

Historical Development of a Foredune Plain at Desperate Bay, Western Australia

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ABSTRACT

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Coastal accretion in Desperate Bay at Coolimba on the Central West Coast of Western Australia has resulted in formation of a small foredune plain. Since the area was first surveyed by aerial photography in 1944 the plain, which is approximately 150 metres wide and 1 km long, has partially filled a sheltered embayment and has linked with an islet to form a small tombolo. Deposition was particularly rapid between 1965 and 1990 with approximately 97,000 m³ accumulating on the coast during that time. Such levels of accretion are unusual in Western Australia and apparently elsewhere. Development of the plain has been investigated photogrammetrically through a geographic information systems (GIS) analysis of maps of shoreline movement and sequential aerial photography, field surveys of marine processes and coastal stratigraphy, and laboratory analyses of sediment characteristics and distribution. Historical records of shoreline movement show that the plain developed rapidly, with much of its formation taking place since 1965. Stratigraphic surveys are consistent with interpretation of the historical records that the plain has developed within recent historical time. Sediments within the landward part of the stratigraphic sequence include nylon rope similar to that currently used by the local rock lobster fishery. They also indicate that deposition of sediment occurred gradually, albeit with some variation in quantity induced by storm activity and deposition of wrack on the beachface. The process measurements indicate that mechanisms for deposition are related to increased southerly wind activity, coincidental with a decline in the frequency of northwesterly storm events during the past 30 years, and formation of a tombolo in the northern part of Desperate Bay. Foredune formation in Desperate Bay has occurred in an environment where there are very low levels of wave and tidal activity, compared to sea level ranging associated with frequent storm events. The foredunes have formed in response to intermittent washover of the backshore area of the beach during winter storms, when water levels and wave heights are raised. The storm deposition contributes sediment to the upper surface and lee side of the active foredune ridge to heighten and broaden it while producing a slow migration inland. Subsequent calm-weather accretion contributes a small aeolian cap to the foredune, gradually widens the beach, and eventually strands the ridge. In this respect, the foredunes of this very low energy coast primarily are considered to be a function of local surge height, and secondarily a result of sediment trapping by pioneer vegetation. However, more direct measurements of sediment transport processes and their interaction are required to test this proposition.

ADDITIONAL INDEX WORDS: *Coastal accretion, tombolo, shoreline movement, beach ridges.*

INTRODUCTION

Foredune plains have been examined from numerous locations around the world and several models proposed for their mode of formation. In Australia much of the literature has focussed on examples of relict foredune ridges. For example, BURGESS and DROVER (1953); GARDNER (1955); GILL and BANKS (1956); DAVIES (1957, 1958, 1961); MCKENZIE (1958); JENNINGS (1959); BIRD (1960, 1961, 1963, 1965, 1969, 1976); THOM (1964, 1965); JENKIN (1968); HAILS (1969); WRIGHT (1970) and HESP (1982, 1983, 1984a, 1984b). Foredune plains that have formed within the historical period are apparently unusual in Australian coastal environments (THOM, 1964; HESP, 1984a, 1984b; and SHEPHERD and ELIOT, 1995), although they may be common to the downdrift, leeward flanks of cusped forelands on the central west coast

of Western Australia (MAXWELL, 1995) between Cape Naturaliste and Geraldton (Figure 1).

Morphostratigraphic investigation of a small foredune plain at Desperate Bay, Western Australia (Figure 1) was undertaken in conjunction with examination of shoreline change over the past 40 years to establish its mode of formation and to provide additional insight into the formation of beach ridge sequences on the low wave energy, central west coast of Western Australia.

Aim

The coast is predominantly accreting within Desperate Bay, a shallow embayment north of the main area of squatter occupation at Coolimba, on the central west coast of Western Australia (Figure 1). As a result, a 150m wide foredune plain has formed in the embayment, on the northern, downdrift side of the rocky headland and seaward of high parabolic

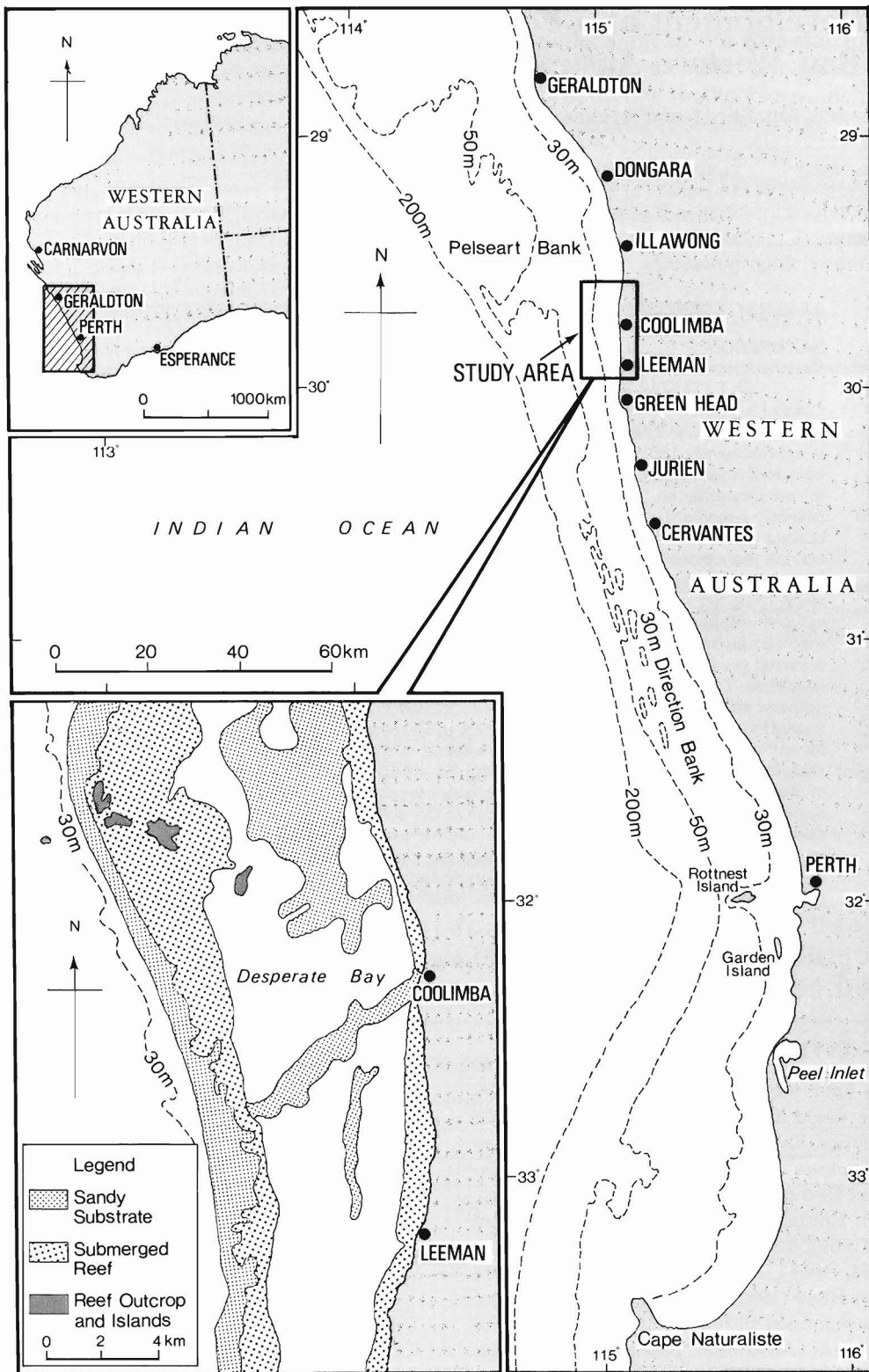


Figure 1. Regional setting of the foredune plain at Desperate Bay, Western Australia.

