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Holocene Evolution of the Sixteen Mile Beach Complex, Western Cape, South Africa

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ABSTRACT

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The Sixteen Mile Beach Complex is one of numerous active dune accumulations along the West Coast of southern Africa. The beach complex is composed of a sandy beach, coast-parallel dunes, and a dune cordon. Grain size analyses, calcium carbonate content, sand texture and composition, and radiocarbon ages were determined to understand the Holocene evolution of the Sixteen Mile Beach Complex. Changes in sand grain size and dune morphology allow the complex to be divided into three parts. The beach and the dune cordon at the southern end are composed of fine sand. The central beach has a rapid decrease in the fine sand fraction that coincides with the transition from the dune cordon to a single large coast-parallel dune ridge. The northern beach is composed of medium sand and consists of a series of prograded, vegetated coast-parallel dune ridges. The formation of these distinct regimes is a reflection of the different amounts of wave energy received by the complex from the predominant southwest swell.

The radiocarbon analyses of bulk sand samples show a progressive younger age of the carbonate beach sand toward the north, which reflects an increase in grain size and recently broken shell. The mean age of the beach is 2.4 ka based on an accelerator mass spectrometry (AMS) date of picked pink-colored carbonate grains. The fresh bulk carbonate beach sand has a mean age of 7.4 ka and reflects the presence of reworked Pleistocene beach and dune sand. Corrected bulk sand radiocarbon ages indicate that the dune cordon has been active since 4.5 ka with a mean dune migration rate of 5.3 m/y. However, variations in sand supply, sea level, and climate indicate a complex and erratic evolution of the dune cordon.

ADDITIONAL INDEX WORDS: *Sand dunes, aeolian, coastal evolution, sea level, dune cordon, beach, Quaternary, radiocarbon dating.*

INTRODUCTION

Coastal dunes and dune fields 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 many impressive coastal aeolian deposits (TINLEY, 1985). Along the West Coast of southern Africa aeolian deposits date from at least the Miocene, producing extensive and often complicated sequences of dune stratigraphy (COMPTON and FRANCESCHINI, 2005; FRANCESCHINI and COMPTON, 2004; FRANCESCHINI, COMPTON, and WIGLEY, 2003; PETHER, ROBERTS, and WARD, 2000; ROBERTS and BRINK, 2003; TINLEY, 1985). Radiocarbon dating of shell material associated with dunes (ILLENBERGER and VEERHAGEN, 1990; MILLER *et al.,* 1993) and thermoluminescence and radiometric dating of dune palaeosols (LEES *et al.,* 1995) and aeolianites (BATEMAN *et al.,* 2004; ROBERTS and BERGER, 1997) have increased our understanding of the dynamics of coastal dunes. The evolution of aeolian deposits is of interest because they contain information on changes in sea level, sediment supply, and climate. Dunes represent an important transfer of marine sands to the terrestrial environment and include economic diamondiferous aeolian deposits along the Namibian coast (CORBETT, 1989). However, the factors that determine the morphology and evolution of beach and dune sand deposits along the coastal plain of southern Africa remain poorly understood.

The Sixteen Mile Beach Complex is one of a number of significant active dune accumulations on the West Coast. It is located 80 km north of Cape Town in the Western Cape (Figure 1) and presents a number of coastal environments and morphologies. In this study, the composition, texture, and age of beach and dune sands are used to develop a model for the Holocene evolution of the Sixteen Mile Beach Complex. The results of this study are integrated with evidence of sea-level fluctuations from the salt marshes of adjoining Langebaan Lagoon (COMPTON, 2001) and the geoarchaeology of the area (COMPTON and FRANCESCHINI, 2005) to improve our understanding of the Holocene evolution of the southern African coastline.

Study Area

The morphology of the present-day coastline of the West Coast of southern Africa is defined by long stretches of rela-

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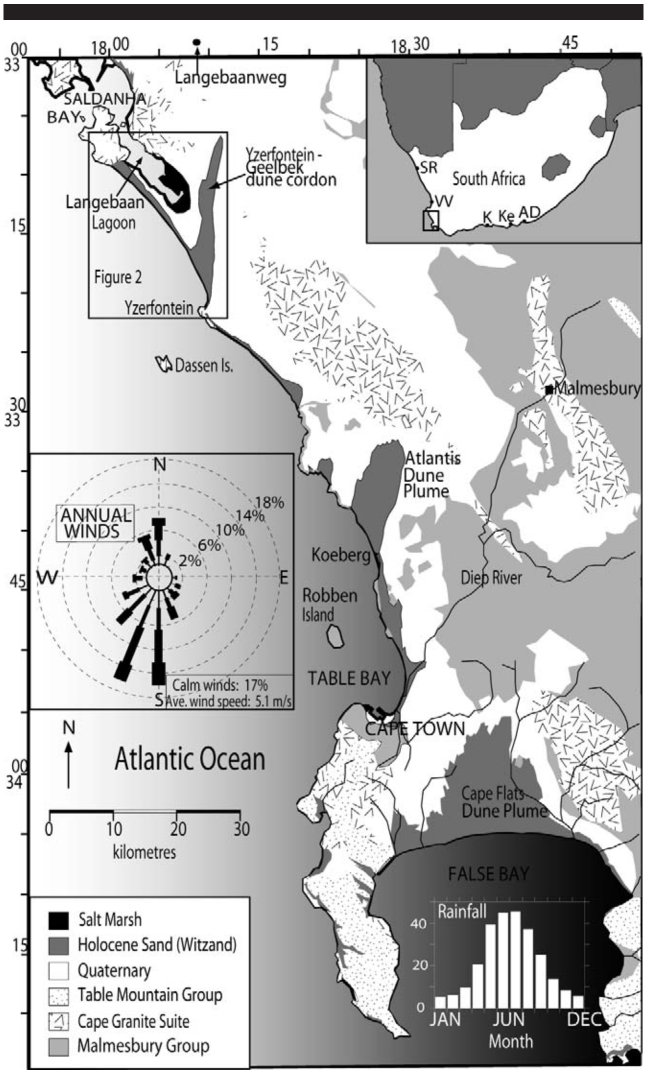

