DYNAMICS OF SOME PARABOLIC DUNES IN THE MANAWATU REGION, NEW ZEALAND

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Jeffrey David Page
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Abstract

Parabolic dunes are U-shaped dunes which may be found in deserts and coastal locations around the world. They occur along much of the coastal area of the West Coast of the North Island of New Zealand, including the Manawatu Region. The parabolic dunes of the Manawatu coast comprise the largest parabolic dune fields in New Zealand.

This research was conducted to identify the rates of movement of the parabolic dunes, and establish whether there is a relationship between parabolic dune development along the Manawatu coast and El Nino Southern Oscillation. Morphological changes in parabolic dunes over time are also examined, and a model of parabolic dune development which deals specifically with the parabolic dunes of the Manawatu coast is produced.

Examination of the parabolic dunes was conducted by ground surveying using Global Positioning System (GPS) and through the use of aerial photographs and aerial photograph mapping.

Rates of parabolic dune migration along the Manawatu coast were found to be significantly higher than has been recorded elsewhere in the world. By examining the wind regime and the El Nino Southern Oscillation, and comparing these with parabolic dune migration a pattern of increased parabolic dune activity under El Nino conditions was identified. A pattern of parabolic dune formation from blowout initiation through to parabolic dune maturity was identified and a model for parabolic dune development along the Manawatu coast designed.

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Chapter One: Introduction

1.1 Introduction

Parabolic dunes are U-shaped dunes which can be found in many deserts and coastal locations around the world. They occur along much of the coastal area of the West Coast of the North Island of New Zealand, including the Manawatu Region. Parabolic dunes in the Manawatu Region commonly form from blowouts in the foredune. The parabolic dunes then develop and move inland from the foredune. The Manawatu Region contains the largest parabolic dunefield in New Zealand (Hesp, 2000; Hesp 2001). This thesis research aims to examine some parabolic dunes in one area of the Manawatu region.

The Manawatu coastal zone consists of a low wave energy, mesotidal, dissipative beach characterised by high wind energy. There is an erosional foredune, and blowout complex, with parabolic and transgressive dunefields to landwards. The Manawatu coast is a progradational environment accreting at a rate of 0.5 to 1 metre per year (Hesp, 2001). The dune belt of the Manawatu Region is located between the coast and the floodplain, covers 312 km^2 and extends as far as 19 km inland (Hesp & Shepherd, 1978). Dune development in the Manawatu Region has occurred in a number of phases throughout the Holocene (Cowie, 1963).

While there have been a few studies conducted on dynamics in the dunefield, (e.g. Holland 1983, Hesp, 2000), very little research has been carried out on individual dune dynamics, rates of dune movement, parabolic dune evolution, and changes in dune volume. The limited studies have shown that the parabolic dunes of this coastal dunefield do not behave as the worldwide literature suggests, as the rates of movement identified are much higher than anywhere else in the world.

1.2 Location

The Manawatu coastal region is located along the South West Coast of the North Island. The Manawatu coastal region extends from just north of Tangimoana at the

Turakina river mouth, to just south of Foxton Beach at the Manawatu River Mouth (see Figure 1.1). The seaward margin of the coastal zone is less easily defined, although the New Zealand Coastal Policy Statement defines the landward boundary as Mean High Water Spring mark.

The study site is approximately half way between the townships of Himitangi Beach and Foxton Beach, some 250 metres north of the mouth of Three-Mile Creek. At this site four parabolic dunes all occur within a few hundred metres of each other (see Figure 1.2).

Figure 1.1 Topographic map showing part of Manawatu coastal region and location of study site.

Figure 1.2 Aerial photograph showing study area.

1.3 Climate

Coastal dune development in the Manawatu dune field is, and has been affected by the present climate and past climate changes. Cowie (1963) identified four dune phases of the Manawatu dune field, which developed during the Late Pleistocene and Holocene. The oldest phase identified was between 10,000 and 20,000 years B.P. and the youngest was less than 100 years old (Cowie, 1963). Climate and climate change in New Zealand during the Late Pleistocene and the Holocene will be considered here, as well as current weather and climatic conditions for the Manawatu.

Studies of the New Zealand climate of the Late Pleistocene suggest that it was one to two degrees Celsius cooler than present (Salinger & McGlone, 1990). Minimum sea levels and sea surface temperatures are believed to have occurred during the Late Pleistocene between 15,000 and 20,000 years B.P., indicating colder climatic conditions. A study of an ice core from Antarctica (Sturman & Tapper, 1996) showed an increase in dust levels, indicating an arid climate with higher wind speeds. These conditions are believed to be characteristic of the Southern Hemisphere during the Pleistocene. The driest conditions indicated from pollen and lake level records occurred between 11,000 and 15,000 years B.P. possibly as a result of a decrease in effective precipitation associated with increasing temperatures and evapotranspiration (Sturman & Tapper, 1996).

The Holocene began 10,000 years B.P. and was a period of higher temperatures than during the Pleistocene (Salinger & McGlone, 1990). Temperatures reached their highest (some two degrees Celsius warmer than present) during the early Holocene, around 10,000 years B.P. (see Figure 1.3). The climate of the Early Holocene was relatively warm with notable summer rainfall, although winter rainfall was significantly lower (Sturman & Tapper, 1996).