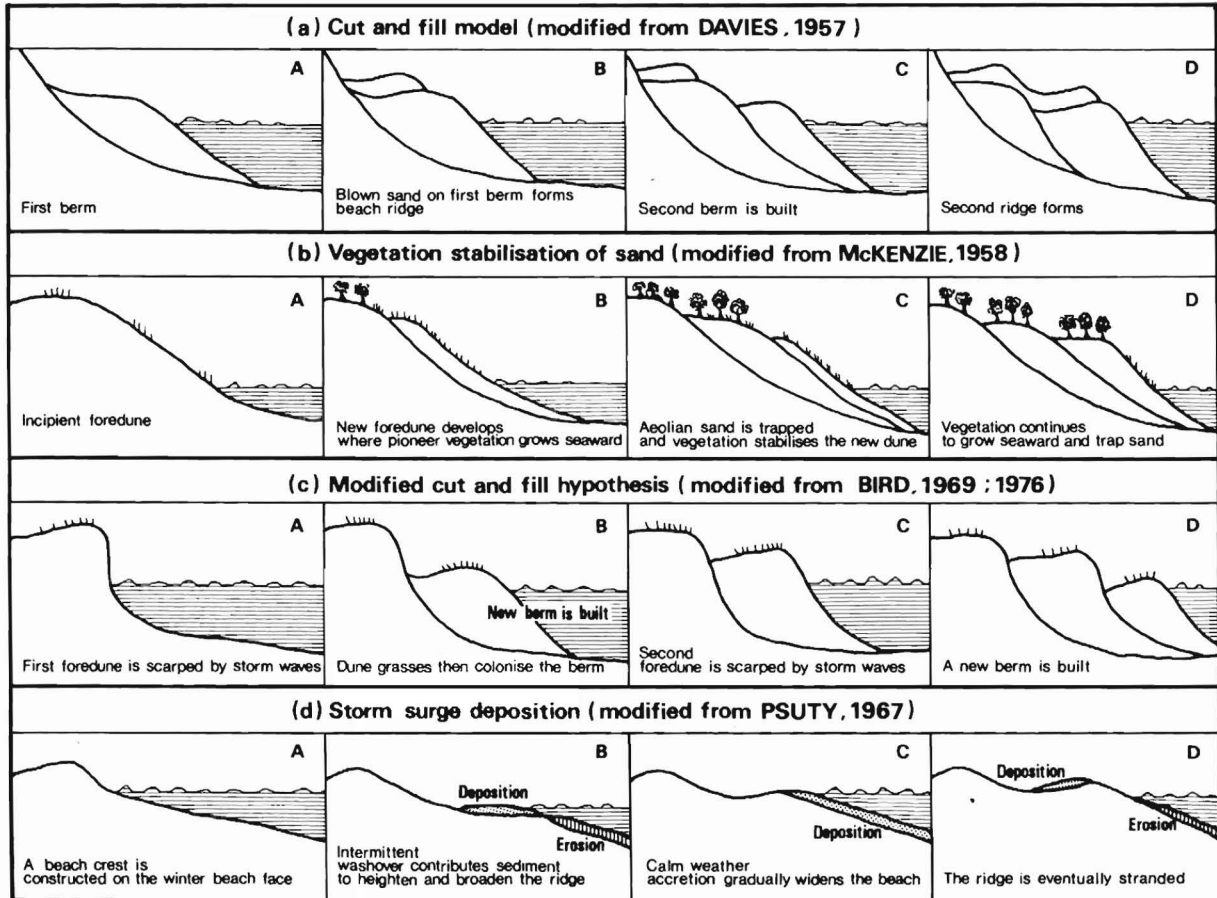


Figure 2. Fore-dune plain development models.

dunes. Further, an islet at the northern end of the embayment has become tied to the shore within the period for which records of shoreline change are available. Maps of shoreline movement occurring between 1944 and 1982 (PUBLIC WORKS DEPARTMENT, 1983; now the Department of Transport), show that the shoreline was undergoing erosion from 1944 to 1965. It then advanced seaward until 1982 when the plain had substantially formed.

In the historical context, consideration of modern shoreline stability at Desperate Bay necessarily includes examination of the contemporary oceanographic processes in the area as well as stratigraphic development of the foredune plain. Hence, field surveys of the nearshore water circulation system and stratigraphic investigations of the dune sequence have been undertaken. They were conducted to establish the

- (1) stratigraphy of the Coolimba foredune plain;
- (2) rate and style of development of the beach ridges;
- (3) type of beach sediments being supplied to the foredune plain;
- (4) direction of sediment transport along the shoreline; and
- (5) possible relationships between contemporary atmospher-

ic and nearshore processes and development of the fore-dune plain.

Context

TAYLOR and STONE (1996) recently reviewed literature on beach ridge and foredune plain development, emphasising the diversity of models describing evolution of beach ridges in coastal settings. They also examined causative mechanisms used to elucidate the genetic models and identified common linkages between the disparate groups of models. Four modes of foredune ridge development have been debated and modified by a number of researchers in Australia (THOM, 1964, 1965; JENNINGS, 1959; JENKIN, 1968; HALLS, 1969; WRIGHT, 1970; DAVIES, 1977, 1980). These are illustrated in Figure 2. In the debate, discussion ranged around the relative contribution of marine versus aeolian processes in ridge formation. HESP (1988) has since pointed out that foredune height varies with the morphodynamic state of sandy beaches of New South Wales. He notes that high foredunes are associated with energy dissipative beaches while low foredunes form on energy reflective beaches, and

that foredunes on the high energy beaches have a wider range of heights. By extension of HESP's (1988) argument, it is anticipated that foredune heights would also vary systematically with beach state for the low-energy, sheltered beaches identified by NORDSTROM (1992) and HEGGE *et al.*, (1996).

Most reported instances of foredune formation are from wave dominated coasts. In these environments sandy foredune ridges, such as those described as forming due to 'cut and fill' processes, build during fair weather conditions and erode during storm events on wave dominated coasts. PSUTY (1967), WARD (1983) and HESP (1984b) provide descriptions of ridge development in low energy environments that are dissimilar to this process. From field observations at Tabasco, Mexico, PSUTY (1967) describes a process in which the ridges form in a manner analogous to the construction of pebble ridges. His explanation constitutes the fourth mode of ridge building (Figure 2D). In this case, a beach crest is constructed on the winter beach during frequent winter storms when water levels and wave heights are raised. Intermittent washover deposition contributes sediment to the upper surface and lee side of the ridge to heighten and broaden it while producing a slow migration inland. Subsequent calm-weather accretion gradually widens the beach and eventually strands the ridge.

WARD (1983) and HESP (1984b) describe the formation of foredune ridges on the northern, sheltered flank of a cusped foreland at Cervantes, approximately 40 km south of Desperate Bay. The foredune ridge at Cervantes developed over a 35 year period, with the shoreline prograding between 2.0 and 5.2 m per year. Initially *Cakile* plants germinated at the upper limit of spring tide swash on the upper beach, trapping aeolian sand and forming a broad hummocky terrace. This terrace was then colonised by other plant species (especially *Spinifex longifolius* and *Tetragonia decumbens*) spreading seawards from the landward incipient dune. The foredune gradually increased in size by aeolian sand deposition accompanied by progradation of the subaerial beach. Sand supply to each ridge was reduced due to seaward progradation and the formation of new ridges, and pioneer species were replaced by intermediate and heath species in a well defined successional sequence (WARD, 1983).

HESP (1984b) did not observe successful colonisation of berm crests by pioneer plant seedlings, as suggested by DAVIES (1957), even under rapid progradational conditions. Vegetation colonisation was consistently restricted to the backshore zone at or above the spring high tide line. For the specific sites he examined, the studies of HESP (1984a, 1984b) provide evidence for an aeolian, back-beach genesis of sand beach ridges rather than the marine genesis suggested by DAVIES (1957) and BIRD (1976). Which mode of ridge development is occurring at Desperate Bay is open to question. The foredune plain has similarities with Cervantes but its general morphology is closer to that described from sheltered coast at Tabasco by PSUTY (1967).