Figure 1. Location of the Sixteen Mile Beach Complex in the southwestern Cape, based on the 1990 1:250,000 Council for Geoscience map. Mean average monthly rainfall at Langebaanweg for the period 1915–1988 and mean annual average wind direction and velocity at Langebaanweg for the years 1975–1998 (SA Weather Bureau, personal communication, 1998). SR is the Swartlintjies River mouth, VV is Verlorenvlei, AD is Algoa Dunefield, K is Knysna, and KE is Keurbooms.

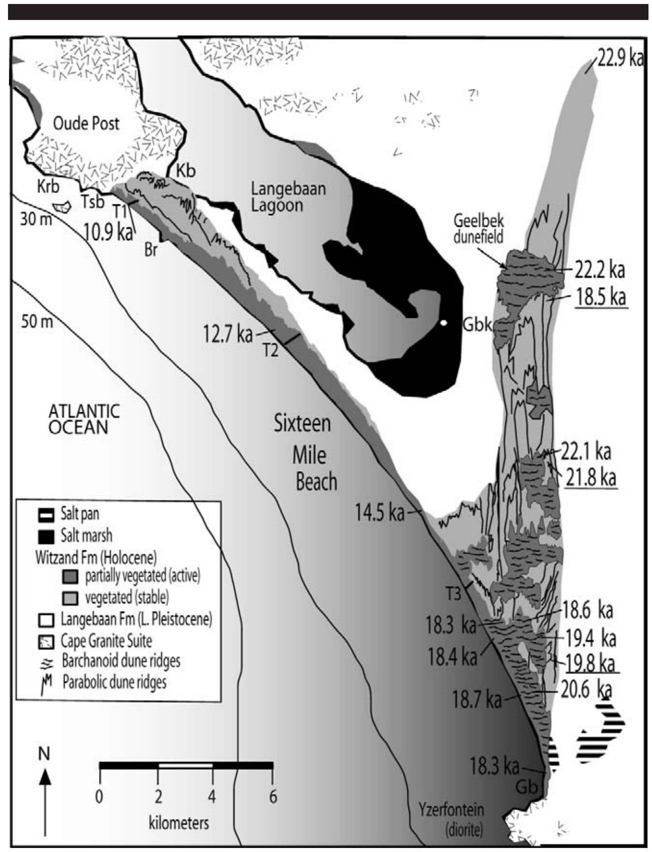

Figure 2. The Sixteen Mile Beach Complex between Yzerfontein and Kreeftebaai based on aerial photographs taken between 1938 and 1993. Underlined radiocarbon ages are from vegetated dunes. Kb is Kraalbaai, Krb is Kreeftebaai, Tsb is Tsaarbank, Br is Black Rock, Gbk is Geelbek, Gb is Gabbro Point. Sample sites are indicated along with their calibrated radiocarbon ages (Table 1).

tively straight, steeply sloping beach separated by rocky headlands (CORBETT, 1989). The weather patterns influencing the southern section of the West Coast are linked to the temperate westerlies. Swell waves generated in the southern Atlantic Ocean approach the coast obliquely from a southwest direction. In winter, because of the northerly migration of the westerlies wind belt, the coastline is subject to periods of intense northwest storm winds. The coastline is therefore predominantly exposed to long-amplitude southwest ocean swells, and the net transport direction of seabed material is northward owing to the prevailing southwest swell direction. However, during winter storms, there are periods of high-intensity northwest winds that result in significant transport of beach material south (SWART, 1983; SWART and FLEMMING, 1980).

Sixteen Mile Beach is one of a series of log-spiral sandy beaches in South Africa (BREMNER, 1983) that extends for 26 km between the rocky headlands at Yzerfontein and Oude Post. Small rocky outcrops are also present at Gabbro Point and at Black Rock (exposed only during spring tide). These rocky outcrops are of the Late Precambrian to Cambrian Cape Granite Suite and range in composition from granite to gabbro. The region is covered extensively by Quaternary aeolianites and calcarenites (DALE and MCMILLAN, 1999; PETHER, ROBERTS, and WARD, 2000; ROGERS, 1980; TANKARD, 1976). Along with igneous headlands, the Pleistocene and Holocene dunes make up the western peninsula that separates Langebaan Lagoon from the Atlantic Ocean (Figure 2). The variably cemented, intertidal shelly beach sands of the Eemian Velddrif Formation are overlain by aeolianites and calcrete horizons of the Langebaan Formation. The age of the 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).