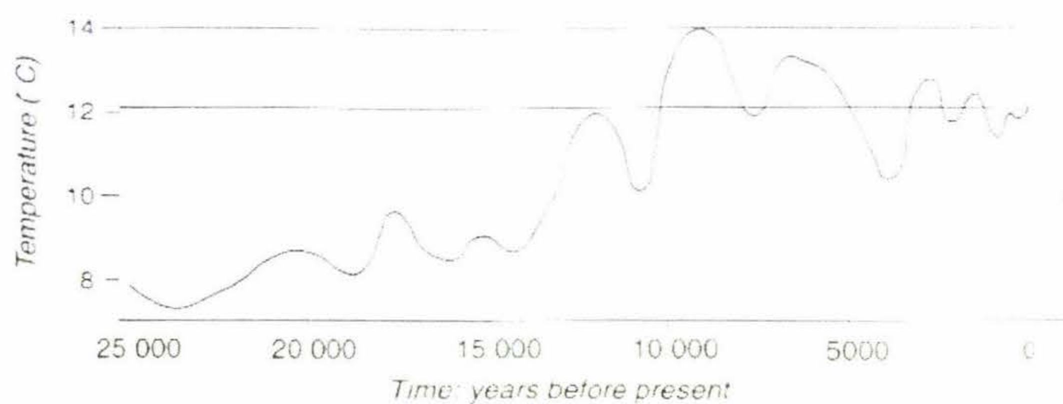


Figure 1.3 New Zealand average temperatures for the last 25,000 years from Sturman & Tapper, 1996.

During the Mid Holocene (about 5,000 years B.P.) temperatures began to fall again with a major advance of the glaciers of the Southern Alps. Since this time there have been at least 11 major glacial advances, with the last finishing approximately 100 years ago. These glacial advances are an indication of changing climatic conditions, including cooler temperatures. The climatic conditions favorable for glacial advance in the Southern Alps are increased south to southwesterly winds and cooler temperatures allowing more snow to fall in the zone of accumulation (Sturman & Tapper, 1996).

By the Late Holocene the climate was characterised by drier, warmer summers and cooler wet winters. It is also worthy to note that fire frequency increased during this time (Salinger & McGlone, 1990), which could have reduced coastal vegetation, triggering dune mobilisation.

The instrumental record began in New Zealand in the 1850's. This record shows a general increase in temperatures since the 1950's, with temperatures staying around the long-term average prior to that time (see Figure 1.4). The change in temperature has been associated with a change in the pattern of airflow over New Zealand. There are now more winds from the north and east than previously with a decrease in winds from the south to southwest. The cause of this may be linked to more blocking anti-cyclones situated to the east of the South Island (Salinger & McGlone, 1990; Sturman & Tapper, 1996). This change in weather pattern has led to a decrease in rainfall in the south and west of both islands (Salinger & Mcglone, 1990).

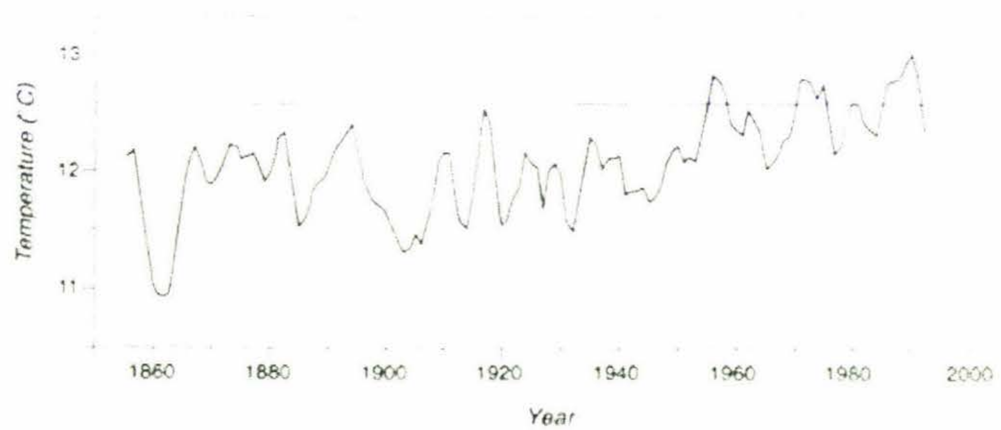


Figure 1.4 Observed average annual New Zealand temperatures over 130 years to the mid 1990s. Horizontal line is average temperature over the period of 1961 to 1990 from Sturman & Tapper, 1996.

1.3.1 Manawatu Climate

The weather and climate of the Manawatu Region is dominated by west to northwest winds. The prevailing wind direction in the Manawatu dunefield is westerly through to northwesterly. Winds from this direction blow from between 30 and 50 percent of the time through the region, increasing towards the coast (see Figure 1.5). At Ohakea Aerodrome, which is the closest weather station to the dunefield, wind speeds over 60 kilometres per hour occur 80 days per year on average. Wind speeds over 90 kilometres occur an average of 9 days per year. Mean daily wind speeds in the region vary from between 15 and 54 kilometres per hour. Over coastal Manawatu, mean daily wind speeds average between 15 and 18 kilometres per hour (Burgess, 1983). There is little seasonal variation in wind speed but winds are generally lighter through autumn and winter. Windy conditions (wind speeds greater than 30 kilometres per hour) are also reduced from March through to August (Burgess, 1983).

Rainfall in the Manawatu dunefield is just under than 900 millimetres per year making it one of the driest places in the North Island. However this is usually sufficient for agriculture, except in summer. There is a pronounced seasonal variation in rainfall distribution with a winter maximum, and January and February being the driest months. Extended periods of dry weather, defined by Burgess (1983) as, more than 14 consecutive days with less than 1.0 mm daily, occur infrequently despite the low rainfall over the summer months. Dry spells occur on average two to four times a year (Burgess, 1983).

The temperatures of the Manawatu Dunefield are moderate with no great extremes (Burgess, 1983). The mean range is 13 -22.3 degrees Celsius for summer and 4.2 - 12.3 degrees Celsius for winter (Burgess, 1983).