REGIONAL SETTING

Desperate Bay is situated north of Leeman, Western Australia (Figure 1), at the western end of the Leeman-Eneabba

Road extension. The local coast is comprised of fine to medium grained calcareous Holocene sands (Safety Bay and Becher Sands) abutting and in places overlying Pleistocene Tamala limestone (SEARLE and SEMENIUK, 1985). In the vicinity of the settlement at Coolimba the shoreline is commonly rocky with calcarenite limestone headlands interspersed with sandy embayments and pocket beaches (Figure 3). Variation within these units contributes to the wide range of coastal morphology and several coastal geomorphic units can be recognised in the region. They include limestone topography, such as offshore reefs, cliffs, bluffs and headlands; foredune plains; deflation plains; and lagoonal plains. The main area of settlement at Coolimba is situated on a cliffed limestone headland. To the north lies Desperate Bay, an embayment containing the foredune plain and older Holocene dunes. Outcrops of limestone occur as pavement and reef outcrops in the nearshore zone. The coast is subject to prevailing southwesterly winds as well as the impact of summer southwesterly seabreezes and winter west to northwesterly storms.

Geology and Landforms

The central west coast of Western Australia is the coastal terrestrial fringe of the Perth Basin which flanks the Pre-Cambrian igneous, metamorphic and sedimentary rocks of the Yilgarn Craton (PLAYFORD *et al.*, 1976). The Perth Basin is underlain by Phanerozoic sediments, mainly sandstones and limestones which extend offshore to form a wide continental shelf (50 km). Quaternary coastal deposits including lithified Pleistocene calcarenites and unconsolidated Holocene calcareous sands (WOODS *et al.*, 1985) overly the Phanerozoic sediments. The Pleistocene limestones outcrop offshore as shore parallel chains of reefs and islands, and onshore as lithified dunes and rocky headlands. Holocene sediments have accumulated onshore as unconsolidated coastal dunes and subaqueously as mobile sand bodies behind the offshore reef chain (SEARLE and SEMENIUK, 1985).

The offshore reefs (Figure 1) sheltering Desperate Bay are of Pleistocene origin. They are part of a chain that provides considerable protection to the mainland beaches of Western Australia, between Mandurah and Geraldton. The configuration of the reef chain has exerted structural control on the development of coastal sedimentary accumulation forms during the Holocene and continues to do so at present. In Desperate Bay, the Holocene sediments have formed moderately high (10 m) parabolic dunes overlying Pleistocene Tamala Limestone ridges. In contrast to this, the foredune plain is low-lying, generally less than 2.5 m above mean sea level. It overlies a reef platform approximately 3–5 m below sea level.

Mechanisms underlying the formation of the plain are the subject of this project. Along the coast, the foredune plain extends from the rocky cliffs at Coolimba, adjacent to the Eneabba-Leeman Road, northwards for approximately 1 km. The plain encompasses recent tombolo development where the shoreline has built out to meet a small rocky limestone islet that was 30 m offshore in 1944 (Figure 3). The rocky island is approximately 10 m wide and 36 m long. With the tombolo, it provides a significant barrier to longshore sedi-

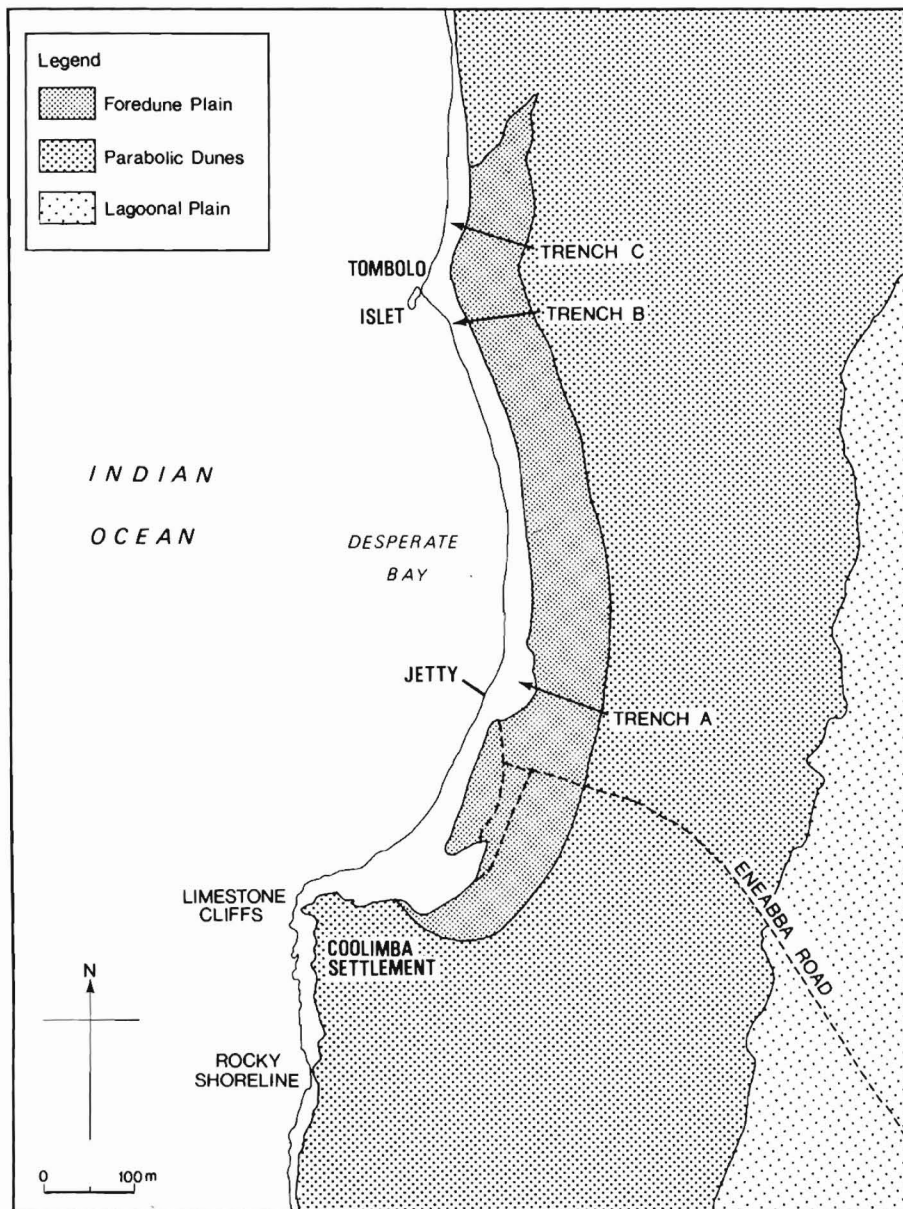


Figure 3. Surficial geology and landforms of the foredune plain at Desperate Bay.

ment transport. Across the coast, the central part of the foredune plain extends landwards from the shoreline to the first large parabolic dune, approximately 150 m from the shore. A series of foredune ridges have developed ranging in elevation from approximately 1 m to 4 m above mean sea level. The ridges have been stabilised by coastal dune vegetation, which has been described by GRIFFIN (1993). Large deposits of flotsam, mainly seaweed wrack, and some jetsam about the most seaward ridge. During extreme storm events, such as occurred during May, 1995, the wrack is strewn in swales and though vegetation on the active foredunes (author's observations).

Similar Landforms Elsewhere in Southwestern Australia

The foredune plain at Coolimba is similar in morphology to a number of other small beach ridge plains along the central and southwestern coasts of Western Australia. MAXWELL (1995) identified foredune plains along the southwestern coast of Western Australia and noted that they are characteristically found within north facing embayments and on the north sides of cusped forelands. Foredune plains within embayments include sites such as Koombana Bay, Busselton, Rockingham, Quinns and other small embayments along the

Table 1. Frequencies for daily (3pm) and wind speed and directional observations at Jurien over the period 1969 to 1996. (Data obtained from the Bureau of Meteorology, Western Australia).

Season	% Frequency of S-SW Winds	% Frequency of N-W Winds	% Frequency of S-SW Winds (>30 kph)	% Frequency of N-W Winds (>30 kph)
Summer	82	8	37	1
Autumn	60	21	11	3
Winter	33	43	3	9
Spring	69	22	15	4

Central West Coast between Perth and Dongara. Large cusped forelands such as Becher Point, Wedge Island, Kangaroo Point Cervantes, and Island Point Jurien, support extensive foredune plains on their northern flanks. Each of these sites exhibits continued accretion of the foredune ridges over the historical period.