The Sixteen Mile Beach Complex is composed of a sandy beach, coast-parallel dune ridges, and a dune cordon (Figure 2). Active foredunes and numerous coast-parallel vegetated relict dune ridges are found behind the northern part of the beach. These coast-parallel dunes have prograded seaward in response to the overall regression since the mid-Holocene 3-m high stand (COMPTON and FRANCESCHINI, 2005). At the southern end of Sixteen Mile Beach, a cordon of vegetated and nonvegetated Holocene dunes (Witzand Formation) extends 24 km inland to the north (Figure 2). The dunes contain several roads and fences and have been partially planted for stabilization 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, semiarid climate with a mean annual rainfall of 240 mm, received mostly during the winter months between May and August (Figure 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 southern Western Cape, the winds are highly variable. In Cape Town the winds are predominantly from the south–southeast, whereas at Langebaanweg, 12 km east of the study area, the predominant wind direction is from the south to southwest (Figure 1). 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 study area, but gale-force winds exceeding 52 km/h are experienced less than 4% of the year (SA WEATHER BUREAU, personal communication, 1998). Waves generated in the Southern Ocean, and local wind-generated surface waves, approach the Atlantic coastline obliquely, approximately from the southwest (SWART, 1983; SWART and FLEMMING, 1980). The coast is microtidal (mean spring tide range of 1.4 m and a maximum astronomical tidal range of 2 m) 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; annual net longshore transport is to the north (SWART and FLEMMING, 1980). Beach sand compositions vary from 85 wt% terrigenous material in Table Bay to 60 wt% terrigenous material along Sixteen Mile Beach (FRANCESCHINI, COMPTON, and WIGLEY, 2003). The decrease in terrigenous material northward along the southern part of the West Coast reflects the decrease in terrigenous sand delivered by rivers. False Bay and Table Bay have perennial rivers that drain catchment areas receiving an average annual rainfall of 600 mm, whereas ephemeral rivers with small catchment areas drain the semiarid West Coast region south of Saldanha Bay (273 mm of annual rainfall at Langebaan).

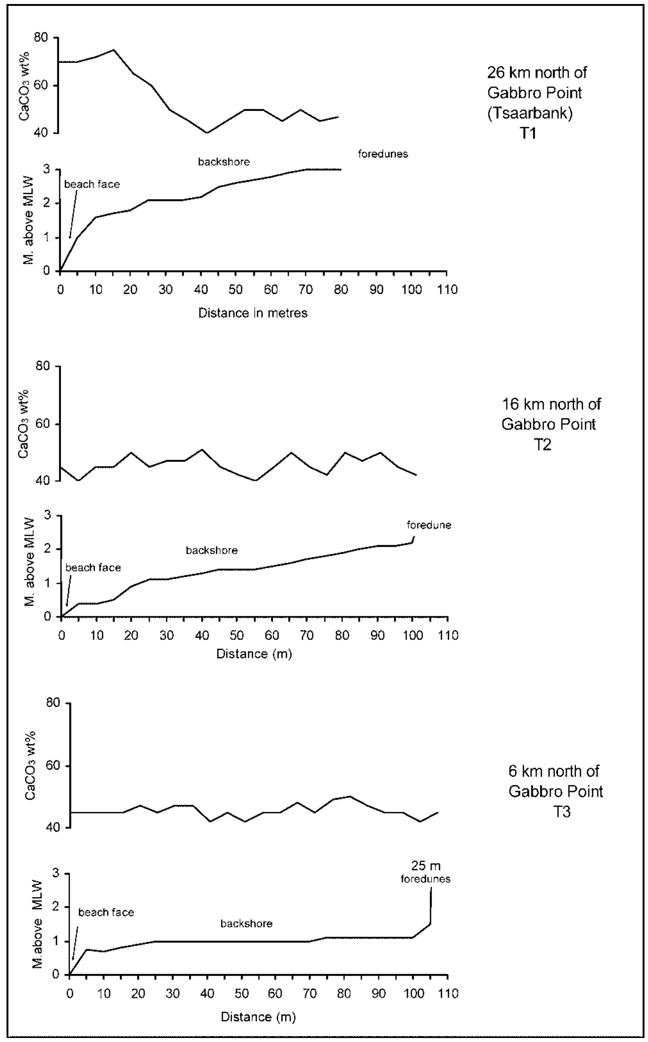

Figure 3. Beach profiles and calcium carbonate weight percent along the three transects of Sixteen Mile Beach (Figure 2).

METHODS

A total of 27 samples of approximately 1 kg of beach sand were collected every kilometer between the rocky outcrops at Gabbro Point at the southern end and Tsaarbank at the northern end of Sixteen Mile Beach. Samples were taken 10 cm below the surface at mean high water (MHW) 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 end (T3) of the beach located 6, 16, and 26 km north of Gabbro Point, respectively (Figures 2 and 3). Beach profiles were measured using a 50-m long tape and a staff. Sand samples were collected in rocky pools at Yzerfontein, Gabbro Point, and Tsaarbank. Dune sand was sampled from 50 to 60 cm below the surface of the active and vegetated Yzerfontein–Geelbek dune cordon at 6, 12, 18, and 24 km from the coast (Figure 2).