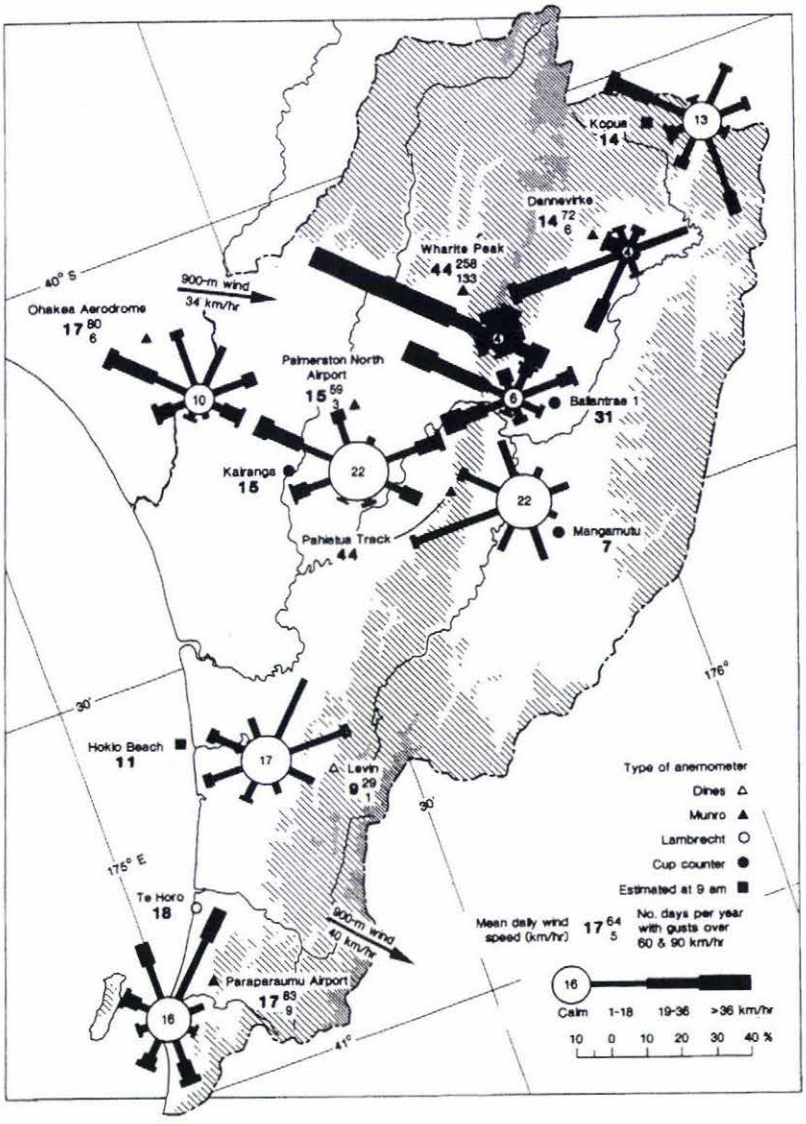


Figure 1.5 Wind roses of weather stations in the Manawatu, indicating prevailing surface winds and mean daily wind speeds from Burgess (1983).

1.4 Geomorphology of the Region and the Manawatu Dunefield

The Manawatu District is bounded on the west by the Tasman Sea and on the east by the Tararua and Ruahine Ranges. The northern and southern boundaries are determined by the Rangitikei and Manawatu Rivers respectively (Esler, 1978). The geology of the district is composed of sedimentary rocks ranging in age from Triassic-Jurassic (150-200 million years old) through to Recent represented by present day alluvial and marine deposits, as well as widespread loess deposits (Heerdegen, 1972). The area is geologically young as it was submerged during the Late Tertiary, with the exception of parts of the Ruahine and Tararua Ranges which were being uplifted (Heerdegen, 1972).

The sand country of the Manawatu has been shaped by marine, fluvial and aeolian process over time. Hesp & Shepherd (1978) described three topographic units which make up the lower Manawatu Valley as the Tokomaru Marine Terrace, the Manawatu floodplain and a coastal dune belt. The Tokomaru Marine Terrace occurs along the western margin of the Tararua Ranges (Hesp & Shepherd, 1978). Subsequent fluvial activity has lead to the development of box and V-shaped valleys along the eastern margin of the terrace (Hesp & Shepherd, 1978). A phase of fluvial deposition saw the development of an alluvial plain with broad natural and back swamps (Shepherd & Lees, 1987). The subsequent aeolian phase has covered these fluvial deposits as dunes formed and moved inland (Hesp & Shepherd, 1978; Shepherd, 1985). In some places the dunes have moved up to 19 kilometres inland (Heerdegen, 1972). The Manawatu sand country can be separated into two zones, a foredune area and associated young and unstable dune complex behind, and an older, more stable inland complex (Heerdegen, 1972). The dunes of the sand country are aligned to the prevailing northwesterly wind rather than parallel to the coast as is more common in other coastal regions of New Zealand (Molloy, 1988).

1.5 Human Impact

Human impact in New Zealand is widespread and in places has been quite profound. The coastal zones in many areas have been particularly severely impacted, and the Manawatu coastal dunefield is no exception.

The first Maori may have arrived in the Manawatu region at least 650 years ago. McGlone and Wilmshurst (1999) concluded that Maori began having an environmental impact in New Zealand between 750 and 550 years before the present. Investigation of a Moahunter site two kilometres north of the Manawatu River and 2.5 kilometres inland together with shell middens at Himitangi beach have yielded radiocarbon dates of 820 to 570 B.P. and 550 to 350 years B.P. respectively (McFadgen, 1985).

While there has been debate over when Maori arrived in New Zealand, this study is only concerned with their impact on the environment and it's timing. Maori regularly utilized fire as a method of clearing vegetation for maintaining and creating tracks, keeping vegetation away from dwellings, clearing sites for cultivation and to promote the growth of bracken (*Pteridium esculentum*) which was a major food source (McGlone & Wilmshurst, 1999). This burning of vegetation is likely to have occurred within the Manawatu, severely reducing the coastal vegetation (Bussel, 1988; McKelvey, 1999). Bussel (1988) also states that Pre-Polynesian fires could have had a significant affect on the vegetation. Hesp (2001) states that these disturbances of the vegetation could have started a phase of dune mobilization, and would have also caused remobilization of vegetated dunes.

Europeans began arriving in the Manawatu during the 1840's (Hesp, 2001). These settlers began grazing stock and burning vegetation on the older established dunes, re-mobilising them (McKelvey, 1999). European settlement inland from the coast also had an effect on dune mobilisation, as wide spread forest clearance of the hill country for pasture caused increased soil erosion which increased the sand supply to the coast and subsequently to the dune system (McKelvey, 1999).