Climate

In common with much of southwestern Australia (GENTILI, 1971), the coast near Desperate Bay experiences a Mediterranean climate with mild, wet winters and hot dry summers. Although there are no meteorological stations in the squatter settlement at Coolimba, the climatic conditions of the area can be inferred from stations at Jurien and Geraldton (BUREAU OF METEOROLOGY, 1986). Winds in the region are generated by several synoptic weather systems (GENTILI, 1971; STEEDMAN, 1977) including anticyclones, mid-latitude depressions and infrequent tropical cyclones. Strong sea breezes are experienced on approximately 60% of days per year (PATTIARATCHI *et al.*, 1993). Wind speeds in the sea breezes are frequently over 40 kph and their prevailing southwesterly winds directly influence nearshore water movement, littoral drift and aeolian transport of sand over long reaches of coast. Indeed, MASSELINK (1996) has demonstrated that sea breeze generated waves may persist in an attenuated form for several hours after the wind has ceased to blow, indicating the regional significance of the winds. Prevailing northerly alongshore drift generated by sea breeze activity in summer tends to be, but is not always, balanced by westerly and northwesterly winds associated with winter storms. Over the past 20 years storm frequency and intensity in the region has declined. Consequently there is an apparent net northerly current in the lagoonal waters of the central west coast region, including Desperate Bay.

Long term records describing the percentage frequency of wind velocity and direction have been obtained for 3.00 pm observations at Jurien from the Bureau of Meteorology, Western Australia. This is the closest meteorological station to Desperate Bay (Figure 1). The afternoon observations include the contribution of the sea breezes, particularly from late spring (November) to mid autumn (April) when they are a main source of southwesterly winds. The wind records have been averaged over a 25 year period, from 1969 to 1994, to obtain the mean wind frequencies of directional components for each season (Table 1). As anticipated, the results show that the prevailing winds are south to southwesterly, except

during winter when winds from the northwesterly quadrant prevail for almost half of the time.

Although sediment moves at lower wind velocities, winds of over 30 kph are significant contributors to sediment transport on the beaches. These winds are predominantly from the south to southwest and they drive the onshore movement of sediment through generation of wind waves, as well as through direct transport of sand on the beaches. Several indicators from Fremantle, approximately 250 km south of Desperate Bay, suggest that there has been a general decline in the frequency of storm events. The decline has occurred coincidentally with a slight increase in storm intensity (PANIZZA, 1983; SHEPHERD and ELIOT, 1995). This proposition has been examined for the wind records from Jurien where there has been a decline in the frequency of events since 1970 (Figure 4).

Oceanographic and Nearshore Processes

The micro-tides of the region have a mixed, mainly diurnal form (DEPARTMENT OF DEFENCE, 1994). Based on the nearest standard port at Geraldton, their lowest to highest astronomical tide range is 1.3 m, while the spring tide range is 0.9 m between MLLW and MHHW. Although the tidal range is low it affects coastal processes through the submergence or exposure of reef outcrops as well as through the generation of minor tidal currents. Tidal impacts on the coastal geomorphology are less marked than the impacts of wind driven water circulation, water level set-up during storm surge events, and sediment transport driven by persistent onshore winds. Indeed, local surge levels may frequently equal or exceed the spring tidal range, with surges of up to one metre occurring approximately annually during the onset of mid-latitude depressions. HEGGE (1994) has described surge from Fremantle and Geraldton and has shown that large surge elevations are associated with increasing berm widths and decreasing berm slopes. However, these effects can only be indicative because local conditions related to bay shape and orientation are likely to produce considerable geographic variation in surge elevation and duration.

Wave refraction and diffraction are also common phenomena along the central west coast. Ocean swell waves are attenuated by the offshore reef chain in the region, giving rise to relatively calm, shallow (4 to 10 m deep) lagoonal areas shoreward of the reef system. As a result, sandy beaches are considerably protected from the direct impact of the high-energy offshore swell. The presence of the offshore reef chain, with its topographic high and low areas, also causes the alongshore distribution of wave energy to be highly sensitive to deep water wave direction and to variation in the local wind wave regime (STEEDMAN, 1977). Swell may be either propagated through gaps in the reefs or attenuated by them, depending on its direction of incidence. In this respect, the processes of wave diffraction and refraction are fundamental to the distribution of wave energy along the coast, and hence to sediment transport at the shore. In Desperate Bay the main patterns of wave refraction and diffraction are determined by the offshore reef structures, particularly the reefs south of the Beagle Island complex.

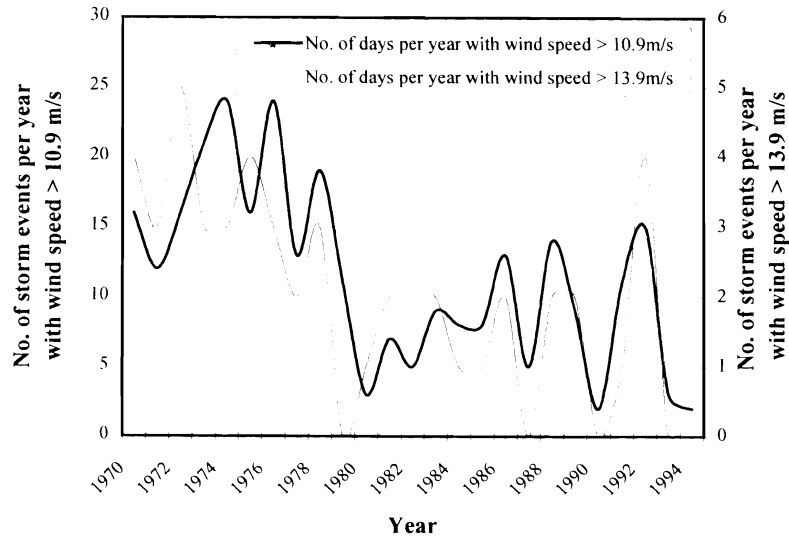


Figure 4. Storm frequency at Jurien (1970–1994).

Coastal morphology along the central west coast therefore is tied to the structure of the reefs as well as the wave and current processes associated with them (STEEDMAN, 1977). The dominant processes of the inner continental shelf, landward of the 20 m isobath include refraction, seiching, wave and tidal pumping of water across the reefs, and effects related to wave groupiness immediately after the passage of storms. The effect of the offshore reefs on filtering and dampening incident wave energy is particularly apparent in locations similar to Desperate Bay on the central west coast where shore parallel ridges attenuate, on average, 39% of the offshore wave energy (STEEDMAN, 1977). More recently, HEGGE (1994) and LEMM (1996) have shown that the reefs and shallow inshore waters may cause up to approximately 90% attenuation of swell. Wave energy is also dissipated through refraction around offshore reefs, islands and headlands, and diffraction through gaps in the reefs. Wave energy conditions during summer to autumn are relatively low and remarkably constant with minimal annual variation, however, wave energy is significantly greater during the winter-spring period, and greater interannual variation is possible (RIEDEL and TRAJER, 1978). The passage of storms associated with the movement of extra-tropical cyclones (CROWDER, 1995) leads to high variability of wave energy during winter and spring.

Broad patterns of erosion and accretion along the shoreline are associated with the swell refraction patterns, variation in the magnitude and direction of wind wave activity and water circulation in the lagoonal areas (DEPARTMENT OF PLANNING AND URBAN DEVELOPMENT, 1994; SANDERSON, 1992). As a result, sediment distribution along the shore tends to be compartmentalised, with discrete cells identifiable on the basis of sediment size, mineralogy and grain characteristics (SEARLE and SEMENIUK, 1985; SANDERSON, 1992). To a limited extent, the cellular patterns are obscured by littoral

transport in the swash and inshore zones of the coast due to wind waves and currents generated by strong sea breeze activity. Locally generated wind waves are superimposed on the prevailing swell. Due to their short period of less than 9 seconds and short wavelength they pass unattenuated across the offshore reefs. During onshore wind conditions wind waves may be generated within the nearshore lagoon, particularly by sea breeze activity. At Desperate Bay waves generated in the lagoon have periods of less than 5 seconds and significant heights of less than 20 cm (HEGGE, 1994). Closer to shore, a small limestone outcrop to the north of the foredune plain refracts oncoming swell and wind waves. This process has contributed to formation of the tombolo (SANDERSON and ELIOT, 1996).

