parkinsoniana* (60) - *Ammonia japonica* (40)
Unit 7	10	*Ammonia parkinsoniana* (60) - *Ammonia japonica* (40)
Unit 6	9	*Elphidium crispum* (90) - *Glabratella australensis* (10)
Unit 5	8	*Ammonia parkinsoniana* (50) - *Ammonia* sp. A (10) - *Elphidium* sp. A (20), *Quinqueloculina* sp. A (20)
Unit 5	7	*Ammonia parkinsoniana* (60) - *Ammonia japonica* (40)
Unit 5	6	*Ammonia parkinsoniana* (30) - *Ammonia japonica* (20) - *Elphidium* sp. A (40) - *Elphidium articulatum* (10)
Unit 4	5	Not identifiable - Abraded ?*Elphidium* spp. - *Glabratella australensis*
Unit 3	4	Not identifiable - Abraded ?*Elphidium* spp.
Unit 2	3	*Ammonia parkinsoniana* (60) - *Ammonia* sp. A (40)
Unit 1	2	Not identifiable
Unit 1	1	Not identifiable

Units	Sample No.	Macrobenthos
Unit 8	12	*Theba pisana, Trigonephrus globulus*
Unit 7	11	*Assiminia globulus*
Unit 7	10	*Assiminia globulus, Tomichia ventricosa*
Unit 6	9	*Choromytilus meridionalis, Donax serra*
Unit 5	8	*Assiminia globulus, Tomichia ventricosa*
Unit 5	7	*Solen capensis*
Unit 5	6	*Assiminia globulus, Tomichia ventricosa*
Unit 4	5	*Donax serra*
Unit 3	4	
Unit 2	3	
Unit 1	2	
Unit 1	1	

Appendix 1. Foraminiferal count and macrobenthos of the units exposed at Monwabisi.

Units	% foraminifera species
Sixteen Mile Beach 1	*Ammonia* sp. (40), *Elphidium* sp.(50), Glabratella sp. (10)
Sixteen Mile Beach 2	*Ammonia* sp. (45), *Elphidium* sp.(50), Glabratella sp. (5)
Sixteen Mile Beach 3	*Ammonia* sp. (36), *Elphidium* sp.(48), Glabratella sp. (12)
6 km	abraded Ammonia sp., Elphidium sp., Glabratella sp.
12 km	abraded Ammonia sp., Elphidium sp.
18 km	abraded Ammonia sp., Elphidium sp.

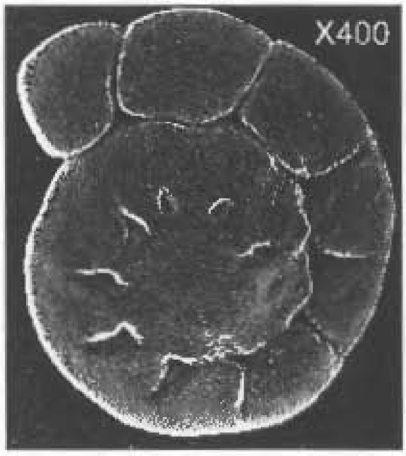
Appendix 2. Foraminiferal count for Sixteen Mile Beach and the Geelbek-Yzerfontein dune plume.

Units	% foraminifera species
Unit 5	Abraded *Pararotalia nipponica*, *Haynesina* sp., *Globigerina bulloides,* Elphidium sp., *Rosalina* sp., *Lobatula lobatula*, *Glabratella 'australensis'.*
Unit 4	Abraded *Rosalina 'diazvillea', Pararotalia nipponica, Elphidium* sp., *Eponides* sp.
Unit 3	Reworked Ammonia spp., *Elphidium* spp., Haynesina sp., Pararotalia nipponica, Lobatula lobatula
Unit 2	Ammonia sp. (40), *Haynesina* sp. (15), *Pararotalia nipponica (10), Oolina* sp. (10), *Siphonaperta* sp. (9), *Rosalina* sp.(8), *Uvigerina* sp. (5), *Quinqueloculina* sp. (3), *Lobatula lobatula* (2)
Unit 1	*Ammonia* sp. (33), *Elphidium* cf. *crispum (20), Elphidium* sp. (10), *Glabratella 'australensis' (17), Lobatula lobatula (8), Pararotalia nipponica (7), Quinqueloculina sp. (5), Uvigerina* sp., *Rosalina* sp.
Unit 0	Reworked *Ammonia* spp., *Elpidium* spp.

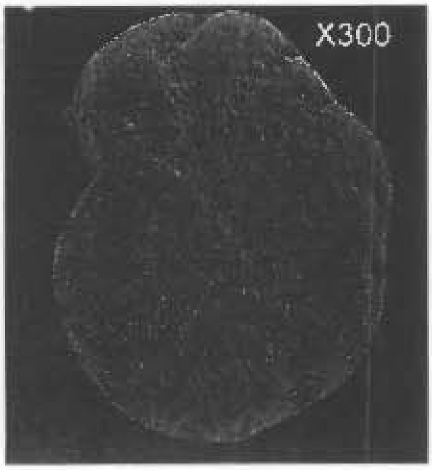
Units	Macrobenthos
Unit 5	*Trigonephrus globulus, Diamantornis wardii*
Unit 4	
Unit 3	*Trigonephrus globulus*
Unit 2	*Donax rogersi*
Unit 1	*Donax serra*
Unit 0	*Donax serra, Patella* spp.

Appendix 3. Foraminiferal count and macrobenthos for the units decribed in Chapter 5.

Ammonia japonica



Ammonia parkinsoniana



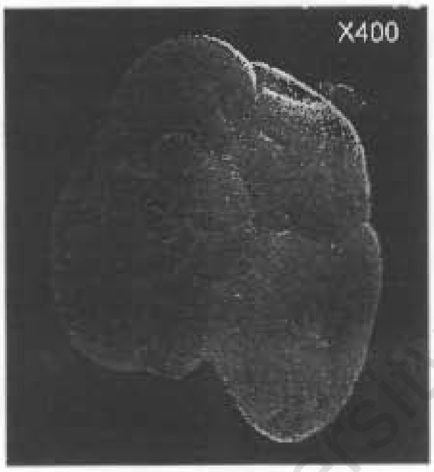
Elphidium cf *articulatum*

Elphidium sp.A

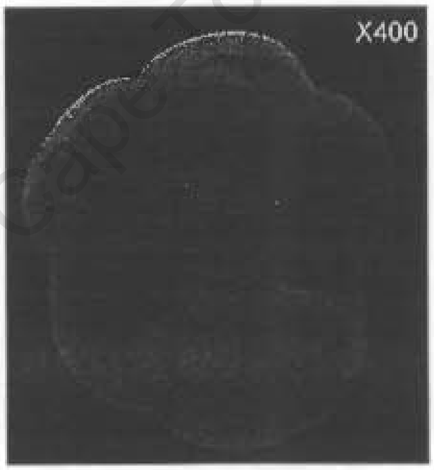
Quinqueloculina sp.

PLATE 1

Jadammina macrescens



Trochammina inflata



Trochammina inflata

PLATE 2