The arrival of Europeans in the region also saw the arrival of many introduced species of animals including deer, rabbits, sheep and cattle. Sambhur deer were released in 1875 into the Rangitikei District (McKelvey, 1999) and rabbits are thought to have been introduced by the 1870's (Hesp, 2001). Both of these animals had a great effect on the native vegetation of the dunefield. The sale of land to private ownership saw the introduction of stock to the area. This also had a pronounced impact on the native vegetation as stock was grazed on the foredune and immediately landwards, often with heavy stocking numbers. By 1881 it was noted that there were extensive mobile dunes as a result of this grazing throughout the dunefield. Other impacts of European settlement included burning and clearing vegetation and draining wetlands for pasture (Hesp, 2001).

By the early 1900's efforts were beginning to be made to control mobile sand in the region. This was done through the planting of both introduced and native plant species, mainly marram grass and lupin species followed up with pines, and the construction of drift wood fences across blowouts (Hesp, 2001). Much of the control work in the Manawatu was conducted by the State Forest Service, which was established in 1919, and the Public Works Department (McKelvie, 1999). Attempts to control the mobile dunes have continued up until today.

1.6 Aims of Study

The first aim of this study is to identify the rates of movement and the distances covered by the parabolic dunes over different time periods.

The second aim of the study is to establish whether a connection exists between wind energy, El Niño Southern Oscillation events and dune behavior, by comparing wind data from El Niño years and non El Niño years.

The third aim is to identify modes of parabolic dune evolution and examine the morphological changes in the dunes over time.

The fourth aim is to produce a model of parabolic dune development which deals specifically for the parabolic dunes of the Manawatu coast.

Chapter Two: Literature Review

2.1 Introduction

This chapter examines the previous literature on the initiation, development and dynamics of parabolic dunes. Previous research has examined aspects of sand dunes and dunefields, and several authors have completed summaries on dunes in both the coastal setting (Pye & Tsoar, 1990; Pye, 1983), as well as in the desert setting (Cooke et al, 1993). The classification of dunes by different authors will be discussed, as there are some differences in the terminology used.

2.2 Parabolic Dune Classification

A parabolic dune is composed of a blowout and deflation basin, trailing arms, a depositional lobe and a surge lobe as shown in Figure 2.1. Cooper (1958) describes parabolic dunes as a large trough blowout, which has substantial terminal and lateral walls, and which is in a state of quasi-permanence due to its size. Cooke et al (1993) agree with this definition of a parabolic dune being an enlargement of a trough blowout. The dune is half canoe shaped in size and is usually two to four times longer than it is wide (Cooper, 1967).

Terms Cooke et.al (1993) used to describe parabolic dunes include

"garmada", "U-shaped", "upsiloidal", "V-shaped", or "hairpin" or "dune plumes." (Cooke et al, 1993, pp 361).

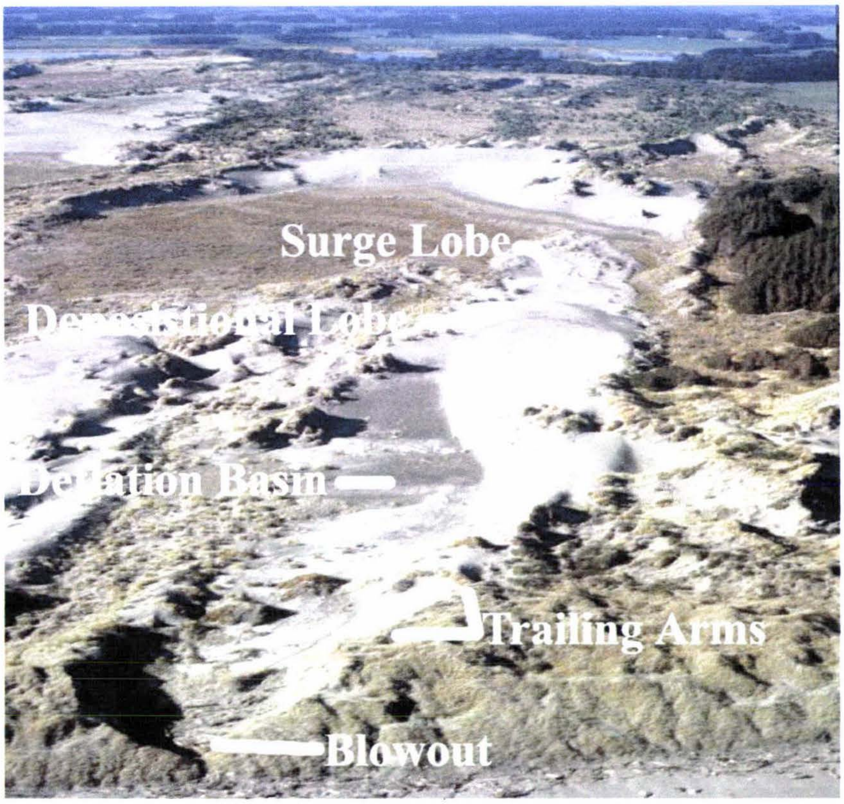


Figure 2.1 Aerial photograph showing the features of a parabolic dune.

The term parabolic dune is used to describe both V and U shaped dunes (Thompson, 1983), however J. K. Steenstrup originally introduced it in 1894 to describe U-shaped dunes found along the coast of Denmark (Thompson, 1983). According to Pye and Tsoar (1990), parabolic dunes tend to have a steep lee slip face at the downwind end of a large sand mound. Some parabolic dunes do not, however, have this high slip face and instead conclude in a low ridge or lobe of sand. Particularly large dunes may in fact have multiple crests and slip faces. Partly or fully vegetated trailing arms characterize all parabolic dunes. Pye and Tsoar (1990) also make mention of the distinction between what they call elongate parabolic dunes and parabolic dunes. Pye (1982) and Pye and Tsoar (1990) cite Price's (1950) definition of elongate parabolic and parabolic dunes. Parabolic dunes are "an open, bow-shaped structure which has not migrated" while elongated parabolic dunes are a "larger, clearly developed U-shaped dune developed from a spot blowout which has migrated" (Pye & Tsoar, 1990, pp 200).