DEVELOPMENT OF THE FOREDUNE PLAIN

Development of the foredune plain is known to have taken place in the historical period, particularly during the past 50 years, through comparison of maps showing change of shoreline position since 1944 as well as through interpretation of vertical aerial photography. The aerial photography was originally taken by the Commonwealth Government (Department of Defence) in 1944 and by the State Government (Department of Land Administration) since that time. The maps showing shoreline movement were compiled from aerial photography for the period 1944 to 1982 by the State Public Works Department (1983) (now the Department of Transport). Here, a research objective is to update the record of shoreline change by comparison of the existing records with the most recent available aerial photography which was obtained by the Western Australian Department of Land Administration in 1990. Additionally, field surveys of the stratigraphy of the foredune plain were undertaken to establish a broader context for its development. Coastal processes af-

fecting nearshore and foreshore sediment transport were examined through field and laboratory research as a first step to determine contemporary depositional mechanisms contributing to the continued formation of the plain.

Historical Shoreline Change

Historical records showing change in shoreline position are available from 1944 to 1990 and either have been established from aerial photographs or are aerial photographs. No earlier maps based on ground surveys are available for the coast of Desperate Bay. Neither was more recent photography available at the time of writing. Thus the record is restricted in its length and is derived from photography with scales varying between 1:15 840 and 1:25 000. Nevertheless, changes to the coast have been dramatic in the historical period, with the shoreline advancing seaward over 150 m at the widest part of the plain in the 46 years of observation. Here the sequence of shoreline change is established from the available shoreline position charts and more recent aerial photography.

Shoreline Charts

Build-up of sediments on the Coolimba foredune plain has been examined in a historical time frame from the shoreline position charts. Mapping of water and vegetation lines from the original aerial photographs, followed by overlaying of the results, has enabled analysis of the overall shoreline position changes and estimations of the rate of shoreline changes to be made. The aerial photographs of the area from 1944 have been compared photogrammetrically with photographs from 1958, 1965 and 1982 (Figure 5).

The charts of shoreline position indicate that the coast experienced substantial erosion prior to 1958, particularly in the southern part of the embayment. There is little change in the configuration of the shoreline between 1958 and 1965, although some erosion occurred in the southern part of the embayment (Figure 5). Since 1965 the coast has rapidly accreted. The plain formed as the shore prograded, with progradation rates of over 3.5 m/yr at its widest point between the jetty and the headland at Coolimba (Figure 5). The rate of sediment accretion along the foredune plain declines from approximately 3 m/yr in the southern part of the embayment to near stable conditions approximately 400 m south of the tombolo. In contrast to this erosion has occurred at a rate of approximately 0.5 m/year north of the tombolo. Erosion in the northern part of the foredune plain is apparently due to the growth of the tombolo and subsequent blocking of alongshore sediment movement to the north. In volumetric terms, and assuming the beach profile configuration (Figures 6a-c) has been similar over time, approximately 97,000 m³ or 3900 m³/year of sediment was deposited during the historical period 1965 to 1982. The extensive changes and the rapid rate of change is significant in terms of the small size and shallow inshore waters of the embayment.

Changes in shoreline position are not regular around Desperate Bay. Instead, some parts of the embayment shore accrete while others undergo erosion, although the overall change around the embayment is one of net accretion. Be-

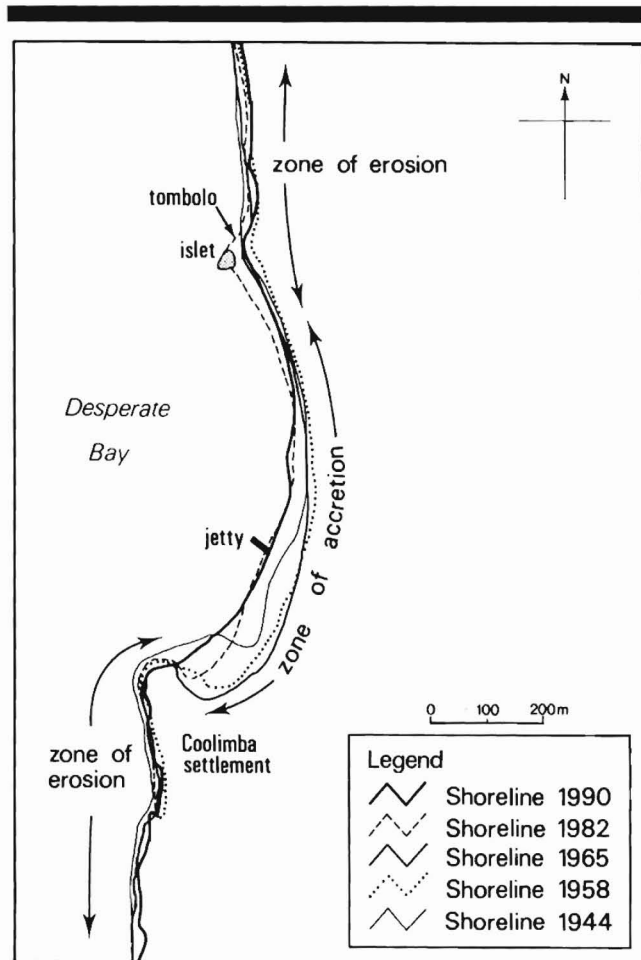


Figure 5. Shoreline movement at Desperate Bay. Shoreline positions are determined photogrammetrically from 1944, 1958, 1965 and 1982 aerial photography. The 1990 shoreline was determined by GIS (ARC/INFO) analysis of scanned aerial photographs.

tween 1944 and 1965 the shoreline retreated approximately 100 m at the southern end of the foredune plain, in the vicinity of the rocky cliff near Coolimba. From 1958 to 1965 erosion generally continued, although accretion of between 15 m and 30 m occurred along the central part of the foredune plain. It is apparent from the early aerial photography that the area now forming the tombolo was still inundated by water under high tide and potentially surge overwash. North of the tombolo the shoreline has eroded approximately 25 m since 1944.

Comparison of the Charts with Recent Aerial Photography

Shoreline positions from dates between 1944 and 1982 are overlain on the 1990 photograph in Figure 5 for the purposes of this research. The method used to analyse change in shoreline position from the aerial photographs and map series was similar to the metric mapping technique described by LEATH-