Bulk beach sand samples were air dried and organic material, mostly fragments of kelp, was removed. The beach sand was then dry sieved through 1000-, 500-, 250-, 125-, and 63-μm mesh sieves. The calcium carbonate content of the bulk sand was determined by digestion in 3% HCl. Foraminifera were picked from the beach and dune samples, and identified using a scanning electron microscope.

Conventional radiocarbon ages of bulk beach and dune samples were determined by the Quaternary Dating Laboratory at the Council for Scientific and Industrial Research

Table 1. *Radiocarbon analyses of bulk samles and AMS date from Sixteen Mile Beach and surrounding coastal dune areas. The location of the samples is shown in Figure 2. (Pta = Pretoria; LLNL = Lawrence Livermore National Laboratory.)*

Sample	Material Analyzed	Analytical No. Pta-	δ ^{13}C‰ PBD	^{14}C Age (BP)	^{14}C Age (Calibrated, BP)	2 σ Range (Calibrated, 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	19,725	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
B3†	Pink grains	LLNL 104274	0.0	2,875 ± 35	2,370	2,345–2,450

* From Compton and Franceschini, 2005.
† AMS sample.

in Pretoria (Table 1) Selected, hand-picked shell fragment grains from the bulk beach sample B3 were analyzed by AMS at Lawrence Livermore National Laboratory (Table 1). Calibrated ages were determined from the CAL4C (WC93) program (Talma and Vogel, 1993), which uses the marine data set of Stuvier and Braziunas (1993) and assumes a reservoir age of 550 y for upwelled surface waters off the West Coast. Calibrated ages are reported as ka [thousands of years before the present (1950)].

RESULTS

Sixteen Mile Beach

The steepness of the beach face and backshore increases from south to north (Figure 3). The beach sand is primarily composed of quartz grains and shell fragments. The carbonate shell content of the bulk sand collected from the three beach transects ranges from 41 to 78 wt%. The carbonate shell content becomes increasingly variable from south to north, and there is an overall increase in the percent carbonate sand from south to north (Figure 3). The carbonate shell content is greatest adjacent to the rocky headlands at Tsaarbank, where abundant shells are fragmented against the rocks. Carbonate shell fragments are primarily derived from mollusks 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*), which also occurs as gull-dropped shells on the wind-deflated foredune surface. The black mussel (*Choromytilus meridionalis*) along with several species of gastropod and barnacle are locally abundant near rocky shorelines. A total of three nonabraded genera of benthic foraminifera were recovered from all of the rocky pool areas. *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.

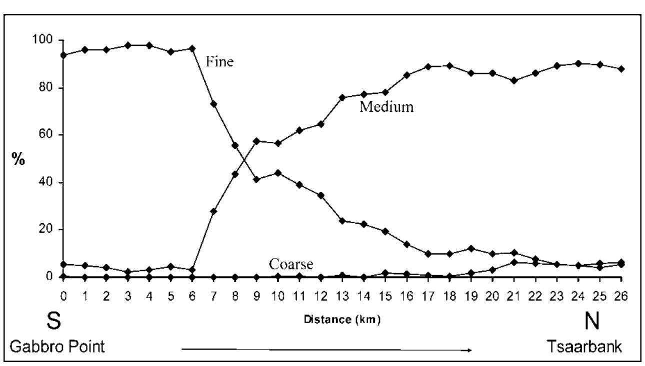

Figure 4. Grain size distribution of bulk sand samples from mean high tide along Sixteen Mile Beach.

The grain size of bulk sand collected at MHW increases northward (Figure 4). The sand is uniformly composed of 95% fine sand and 5% medium sand to 6 km north of Gabbro Point. The medium sand size fraction increases rapidly from 5% to 58% between 6 and 9 km. The medium sand fraction then increases gradually from 58% to 89%, and the fine sand fraction decreases from 41% to 10% between 9 and 17 km. 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. The sand from 23 to 26 km is 89% medium sand, 6% coarse sand, and 5% fine sand (Figure 4).

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 toward 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; Figure 2).

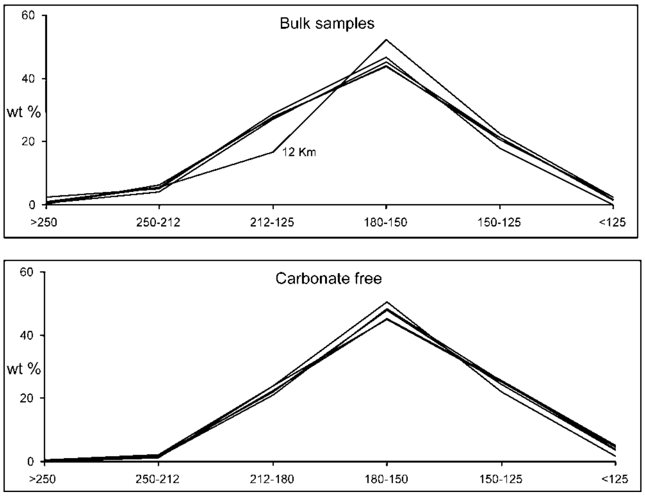

Figure 5. Grain size distribution in bulk sand samples from the Yzerfontein–Geelbek dune cordon.