Pye and Tsoar (1990) describes parabolic dunes as follows

"Simple parabolic dunes are U- or V-shaped in plan with two trailing arms which point upwind." (Pye & Tsoar, 1990, pp 200).

Pye (1982) classifies some dunes of the North Queensland coast, which have migrated downwind as parabolic dunes rather than as elongate parabolic dunes, as they have a length to width ratio of less than 3. Dunes with a length to width ratio of greater than 3 are classed as elongate parabolic dunes (Robertson-Rinoul, 1990). Wolfe & David (1997) make no mention of ratio, describing parabolic dunes as being similar in shape to barchan dunes, however parabolic dunes have a slip face, which is convex in plan view. The trailing arms, which they term wings point upwind in cases where they have developed. Robertson-Rintoul (1990) describes parabolic dunes as U or V shaped dunes with the trailing arms often anchored by vegetation while the nose migrates in the direction of the dominant sand carrying wind. The leeward slope of the nose is typically steep and vegetated while the windward slope is usually bare sand and has a lower slope (Robertson-Rintoul, 1990).

Strahler & Strahler (1996) describe parabolic dunes as having a curving arc shape, and "broad, low dune ridges without steep slip faces. May be elongated into hairpin shapes, with points directed upwind." (Strahler & Strahler, 1996, pp 445). They describe three types of parabolic dune as follows, coastal blowout dune, parabolic dune and hairpin parabolic dune. Coastal blowout dunes form where large amounts of sand are blown inland by strong prevailing winds. A saucer shaped deflation forms and the sand is heaped in an arc shape at the downwind end of the depression. Parabolic dunes form where vegetation is scarce and winds are strong, and groups of parabolic dunes may form in the lee of shallow deflation hollows. When the dune begins to migrate downwind the dune forms long, narrow, parallel sides, which resembles a hairpin shape (Strahler & Strahler, 1996).

Pye (1993) also makes a further distinction between simple, compound and complex parabolic dunes, following definitions made by McKee (1979). The simple parabolic dune form is a single dune containing a nose at the downwind end, two trailing arms which extend up wind, which are either fully or partly vegetated, and a deflation corridor or basin between the trailing arms. The length-width ratio of simple parabolic dunes is variable and this allows them to be sub-classified into four groups (Pye, 1993):

1. Simple *lunate* parabolic dunes have a length-width ratio less than 0.4 (see Figure 2.2).
2. Simple *hemicyclic* parabolic dunes have a length-width ratio of 0.4:1.0 (see Figure 2.2).
3. Simple *lobate* parabolic dunes have a length-width ratio of between 1.0:3.0 (see Figure 2.2).
4. Simple elongate parabolic dunes are all those dunes with a length-width ratio greater than 3.0 (see Figure 2.2) (Pye, 1993).

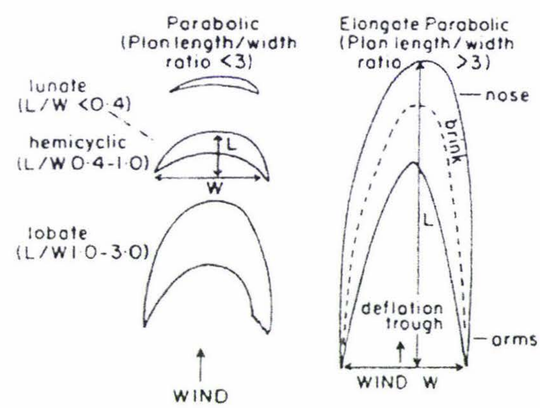


Figure 2.2 Simple Parabolic Dunes from Pye, 1993.

Two or more parabolic dunes which are adjoined or superimposed onto one another are called compound parabolics. Four sub-categories of compound dunes are identified,

1. *Nested,* which are smaller parabolic dunes within a larger parabolic dune (see Figure 3).
2. *En-echelon,* which are several parabolic dunes joined together along the trailing arms (see Figure 2.3).

3. *Digitate,* which are several parabolic dunes joined together to produce a hand like shape (see Figure 2.3).
4. *Superimposed,* which are two or more parabolic dunes which overlie one another (see Figure 2.3) (Pye, 1993).

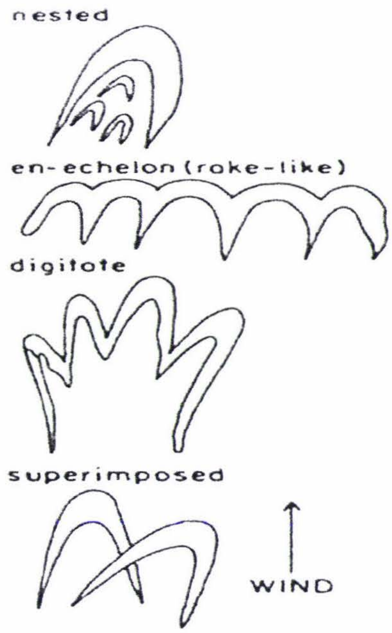


Figure 2.3 Compound parabolic dunes from Pye, 1993.

The third main type of parabolic dune are complex parabolic dunes. These dune types are less easily described due to their complex varying nature. Parabolic dunes of this type may have a wide variety of forms (see Figure 2.4), have passed through several different phases, and be combined in a variety of combinations (Pye, 1993). Pye (1993) describes an example of a complex parabolic dune from Queensland, Australia, as a complex which "consists of a broadly parabolic-shaped sand ramp or sand sheet upon which are superimposed transverse ridges or small barchan forms. The margins of the transgressive sand sheet are often defined by a partly vegetated ridge." (Pye, 1993, pp 29).