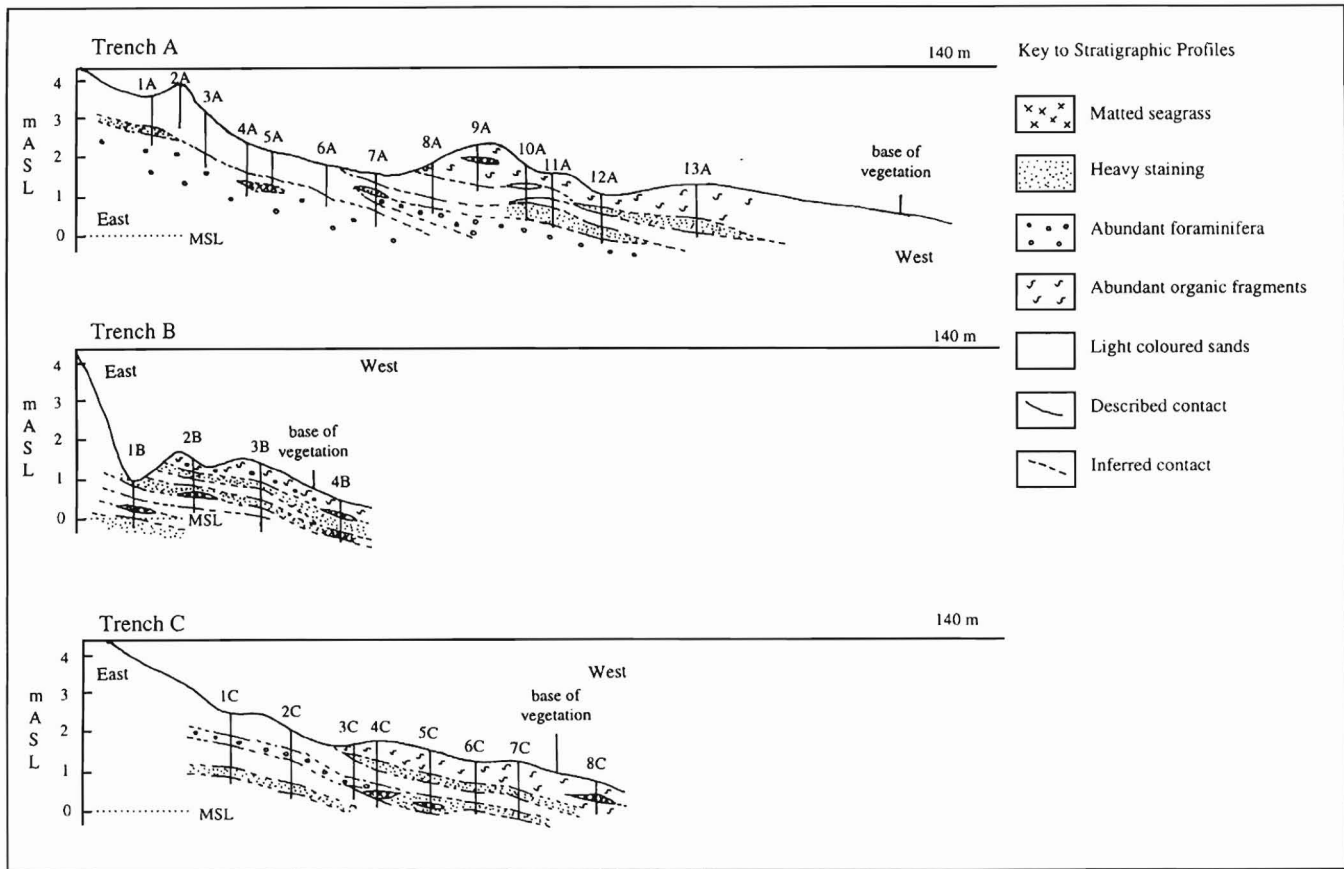


Figure 6. The stratigraphy of the Coolimba foredune plain. Trench A is located near the jetty, trench B is found to the south of the tombolo, and trench C to the north of the tombolo.

ERMAN (1983). Many of the errors affecting aerial photographs such as photo tilt (CROWELL *et al.*, 1991), radial lens distortion, and aircraft tilt and pitch (ANDERS and BYRNES, 1991; CROWELL *et al.*, 1991) can be removed by using functions in ARC/INFO GIS (FULLER, 1995). In the current analysis, a grid of cells (100 m square) was generated and extended from a baseline position to the shorewardmost extent of the region. Aerial photography for 1990 was scanned and adjusted to match topographic marks on the photographs with established marks on the charts. Relative shoreline positions could then be accurately determined by measuring a line segment from the baseline to the shoreline.

Comparison of shorelines plotted on the charts with the 1990 aerial photography indicates that the southern part of the embayment close to the headland at Coolimba has filled; the central sector has remained stable; and the northern sector close to the tombolo has eroded since 1982. The changes are consistent with rotation of the shoreline in the embayment during a period of sustained southwesterly wind and wave activity. Overall, the patterns of change in shoreline position since 1944 are consistent with cellular water circulation and sediment movement within the embayment, pul-

sational transport of sediment along the shore, or some combination of these processes. However, more detailed research is necessary to establish the processes of sediment movement in the embayment.

Stratigraphy

During July 1994 assistance was provided by the Shire of Carnamah, Western Australia, to excavate a series of pits along three trench lines through the foredune plain in Desperate Bay (Figure 3). The pits were dug to groundwater level with a backhoe. The first trench line (Trench A) was dug into the active foredune ridge and extended across the accreted foredune plain towards the fishermen's jetty. A second trench line (Trench B) was dug 50 m to the south of the tombolo structure, while the third trench line (Trench C) was excavated 30 m to the north of the tombolo. Both Trench B and Trench C extended from the landwardmost foredune ridge to the upper beach face. The stratigraphy along each trench line was examined after a series of individual pits were excavated. The structures exposed in the sides of the pits were mapped, photographed, by still photography and video, and sampled

before sediments were replaced. Trench A consisted of 13 pits, Trench B comprised 4 pits and Trench C, 8 pits. The pits were approximately 3m long, 2m deep and 1.5m wide. Pit locations are indicated on Transects A, B and C in Figure 6.

Dune Sediments

All sediments were unconsolidated, carbonate-rich sands. They were analysed by standard techniques to describe sediment composition and grain size (KRUMBEIN and PETTIJOHN, 1938; LEWIS and MCCONCHIE, 1994). Settling velocities were measured with a settling tube similar to that described by SENGUPTA and VEENSTRA (1968). Mean grain size ranged from 2.12 phi to 0.98 phi (fine to coarse sand) with a standard deviation (sorting) of between 0.35 phi and 0.65 phi (moderately well sorted to very well sorted). Carbonate content ranged from 81% to 99%.

Sediments obtained were generally well sorted and subrounded indicating a significant degree of working in the marine environment and consistent energy conditions during deposition. Organic content in the samples was varied, and up to 10%, depending on the content of wrack. The calcium carbonate content of the sediments comprised worked lithoclasts (derived from reefs, cliffs and beach rock platforms), and fresh skeletal material (echinoid spines, bivalves, gastropods, *foraminifera*, *Marginopera* and sponge spicules). Most samples contained abundant *foraminifera*, such as *Marginopera*, as well as echinoid spines and sponge spicules while the presence and content of bivalves and gastropods was varied. A trace of heavy minerals was observed in some samples but the overall content was insignificant.

The proportion of calcite to aragonite in the calcium carbonate grains was also assessed based on microscope analysis of the samples after treatment with Feigl's Solution (FRIEDMAN and JOHNSON, 1982). The determination of mineral constituents, especially the differentiation between quartz, calcite and aragonite is a fundamental part of sediment description and analysis (FRIEDMAN, 1959). The differential staining method (FRIEDMAN, 1959), accepted as a useful technique by WOLF and WARNE (1960), is applicable to single grains and to unconsolidated carbonate sands. It provides a means of establishing the identity of the carbonate minerals under study and to observe the textural and compositional relationships in carbonate sediments. Their methods were adopted for the purposes of examining the sediments from Desperate Bay.

The Stratigraphic Sequence

Stratigraphic profiles for each of the trench lines have been constructed from descriptions of the sediments from each pit, as well as the photographic and video evidence. Stratigraphic cross-sections of each trench are shown in Figure 6a-c. The depth to which each pit was dug is shown and observed sedimentary horizons are indicated. The continuation of individual beds between adjacent pits has been interpolated, based on the detailed sedimentary and stratigraphic descriptions. Features such as the base of the vegetation at the top of the beach face and the location of mean sea level are marked on the figures. Pits were not excavated in the beach zone of the

southernmost trench due to its proximity to the loading jetty and the need for vehicular access to the area to be maintained.

It is apparent from descriptions of the sediments and cross sections of the trenches (Figures 6a-c), that deposition of sediment in Desperate Bay has been occurring gradually and continually since 1965 because it has led to progradation of the foredune plain between the cliff area in the south and the tombolo structure. Northwards of the tombolo, the coast has been slowly eroding, perhaps due to the tombolo acting as a barrier to longshore sediment transport. The presence of mats of seaweed wrack at depth in the excavated pits, overlain by clean, unconsolidated sediments with planar bedding, indicates transport of sedimentary material onto the foredune plain by wash processes. High in the profile the bedding of the clean sand, where it is discernible, indicates a small component of aeolian deposition and the formation of incipient foredunes. Additionally, the wrack beds in the stratigraphic sequence apparently indicate phases of storm activity and beach recovery, since deposition of wrack on the upper profile is contingent on the occurrence of high sea-levels associated with storm surge.

Stratigraphic Evidence of Change in Shoreline Position

Stratigraphic profiles of the Desperate Bay foredune plain provide evidence for the pattern of accretion occurring over the past 30 years. Both the planar nature of sedimentary units, which lack evidence of severe erosional events incorporating cliffing of the frontal dunes, and the presence of flotsam and jetsam spread across beach profiles in the sections, indicates gradual progradation of the shoreline. A number of pieces of nylon rope were found at depth in several of the pits (13A, 3B and 7C). These occurrences support the photogrammetric evidence that development of the foredune plain has occurred rapidly, over the historical time period, as nylon rope was not widely used in the fishing industry until the early 1960s.