Yzerfontein–Geelbek Dune Cordon

The Yzerfontein–Geelbek dune cordon has an area of ~43 km^2 and consists of vegetated parabolic ridges and nonvegetated, active barchanoid dune fields. The Yzerfontein–Geelbek dune cordon extends 24 km inland in an N/NNE direction and, prior to invasion by alien vegetation, mobile barchanoid dune fields occur approximately 0–8, 9–11, 13–14, and 17–19 km from the coast (Figure 2). Comparison of a series of aerial photographs taken between 1938 and 1993 indicates that movement of barchanoid dune fields is highly erratic but that, on average, active dune fields have migrated at a rate of 3.6 m/y. Surveyed archaeological sites within the Geelbek dune field show that individual 15-m high barchanoid dunes can migrate inland at a rate of 5 m/y (N. Conard, unpublished report, South African National Parks, 2000). The aerial extent of the nonvegetated dunes has decreased by approximately 25% since 1938 from the invasion of alien vegetation.

Bulk sand samples collected from the mobile dune sand 6, 18, and 24 km inland are all well sorted and have similar grain size distributions (Figure 5). Carbonate-free samples also have a grain size distribution similar to bulk samples with a mean grain size of 180–150 μm. The exception is the sample from 12 km, which is composed of significantly finer grained carbonate sand than the other active dune cordon samples. Dune samples from vegetated areas, both bulk and carbonate-free samples, also have a mean grain size of 180–150 μm and also show a decrease in the 250–212-μm size fraction between 6 and 24 km (Figure 5). The carbonate shell content of the mobile dune cordon 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. The vegetated dunes show the same trend, but the percentages are lower (from 31% at 6 km to 2% at 24 km). The skeletal fraction of the dune sand is mainly composed of bivalve fragments, echinoid spines, foraminiferal tests (mostly *Elphidium* and *Ammonia*), and barnacle plates. Microfossils from the dune cordon show progressive abrasion downwind such that species identification is difficult beyond 12 km inland. No foraminiferal tests were found at 24 km inland. The organic content of the vegetated dune sand increases from 1 wt% at 6 km inland to 3 wt% at 24 km inland.

Radiocarbon ages of the bulk carbonate fraction of sand samples from the dune cordon range from 18.3 to 22.9 ka (Table 1; Figure 2). The mobile dunes have a radiocarbon age of 19.4 ka at 6 km inland, 22.1 ka at 12 km inland, and 22.2 ka at 18 km. 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, 18.5 ka at 18 km inland, and 22.9 ka at 24 km inland.

DISCUSSION

Sediment Distribution

The Sixteen Mile Beach Complex can be divided into three distinct regimes based on the variation in the beach sand grain size and dune morphology. The southern end from Gabbro Point to 6 km north is almost entirely composed of fine sand and is the take-off point of the 24-km long Yzerfontein–Geelbek dune cordon (Figure 2). In the central part, between 6 and 18 km north of Gabbro Point, there is a rapid decrease in the fine sand fraction from 96% to 10% that coincides with the transition from the inland dune cordon to a single, large coast-parallel dune ridge. The northern part of Sixteen Mile Beach, from 18 to 26 km north of Gabbro Point, consists of 83–90% medium sand with up to 6 wt% coarse sand, a narrow, steep backshore, and a series of prograded, vegetated coast-parallel inland dune ridges.

The variation in grain size of the beach sand along Sixteen Mile Beach reflects the amount of wave energy received from the predominant southwest swell. The variation in dune morphology in turn reflects the beach profile and grain size of the sand exposed to the strong southerly to southwesterly dry summer winds (Figures 3 and 4). The wave energy received along Sixteen Mile Beach generally increases to the north where the waves more directly impact the coast. The southern end receives less wave energy because it sits in the shadow of the rocky Yzerfontein headland as well as Dassen Island located 10 km southeast of Yzerfontein (Figure 1). Much of the energy of the predominant south to southwesterly swell is lost breaking upon and refracting around these rocky shores. The abundance of fine sand is consistent with the width and gentle gradient of the backshore along the southern part of Sixteen Mile Beach (Figure 3), a feature observed on beaches elsewhere in southern Africa (*e.g.,* Marker, 1987). Dassen Island is particularly important in explaining the extent of the fine sandy beaches because the projected wave shadow coincides with the rapid decrease in the fine sand fraction from 96% to 76% between 6 and 7 km north of Gabbro Point (Figure 4). The changes in grain size and backshore gradient are also reflected in the offshore bathymetry, with both the 30- and 50-m bathymetric contours narrowing by more than a factor of two between the southern and northern ends of Sixteen Mile Beach (Figure 2).

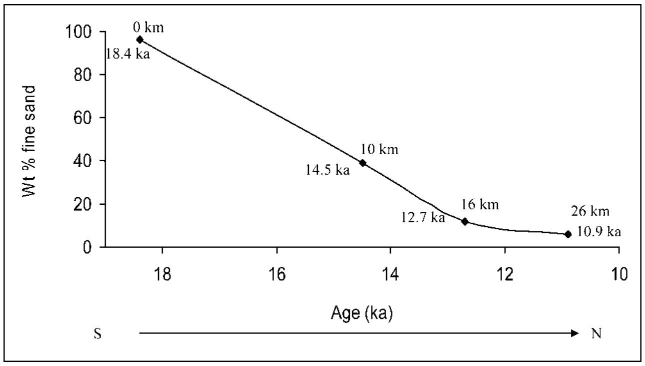

Figure 6. Age of bulk sand samples from Sixteen Mile Beach plotted against percent fine sand fraction.