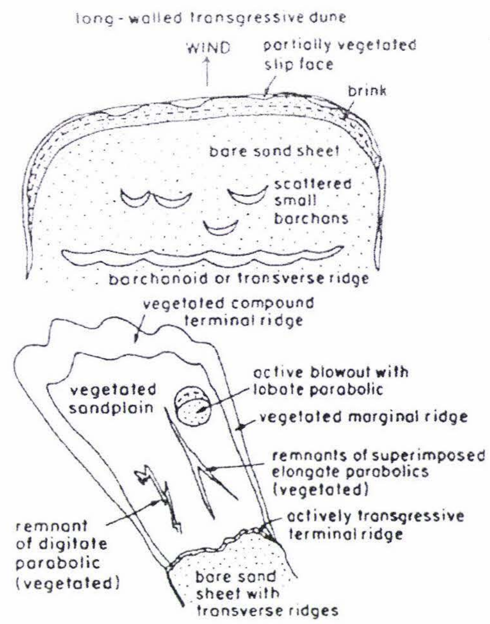


Figure 2.4 Complex Parabolic Dunes from Pye, 1993.

2.3 Parabolic Dune Initiation

Parabolic dune initiation can be due to a combination of a number of factors. Some basic conditions are necessary for initiation and these are discussed as well as the factors for initiation of parabolic dunes in the Manawatu coastal area.

Parabolic dunes are formed through the interaction between vegetation and moving sand (Cooper, 1958; Thompson, 1983). In order for parabolic dune initiation to occur some basic conditions are required. Cooper (1958) identified what he believed were the three prerequisite conditions for parabolic dune initiation. The first factor is a stable surface, which can then be attacked by the wind at a point of weakness. The second factor is significant initial thickness of sand, to prevent sand from just moving in a wide front. The third and final factor is a dominant wind direction, as effective sand moving wind needs to prevail from one direction otherwise the different directions will cancel one another. Pye (1983) agrees with these factors of development. Parabolic dunes are aligned along their long axis to the prevailing wind (Pye, 1983; Landsberg, 1956).

Vegetation, in particular, has a pronounced effect on parabolic dune type and development, and is essential in the building of coastal dunes (Cooper, 1958; Hicks, 1975; Filion & Morisset, 1983; Thompson, 1983). Vegetation acts in direct opposition to the wind by stabilising sand. It does this in two ways: it covers the surface of the sand protecting it from the wind, and it binds the superficial sand layer with root networks of the plants (Cooper, 1958). Cooper (1958) also identifies a third way, in the forests of Oregon and Washington where vegetation cover modifies the physical and chemical properties at the sand surface and leads to the formation of a B-horizon podzolic soil.

Hesp & Thom (1990) discuss sea level rise as a possible mechanism of parabolic dune initiation. Large scale erosion of the shoreline, when combined with significant sediment supply and rising sea level such as occurred during the Post Glacial Marine Transgression may initiate parabolic and transgressive dunefield development. Sea level stabilised somewhere between 6000 and 7000 years B.P. and work by Shepherd & Price (1990) suggests that the Koputaroa dune phase, which is the first phase of Cowie's (1963) dune phases of the Manawatu, had been initiated prior to this.

Parabolic dunes develop in desert environments as well as coastal environments. Parabolic dunes in the Jafurah Desert, Saudi Arabia, develop where areas of low density vegetation are preferentially eroded and a deflation depression forms. As the roots are exposed the vegetation dies off removing the protective cover and deflation continues at a faster rate (Anton & Vincent, 1986).

Blowouts in the foredune may also lead to the development of parabolic dunes in the Manawatu sand country. This is quite common along the Manawatu coast and the processes relating to blowout formation in the foredune along the Manawatu coast are reviewed below.

2.3.1 Blowout initiation along the Manawatu coast

Blowout development along the Manawatu coast is discussed and reviewed here as parabolic dunes are formed from blowout development. Blowouts form initially as a result of wind erosion of a sandy substrate or dune, forming a depression. The eroded sand is then deposited downwind of the depression as a depositional lobe (Hesp, 2000).

Blowouts are typically one of two types, which were identified by Cooper (1958), and are described as either saucer or trough blowouts. Most authors agree with and use these definitions (Carter, 1958; Carter et al, 1990; Hesp & Hyde, 1996). Trough blowouts are typically more common along the Manawatu coast (Hesp, 2000), although both types of blowout have been identified (Brough, 1998; Hesp, 2000). The initiation of blowouts along the Manawatu coast is often in areas of naturally occurring low foredune vegetation (Hesp, 2001). Natural processes which may cause vegetation disturbance include foredune erosion by wave action during storm events, wind erosion during extreme high wind events, fluvial erosion, sand movement burying vegetation (Carter, Hesp & Nordstrom, 1990; Hesp, 2000) and vegetation die back and soil nutrient deficiency (Carter, Hesp & Nordstrom, 1990). Climate change has also been identified as a mechanism, as this may disturb vegetation (Hesp & Hyde, 1996). However in the Manawatu area disturbance is often the result of anthropogenic activity in the foredune, in particular the use of vehicles in the dunes, although other influences include the activities of introduced animals such as rabbits, hares and stock (Carter, Hesp & Nordstrom, 1990; Hesp, 2000; Hesp 2001).

2.4 The Manawatu Parabolics

The coastal parabolic dunefield of the Manawatu is the largest in New Zealand and one of the biggest in the world (Hesp, 2000). Parabolic dunes which occur near the shoreline are often formed as the result of a disturbance of the foredune which may lead to the formation of a blowout, or from disturbance in the vegetation of older sand deposits (Pye, 1983). Due to the high energy nature of the west coast including the Manawatu coastal dune system, blowouts commonly occur in the foredune and from these blowouts parabolic dunes evolve (Hesp, 2000; Hesp, 2001).