Examination of the stratigraphic cross-sections shows some alternation of clean, fine, carbonate rich sediments with organically rich, stained beds. One such example can be found in pit 4B where a bed of matted seaweed containing little sandy material is found between cleaner, organic free sands. The presence of these stained, organic rich sedimentary beds apparently indicates significant accretion following storm events, with much of the organic material being deposited in the immediate, post-storm period. It is common in the region for large rafts of seaweed up to 1.5 m thick to be deposited on overwash fans in the frontal dunes, berm, and on the subtidal beachface immediately after storm activity (author's observations). They apparently eventually become incorporated in the foredune plain as sediments continue to accrete along the shore under lower energy conditions.

Sediments that are accreting along the sandy coast region and building the foredune plain are consistently rich in carbonate material. The sediments apparently are derived from contemporary biological activity and, to a lesser extent, erosion of older reef structures including the limestone cliff ar-

eas. Abundant fresh skeletal material containing *foraminifera* is indicative of derivation from sea grass beds. Most of the skeletal material is unbroken and articulated bivalves were recorded. This indicates a short transport distance in low energy conditions to the site of deposition. As shown in Figure 6a–c, gently dipping planar sedimentary beds rich in calcareous material are interspersed with organic rich sediments. These horizons often comprise matted seaweed, large broken shelly material and are generally less well sorted. Combined with their regular but discontinuous appearance in the stratigraphic record, this indicates that continued build up of the foredune plain by eroded limestone and biogenic material is supported by frequent storm deposition. No evidence of severe erosion was noted in the stratigraphic record, supporting the hypothesis that build up of sediment has been slow and pulsatory but ongoing.

Deposition of wrack, including nylon rope and plastic debris, mainly occurs on the upper beachface during and immediately after storm activity when sea level is higher, followed by burial by clean sand during lower wave conditions when wind conditions move sediment on the upper beachface. This deposition provides a record of major storm events in the stratigraphic column. Evidence for two stages of deposition in Desperate Bay can be found in the occurrence of seaweed rich beds at the base of, and high in the profile of the foredune ridges. Deposition of the seaweed wrack at the base of the profile is likely to take place during normal oceanographic conditions when wrack is often left on the beach face at, and above the high tide level. This material is then covered by finer clean beach sediments through aeolian transportation on the subaerial beach. In contrast to this, storm surge events may overtop the berm and first foredune ridge, depositing additional seaweed wrack and other material above the clean beach sand. The deposition results in the presence of an horizon of organic rich material high in the foredune profile. In Desperate Bay the higher deposition of wrack occurs between 1 m and 3 m above mean sea level.

Contemporary Processes

An examination of contemporary oceanographic processes was made in Desperate Bay to place development of the foredune plain in its coastal process setting. In particular, longshore currents and longshore sediment transport were examined in the nearshore zone adjacent to the foredune plain. Measurements were made between 1 pm and 5 pm on 14th July, 1994 under moderate southwesterly winds. From the long-term averages of wind conditions in the region (Table 1), it is estimated that the longshore currents recorded are indicative of conditions during approximately 33% of the winter season. Also from the climatological record, it is expected that longshore currents would be stronger during severe winter storm conditions, and during summer sea breezes.

Detailed records for conditions under the dominant northwesterly winter storm conditions are not available, although such conditions may be significant in shaping the final form of the foredune ridge. Further field research is required to test this proposition. The observations presented here are in-

tended to provide an indication of the prevailing southwesterly wind conditions that affect the region.

Longshore Currents

The speed and direction of longshore currents were measured at 4 sites in the nearshore zone of Desperate Bay (Figure 7). Eulerian measurements were made using a Marsh McBirney electromagnetic current meter placed approximately 20 m offshore from each site indicated in Figure 7. The sensor of the current meter was mounted on a column attached to a base plate and was located 25 cm above the sea bed. In all instances the sensor was located approximately 25 m seaward off the shoreline. North and east components of current speed were recorded and these have been resolved to give a resultant direction and velocity (Figure 7).

During the moderate winter conditions of the survey, it was apparent that the longshore current was dominantly northerly and varied from onshore to offshore, possibly due to cellular flow patterns within the embayment. The direction of current flow may be directly linked to areas of sediment erosion and accretion along the coast. Throughout the survey it was noticeable that current flow was offshore at the most southern site, and north of the tombolo. This coincides with zones of recent sediment erosion. At sites in the central embayment and to the south of the tombolo, which correspond with zones of recent sediment accretion, the resultant longshore current flowed onshore.

Longshore Sediment Transport

A broader appreciation of water circulation and resulting sediment transport can be inferred from grain-size trends from alongshore sediment samples (MASSELINK, 1992). Hence it was decided to employ this technique at Desperate Bay in order to establish the general transport patterns. Grain-size trends result from transport processes such as abrasion, selective transport and the mixing of sediment from various sources (RUSSELL, 1939). This implies that distinct patterns of grain-size trends are likely to be associated with net sediment transport pathways. However, conflicting results have arisen from attempts to relate grain-size trends to net sediment transport patterns. Mean grain-size has been considered to become finer along transport paths (PETTIJOHN *et al.*, 1972), although coarsening trends along these paths have also been observed (MCCAVE, 1978 and NORDSTROM, 1989). Combined grain-size trends derived from using more than one grain-size parameter have been used in order to overcome this difficulty, following procedures reported by MCLAREN and BOWLES (1985).

Sediment sampling of the shore zone was undertaken in Desperate Bay in order to establish net transport directions. Transport pathways can be inferred from grain-size trends and transport vectors (GAO and COLLINS, 1992), and therefore it was considered more appropriate to use a grid rather than a line of samples (GAO and COLLINS, 1994). Grab samples were to be obtained by free diving in the shallow waters of the nearshore zone to provide areal coverage of sediments in both the alongshore and onshore/offshore directions. However this was not possible because the seabed is largely com-

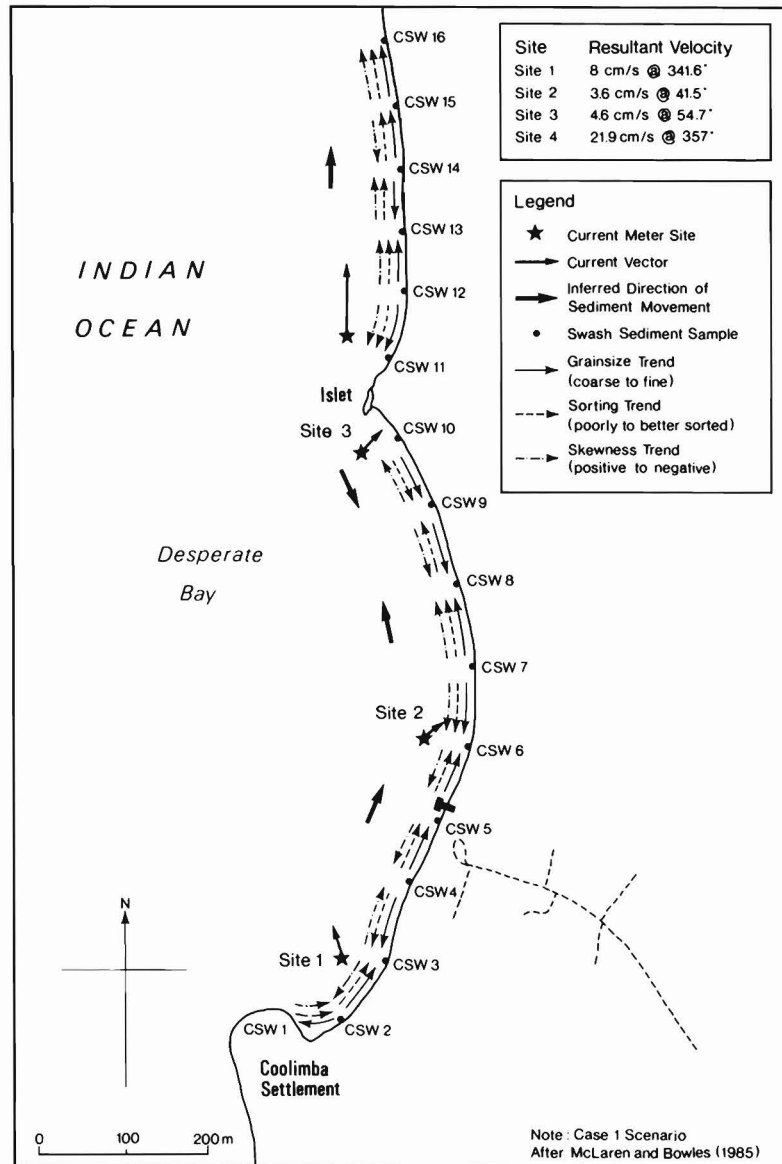


Figure 7. Longshore trends in sediment characteristics and nearshore current velocities measured in the inshore zone of Desperate Bay. The methodology used to map the sediment distribution, as well as the inferred and measured nearshore currents follows that of McLaren and Bowles (1985) and Masselink (1992). Currents were measured with a Marsh McBirney current meter.

prised of limestone pavement with little or no sand cover present. This restricted effective sampling to sixteen sites along the beach and in the central swash zone. Hence, it is difficult to apply the methods of GAO and COLLINS (1994) to Desperate Bay. However, the alongshore sampling regime still allows comprehensive descriptions of the sediments and this provides information on the sediment source, conditions of transport and a general indication of sediment transport pathways. The sediment characteristics are listed in Table 2.