Table 2. *Texture of beach and dune sands from the Sixteen Mile Beach Complex indicating the percent colored, clear, and opaque carbonate grains.*

	Colored (%)	Clear (%)	Opaque (%)
Gabbro Point	5	20	75
Active foredune	2	5	93
Beach sample B3	5	20	75
6-km dune cordon	2	18	80
12-km dune cordon	0	10	90
18-km dune cordon	2	15	83
24-km dune cordon	0	10	90
Tsaarbank	5	55	40
Active foredune	15	50	40
Pleistocene dunes	0	3	97

The accumulation of fine sand as broad, low gradient beaches in the semiprotected waters at the south end of Sixteen Mile Beach provides the source of sand blown inland to form the Yzerfontein–Geelbek dune cordon. The dune cordon is a patchwork of vegetated and nonvegeted dunes. The mobile, nonvegetated irregular barchanoid dunes, of for example the Geelbek Dunefield, move rapidly enough (3.6 to 5 m/y) to avoid stabilization by vegetation. Aerial photographs spanning the last 55 years indicate a complex pattern of dunefield movement within the cordon influenced by climate (rainfall, wind) and fire. The slight downwind decrease in the dune cordon sand size indicates preferential transport of the finer sand grains, whereas the decrease in carbonate reflects dissolution by rain as well as mixing with leached quartzose, upper Pleistocene palaeosols. Planting of aggressively invasive alien vegetation (primarily *Acacia cyclops* and *A. saligna*) has resulted in the stabilization over the last 40 years of much of what were mobile dunes at the southern end of the dune cordon.

Similar to the Yzerfontein–Geelbek dune cordon, the major dune cordons at the Cape Flats and Atlantis occur upwind from relatively low-energy beaches protected from the southwest ocean swell by the Cape Peninsula and Robben Island, respectively (Figure 1). The northward decrease in the aerial extent of the dune cordons from 243 km^2 at the Cape Flats, 88 km^2 at Atlantis, and 43 km^2 at Yzerfontein reflect the rapid decrease in river sediment discharge north of Table Bay (FRANCESCHINI, COMPTON, and WIGLEY, 2003).

The transition from the inland dune cordon to a single, large coast-parallel dune ridge coincides with a rapid increase in medium sand 8 km north of Gabbro Point (Figure 4). The marked change in dune morphology reflects the decrease both in the width of the backshore and in the mobility of medium sand, both of which limit the amount of inland sand transport by wind. A single, large, coast-parallel dune ridge continues to 17 km north of Gabbro Point as the percentage fine sand decreases steadily to 10%. From 19 to 26 km the coarse sand size increases to 6% along the beach and a series of older, vegetated Holocene coast-parallel dune ridges occur inland of the actively accreting foredune ridge. The active coast-parallel dune ridge is mostly accreting vertically. The crest and leeward side of the active, seaward dune ridge is partially vegetated and is migrating inland as beach sand bypasses the deflated dune face, which in many places is covered by a layer of gull-dropped bivalve shells to accumulate in small partially vegetated dunes at the crest of the dune ridge. The wind preferentially removes fine sand from the beaches at the northern end of Sixteen Mile Beach as indicated by the significantly higher fine sand content (75%) of the coast-parallel dune ridges. The dune ridge also migrates inland by large parabolic blow outs. The mean grain size of the wind blown sand is greater, and as a result the rate of inland movement is much slower than that of the southern dune cordon. Based on aerial photographs, the maximum rate of inland migration over the last 50 years is on the order of 0.4 to 2 m/y at the northern end of the dunes. The vegetated coast-parallel dune ridges extend over the much larger 40–60 m high Pleistocene dune ridge inland to the edge of the peninsula at Kraalbaai. Radiocarbon ages indicate that these dune ridges have prograded seaward since 7 ka in response to variations in sediment supply and sea level (COMPTON and FRANCESCHINI, 2005; FRANCESCHINI, 2003). Therefore, the northern end of Sixteen Mile Beach has prograded seaward as a series of coarser grained coast-parallel dune ridges, whereas fine sand at the southern end has migrated farther inland as a dune cordon consisting of a series of episodic, rapidly moving dune fields.

Radiocarbon Ages of Sixteen Mile Beach

The progressively younger age of bulk sand along Sixteen Mile Beach from 0 to 26 km north of Gabbro Point corresponds to an increase in grain size (Figure 6). The correlation between age and percent fine sand indicates an end member mean age of the fine sand of approximately 18.8 and 11.5 ka for the medium sand. The bulk age of 10.9 ka of the sand sample from Tsaarbank, 26 km north of Gabbro Point, falls off the age trend in Figure 6 because it contains 6 wt% coarse, presumably younger, sand grains. In addition to the percent fine sand size, the percentage of colored and transparent grains tends to decrease with increased age of the sand samples (Table 2). Sand-size fragments of modern mollusk shells are more colored and transparent, and less abraded and rounded than older shell fragments observed in samples of upper Pleistocene aeolian deposits at Yzerfontein and Langebaan Lagoon. The Pleistocene dune samples contain no colored grains but do contain a minor component of transparent grains. Therefore, the northward trend to younger ages can be attributed to a greater mean grain size and a greater proportion of recently broken shell material.