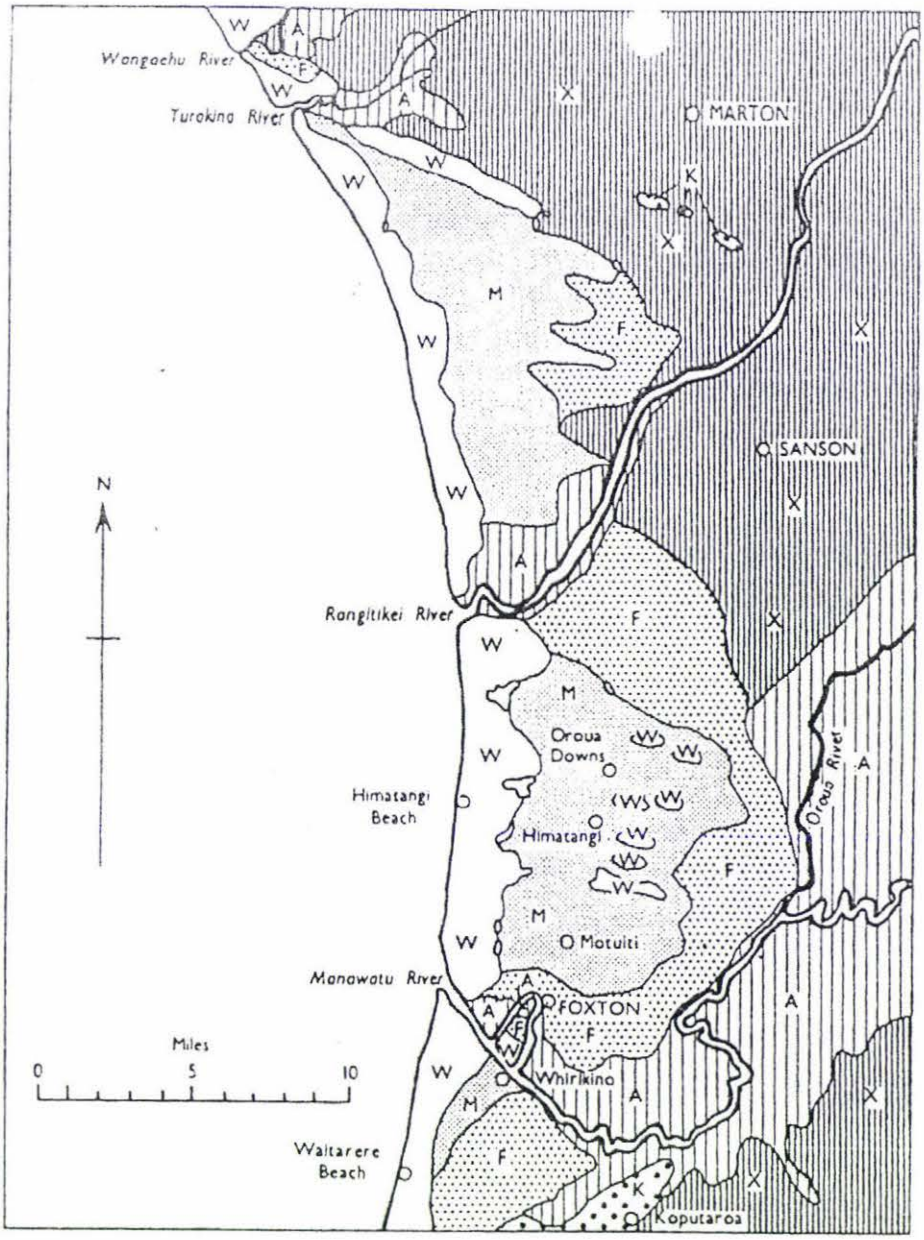
The Manawatu coastal area has been an active dunefield for several thousand years, with the oldest dunes being dated between 10,000 and 20,000 years old (Cowie, 1963). Dune migration and development has been episodic throughout this time. Cowie (1963) identified four phases of dunefield activity (see Figure 2.5). The earliest recognisable phase of activity is the Koputaroa Phase, followed by the second phase of activity which is the Foxton Phase, followed by the third phase of development which is the Motuiti Phase. The fourth phase is the Waitarere Phase, subsequent research by Muckersie and Shepherd (1995) and McFadgen (1985) has seen this phase divided into two stages within the phase.

The oldest recognisable phase is the Koputaroa Phase and this is considered to be 10,000 to 20,000 years B.P. (Cowie, 1963). Work by Shepherd (1985) on the Koputoroa Phase dunes provides dates ranging between 17,000 and 35,000 years B.P. Pollen from within a dune from the Koputoroa Phase was dated at 35,000 $\pm$ 1,700 years B.P. Other dunes contain a layer of Aokautere Ash, which is dated at approximately 20,000 years B.P. However, subsequent work by Wilson (1993) has seen this date of the Aokautere Ash dated at 22,000 years B.P. In places the dunes overlie aggradational gravels with an approximate age of 18,000 - 23,000 years B.P. (Shepherd, 1985). Through thermoluminescence dating of Koputaroa dune sand Shepherd & Price (1990) produced an age of 24,200 $\pm$ 3,700 years B.P. for this phase. The dunes of this phase are only preserved in northern and southern parts of the Manawatu, inland of the second phase and are not well defined (Cowie, 1963).

The second phase identified is the Foxton Phase. This phase was considered by Cowie (1963) to be 2,000 to 4,000 years old. Subsequent research has identified an age of between 5,500 and 6,000 years B.P. (Shepherd & Lees, 1987), or even possibly prior to 6,000 years B.P. (Muckersie & Shepherd, 1995). The dunes of this phase form a belt 3.5 to 6.5 kilometres in length inland of the third phase, and are wind-drift in form and primarily extending west-north-west (Cowie, 1963).

The third phase identified is the Motuiti Phase. It is believed to be 500 to 1,000 years B.P. by Cowie, (1963) and McFadgen (1985). However Muckersie and Shepherd (1995) cite an age of 3,500 to 1,300 years B.P. for the initiation of Motuiti Phase. The Motuiti Phase forms a belt up to 9.5 kilometres inland of the fourth phase, and the dunes have a rugged outline and windrift form (Cowie, 1963). Cowie (1963) believed the Motuiti Phase to be the result of Maori destruction of the vegetation on stabilised dunes, however ages determined by Muckersie and Shepherd (1995) make this most unlikely.