Sediment composition is similar to that found in the excavated trenches. Fine sediments are generally found in areas of sediment accretion while coarse sediments tend to be

found in zones of recent erosion. The coarse sediments on the beach to the north of the tombolo apparently are associated with the strongest northward longshore currents while the fine sediments of the beach in the central foredune plain area are associated with slower northward trending onshore currents. However, the mean grain size, standard deviation and skewness trends (Figure 7) along the beachface in Desperate Bay do not show a consistent pattern either between the sedimentary parameters or with the nearshore water circulation pattern indicated by the current measurements. This has resulted from the low sampling densities used in each case. Neither the current metering nor sediment sampling pat-

Table 2. Sedimentological data from the analysis of sediment samples of the Desperate Bay swash zone.

Samp. No.	mn g/s (φ)	g/s std dev	g/s (skew)	% Carb				Roundness	Sphericity	Colour Desc.	Calc/ Arag	Echi-noids	Bivalves	Gastropods	Fora-mini-fera	Spic-ules
				% qtz	(w)	(s)	% organ									
csw1	1.672	0.485	-0.058	6.6	85	5	0	subr	subd	pale yellow	50/50	yes	fragments?	fragments?	yes	yes
csw2	1.583	0.442	-0.061	5.1	90	7	0	subr	subd	light grey	80/20	yes	fragments?	yes	yes	yes
csw3	1.705	0.439	0.022	8.9	84	3	0	subr	subd	light grey	80/20	yes	fragments?	yes	yes	yes
csw4	1.591	0.464	0.008	6.7	87	3	0	suba	subd	light grey	80/20	yes	fragments?	yes	yes	yes
csw5	1.665	0.445	0.03	5.6	87	5	0	subr	subd	light grey	80/20	yes	fragments?	no	yes	yes
csw6	1.733	0.444	0.003	3.6	90	5	0	suba	subd	v pale brown	60/40	yes	fragments?	fragments?	yes	yes
csw7	1.544	0.515	0.021	3.2	90	5	0	suba	subd	pale yellow	60/40	yes	fragments?	yes	yes	yes
csw8	1.861	0.473	-0.209	2.5	85	13	0	suba	subd	white	60/40	yes	fragments	yes	yes	yes
csw9	1.81	0.407	-0.063	4.5	85	10	0	suba	subd	white	90/10	yes	fragments	yes	yes	yes
csw10	1.661	0.437	-0.138	5.9	85	8	0	subr	subp	white	70/30	yes	fragments?	yes	yes	yes
csw11	1.512	0.44	0.11	3.7	85	7	0	subr	subd-sph	pale yellow	50/50	yes	fragments?	yes	yes	yes
csw12	1.362	0.519	0.125	2.1	90	9	0	subr	subd	white	70/30	yes	fragments	yes	yes	yes
csw16	1.477	0.495	0.099	2.2	93	5	trace	suba-subr	subp	pale yellow	80/20	yes	fragments?	yes	yes	yes
csw14	1.159	0.498	-0.126	1.0	70	29	0	suba	subd	white	90/10	yes	fragments	yes	yes	yes
csw15	1.426	0.543	0.263	2.2	85	14	0	suba	subd	white	80/20	yes	yes	yes	yes	yes
csw16	1.475	0.501	-0.422	2.6	90	8	0	suba	subd	white	60/40	yes	fragments	yes	yes	yes

Key: mn = mean, g/s = grain size, std dev = standard deviation, skew = skewness, qtz = quartz, carb (w) = worked carbonate, carb (s) = skeletal carbonate, organ = organics, subr = sub-rounded, suba = subangular, subd = sub-discoidal, subp = sub-prismoidal, calc/arag = calcite/argonite, v = very.

terns are sufficiently detailed to unequivocally identify all components of an apparently cellular circulation and sediment sorting pattern. More detailed research is required to clearly identify the patterns of sediment movement within the embayment and along the beach.

DISCUSSION AND CONCLUSIONS

The foredune plain at Desperate Bay is one of the few areas on the central west coast of Western Australia that is currently in a phase of accretion. Although some erosion is occurring near the cliffs to the south of the headland, and north of the tombolo, accretion has been shown to be approximately 3 m/year from 1965 to 1990 along the central section of the foredune plain. Here, accretion arguably has been shown to be coincident with sites of onshore current movement and fine sediment accumulation, whereas coarse sediments and offshore currents are characteristic of sites of sediment erosion in the area. In Desperate Bay, the longshore currents are topographically controlled on beaches flanking the foredune plain by the partially emergent reefs immediately offshore, the outcropping limestone cliffs and the orientation of the coastline with respect to prevailing weather conditions. It is anticipated that the foredune plain will continue to accrete under present atmospheric and oceanographic conditions until the area between the tombolo and the southern headland at Coolimba is sediment filled. Erosion of cliffs, rock platforms and offshore submerged reefs, as well as the bio-productivity of seagrass meadows (COLLINS, 1988), ensure a continued supply of sediment.

The foredune plain at Desperate Bay differs from the foredune sequences described from the high energy environments of southeastern Australia by DAVIES (1957), MCKENZIE (1958), BIRD (1960, 1969, 1976) and THOM (1964). There is no evidence of significant erosional episodes incorporating cliffing of the foredunes within the recent stratigraphic record. In this respect, it is unlikely that the wave energies at

the coast would be high enough to cause erosion commensurate with that needed to develop beach ridges through the 'cut and fill' method (DAVIES, 1957; BIRD, 1960, 1969, 1976) except during the most extreme events. The relict foredunes from Cervantes, Western Australia, discussed by WARD (1983) and HESP (1984b) as having an aeolian origin may have some similarity to the foredune plain at Coolimba. However, the foredune plain at Coolimba has more in common with the stormwave-built beach ridges described from the low-wave energy environment of the Gulf of Mexico by PSUTY (1967).

PSUTY (1967) described the marine origin of beach ridges in Tabasco, Mexico, that show accretion of foredune ridges in the absence of quasi-regular erosional events. It is apparent at Coolimba that large amounts of sediment, including seaweed wrack, are deposited at the back of the beach during storm surge events. These are then overlain by clean, unconsolidated sediments, largely of apparent aeolian origin. Thus the foredune plain may be developed as a result of combined marine and aeolian processes, with initiation of foredune development provided by the surge events. Sediments may then be stabilised through colonisation by vegetation and sediment accretion continued through trapping of wind blown sand in the lee of, and within, zones of vegetation.

Development of the foredune plain at Coolimba has taken place over the historical time period. Change in shoreline position has been assessed using aerial photography and GIS techniques, and it is shown that the coastline in the Desperate Bay area has accreted at up to 3.5 m/year since 1965. Erosion has taken place in the lee of the limestone headland and downdrift of the tombolo. Stratigraphic investigation of the prograded foredune plain indicates continuous deposition of sand. No evidence of severe erosion was found, although bands of wrack up to 2.5 m above sea level indicate deposition of material during storm surge events. The mode of formation of the foredune plain has marine and aeolian components but

the exact mechanism of buildup needs to be further investigated through more extensive measurement of sediment transport processes and their interaction.

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