The AMS age of 2.4 ka for pink and purple colored carbonate grains (~300), handpicked from the bulk sand sample B3, 4 km north of Gabbro Point with a bulk age of 18.4 ka, indicates that the sand is a mixture of young and old shell fragments. The young colored carbonate grains are derived from the fragmentation of fresh shells whereas the old shell fragments are derived from the reworking of Pleistocene beach and dune deposits. The percent of colored grains in sample B3 is 5% and implies that the majority of the fine sand was derived from reworking of older deposits whose carbonate grains contain little if any ^{14}C.

The bulk beach sand ages can be corrected for the mixing of old, opaque carbonate grains by assuming that all of the ^{14}C resides in the colored and clear grains. In addition to 5% colored grains, sample B3 contains around 20% clear carbonate grains (Table 2). If the opaque grains are assumed to contain no ^{14}C, then the remaining 25% colored and clear grains in sample B3 have a mean age of 7.4 ka (40% modern carbon). The beach sample L13 from 26 km north of Gabbro Point (Tsaarbank) contains 5% colored and 55% clear grains. If it is assumed again that all of the radiocarbon in sample L13 resides in the 60% colored and clear grains, then they have a mean age of 7.4 ka. Therefore, the age of the colored fine sand in sample B3 of 2.4 ka and the similar mean age of 7.4 ka for the colored and clear grains of samples B3 and L13 indicate that the northward trend of decreasing age mostly reflects an increase in the percentage colored and clear grains rather than simply grain size. This implies that the fragmentation of carbonate shell produces a wide range of grain sizes simultaneously rather than progressively producing smaller grains over time as suggested by Illenberger and Verhagen (1990).

These older, recycled carbonate sand grains were eroded from older dune and beach deposits as well as perhaps transported across the shelf by the migrating strandline as the sea level rose. The relative significance of the two sources is not known, but recent erosion of uppermost Pleistocene beach sand (Velddrif Formation) and dune sand (Langebaan Formation) is clearly visible along parts of the coastline. Strandline migration of sands across the shelf during the most recent marine transgression has been documented in Australia and elsewhere (Bird, 1978, 1996; Bird and May, 1976). Erosion of carbonate sand from the 79 to 117 ka Velddrif and Langebaan formations would contain no ^{14}C, whereas migrated strandline beaches would contain at least some ^{14}C. The high opaque carbonate grain content in the fine sand of Sixteen Mile Beach may result from the large amount of fine sand derived from the erosion of uppermost Pleistocene dune deposits that have a high proportion of ^{14}C-free fine carbonate sand. The high percentage of colored and clear medium sand grains appear to indicate that they are derived primarily from strandline migration of more recent beach sand across the shelf. Therefore, radiocarbon analysis of the bulk sand samples yields maximum ages that depend on how much ^{14}C-dead carbonate they contain. The percent dead carbonate is difficult to quantify from the texture of the grains and complicates the interpretation of bulk sand ages.

In summary, the majority of sand on Sixteen Mile Beach is recycled. Much of the fine sand is derived from the erosion of Pleistocene dune deposits formed during the previous sea-level high stand and much of the medium sand is derived from the migration of beach sand as the strandline transgressed over the shelf since the Last Glacial Maximum. Fragmentation of shell along this high-energy, rocky coast has continually added younger carbonate grains of widely varying grain size to this large reservoir of recycled sand since sea level has returned to its present-day position. The AMS age of 2.4 ka for the fine-fraction colored grains is interpreted to represent the mean age of this Holocene beach sand established approximately 5.5 ka when sea level returned to its near present-day position (Compton, 2001). The mid-Holocene sea-level high stand of approximately +3 m eroded large quantities of sand from the uppermost Pleistocene beach and associated Yzerfontein–Geelbek dune deposits. After the high stand and a return to sea level at more or less present-day levels (±1 m), the beach stabilized and the breakdown of shell material was continually added to the beach since approximately 5.5 ka. The abundance of recycled sand is consistent with this section of generally sediment-starved coast with the closest perennial river located 80 km south (Figure 1).

Radiocarbon Ages of the Yzerfontein–Geelbek Dune Cordon

Subtracting 18.4 ka, the average age of the source of fine sand at the southern end of Sixteen Mile Beach, from the age of the mobile dune sand samples gives corrected ages of 1 ka at 6 km, 3.7 ka at 12 km, 3.8 ka at 18 km (Geelbek dune field), and 4.5 ka at the most distal and vegetated dunes 24 km inland (Figure 2). The corrected age of the mobile dune samples increases with distance from the beach (Figure 2). The mean dune migration rate of 5.3 m/y is higher than the average of 3.6 m/y measured from aerial photographs spanning the last 55 years but comparable to the rate of 5 m/y measured within the Geelbek dune field. The older than expected age of the sample collected at 12 km inland is attributed to its finer carbonate grain size and to fewer colored and clear carbonate grains (Table 2), and suggests that it may have a greater proportion of reworked sand from the underlying uppermost Langebaan Formation dune deposits. The less consistent and generally younger ages of the vegetated dune sand samples within the Yzerfontein–Geelbek dune cordon are attributed to partial recrystallization of the carbonate in association with soil processes of evaporation, growth of roots, and fungus (Geyh and Schleicher, 1990; Grootes, 1983). The corrected ages suggest that the dune cordon has been active since 4.5 ka. An age similar to the 5 ka Cape Recife and Cape St. Francis headland bypass dune fields located in the Eastern Cape (Illenberger, 1988).

The bulk sand carbonate ages and distribution of large mobile dune fields suggest a complex evolution of the Yzerfontein–Geelbek dune cordon during the Holocene influenced by variations in sand supply, sea level, and climate. Sand supply and sea level are believed to be closely linked because of the large percentage of recycled sand from the erosion of older deposits during marine transgressions. The presence of large dune fields within the dune cordon suggests that the sand supply has not been continuous. Pulses of sand in the form of discrete dune fields are commonly observed. For example, the Swartlintjies River dune cordon, located 350 km north of Yzerfontein (Figure 1) has a similar inland reach of 24–27 km, with active dune fields located at 0–7, 11–14, and 21–25 km from the coast (TANKARD and ROGERS, 1978). Three major pulses of sand were proposed for the Holocene Algoa dune fields on the South Coast (ILLENBERGER, 1988). These pulses may result from a sudden increase in sand supply to the beach from erosion during relatively modest marine transgressions or increased supply of sand to the coast via rivers. However, the abundance of recycled older carbonate at Sixteen Mile Beach would suggest that erosion of Pleistocene dunes has been more important than an increase in shell production on the coast or sand supply from rivers.

Pulses of sand as large mobile dune fields in the Yzerfontein–Geelbek cordon are believed to mostly represent relatively modest (±1 m) Holocene sea-level fluctuations. Because of the strong onshore wind, the majority of the large increase in sand supplied to the beach from the erosion during a rise in sea level of previous dune deposits is recycled via the beach and offshore sandbars back onto land (COOPER, 1958, p. 131). In the case of a rapid and large sea-level rise, dunes can be abandoned and submerged offshore. In a modest sea-level fall, the beach is momentarily starved of sand and there is less sand fed into the mobile dune cordon until a new beach is established. At the northern end of Sixteen Mile Beach, the beach has prograded seaward as a series of abandoned dune ridges since the mid-Holocene high stand (COMPTON and FRANCESCHINI, 2005; FRANCESCHINI, 2003). In the south, the abandoned foredune continued to migrate inland. Therefore, the minor fluctuations in Holocene sea level along the coast inferred from the salt marsh deposits in Langebaan Lagoon (COMPTON, 2001) resulted in variations in the sand supply to the beach and the transport of sand inland. In addition to sea-level fluctuations, changes in climate (rainfall, wind strength) and destabilization of dune sand after fire would have modified the amount of sand transported inland. 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 stabilized, at least temporarily, in vegetated trailing parabolic ridges. These complexities in dune movement may account for the variable distribution and age of active dune fields among South African coastal dune cordons.

CONCLUSIONS

Radiocarbon dates used in conjunction with sand texture and grain analyses in this study indicate a complex Holocene history of coastal evolution in the Sixteen Mile Beach Complex. Longshore transport of sand is not uniform with the northward coarsening from fine to medium sand along Sixteen Mile Beach related to coastal morphology. The southern end of the complex in the lee of a rocky headland and offshore island has fine beach sand. This low-energy environment 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 south–southwest deflate the beach. From the southern part of Sixteen Mile Beach, the fine sand is rapidly introduced to the Yzerfontein–Geelbek dune cordon stretching 24 km north. The northward increase in medium and coarse beach sand reduces the amount of material available for beach deflation. 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. Landward of the active foredune, stable coast-parallel dunes cut by parabolic blowout features are present.

River sand and recycled beach and dune sand are the most important sources of quartzose sand to the beach complex. In addition to this quartzose sand, sand grains are derived from the breakdown of carbonate shells, invertebrate skeletons, and other carbonate material. River transport and carbonate productivity along the coast provide a constant supply of sand to the Sixteen Mile Beach dune system via the beach. The northward increase of carbonate sand along Sixteen Mile Beach is related to the coastal morphology, with rocky headlands at the northern end densely populated by shellfish.

The use of radiocarbon dating on bulk beach and dune sand samples must take into account the presence of reworked, ^{14}C-dead carbonate grains. In this study, radiocarbon ages are corrected by the percent pink and purple grains derived from the breakdown of recent shells. The age of the fresh pink and purple grains is 2.4 ka, and the corrected mean age of the bulk fresh carbonate fraction is estimated to be 7.4 ka. These results suggest that the breakdown of shells proceeds by the simultaneous production of fine and medium sand sized grains. The corrected radiocarbon age for the Yzerfontein–Geelbek dune cordon is 4.5 ka, which is in agreement with the age of Holocene dune cordons located in the Eastern Cape (ILLENBERGER, 1988) and the return of sea level to near its present-day position by 5.5 ka (COMPTON, 2001). Sand movement along the active dune cordon is complex and related to changes in climate, particularly rainfall, which influences vegetation and dune stability.

The South African coastline extends for more than 3000 km. Sandy beaches compose 80% of this coastline, and enormous dune systems have been deposited throughout the coastal areas of South Africa since the Late Tertiary. The aim of this study 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 future.

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