The final phase identified (which includes the modern dunes) is the Waitarere Phase. It is less than 120 years old and covers European artifacts and introduced plants in places (Cowie, 1963). McFadgen (1985) suggests that the Waitarere Phase could be divided into two separate episodes with the initial phase likely to have stabilised prior to 1889, and having been initiated between 300 and 500 years B.P. Muckersie and Shepherd (1995) state that this first episode which they call phase III (not the Motuiti Phase identified by Cowie) was initiated no more than 1000 years B.P., and was possibly the result of Maori arrival in the region. The second episode or what is described as phase IV by Muckersie and Shepherd, was likely to have been initiated by European activities (Muckersie & Shepherd, 1995). Between 1990 and 1995 a series of new parabolic dunes began developing from blowouts in the foredune. These dunes are migrating between 50 and 80 metres per year (Hesp, 2001). Hesp (2001) identified a new episode of parabolic dune formation, which began approximately six years ago. Several blowouts in the foredune identified in 1995 have since developed into parabolic dunes, migrating at rates of between 20 - 25 metres per year (Hesp, 2001).



A = Floodplain with Recent Alluvium

W = Waitarere Phase

M = Motuiti Phase

F = Foxton Phase

K = Koputaroa Phase

X = Loess, Ohakes gravels, Tertiary rocks, and greywacke

Figure 2.5 Dune-building phases in the Manawatu from Cowie, 1963.

Once the vegetation on the foredune is disturbed the foredune is prone to wind erosion. The rate of development of a blowout along the Manawatu coast can be very rapid, due to the high wind speeds which often occur along the coast (Hesp, 2000). Once the blowout is initiated wind speeds are increased locally at the blowout, and this wind speed increase markedly increases the potential for erosion and transportation (Cooper, 1958; Hesp, 2000).

2.5 Parabolic Dune Dynamics

The behavior and dynamics of parabolic dunes following their initiation can vary between regions and countries. This is largely due to the physical and vegetation characteristics of the area where they form, the supply of sand to the dune, and the wind regime of the area.

There are a number of factors which may affect the type and size of sand dune which will form. Pye (1993) identified seven main factors, which control sand accumulation:

1. sand availability (supply);
2. grain size distribution;
3. wind velocity and directional variability;
4. vegetation cover and growth characteristics;
5. the nature of the surroundings and underlying topography;
6. climatic and sea level changes and,
7. long-term patterns of tectonic uplift and subsidence.

Several of these factors are inter-dependent with one another and changes in one will affect another, possibly causing complex morphological responses in the dune system (Pye, 1983). Cooper (1958) provides a simpler list of necessary factors for the construction of coastal dunes, these being sand, wind and vegetation.

Once a blowout has formed a parabolic dune begins to develop behind the initial point of the blowout (Cooper, 1967). Battiau-Queney et al (2000) identify a three-stage model of parabolic dune development. Stage One occurs following a breach in the foredune, when deflation occurs through the breach and immediately behind it, forming a blowout and an incipient transgressive dune. Stage Two occurs when further deflation leads to the formation of a transgressive dune behind the original blowout which may then begin moving inland. Stage Three sees the development of the parabolic dune with further deflation occurring, with the trailing arms of the dune being stabilized by vegetation (see Figure 2.6). A crescent dune may form in the deflation basin and a new foredune may develop in the original breach.

It should be noted that Hesp & Thom (1990) reserve the term transgressive dunefield to define "a broad, active (free-moving) sand surface migrating landwards or alongshore" (Hesp & Thom, 1990, pp 254). The term trangressive dune when used as a general term refers to sand deposits, which are actively migrating downwind and transgressing or advancing over established terrain. When used in this generic sense the term can embrace the following morphological features; parabolic dunes, blowouts, cliff-top dunes and long-walled transgressive dunes (Hesp & Thom, 1990).

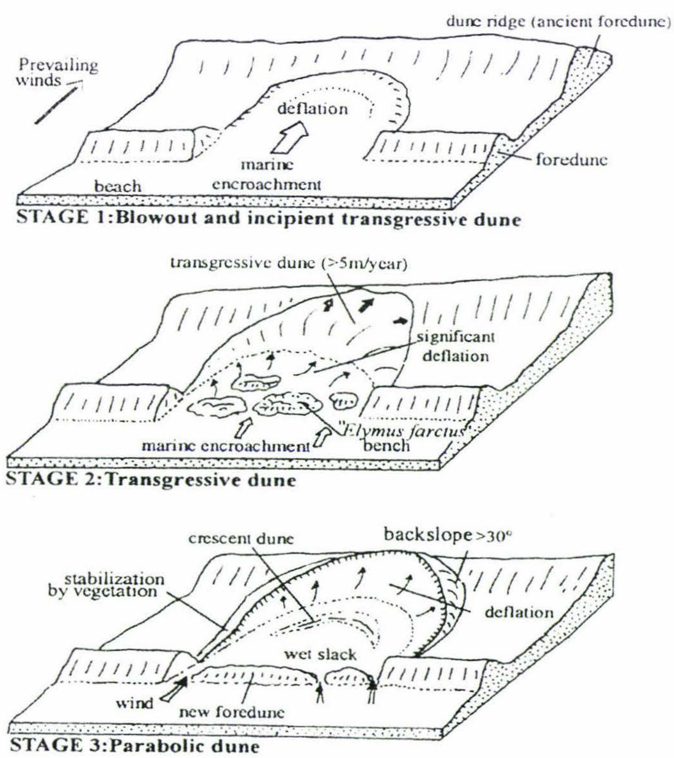


Figure 2.6 Three stage model of Parabolic Dune development from Battiau-Queney, 2000.

Hesp (2000) also identifies a three-stage model for parabolic dune development. The first stage is a disturbance in the vegetation on the foredune and the subsequent formation of a blowout. The second stage occurs as erosion continues, the deflation basin enlarges, a depositional lobe forms and moves downwind, and the parabolic dune forms. In the third stage the parabolic dune continues to move further downwind and the trailing arms are formed. The foredune may then reform across the throat of the blowout (see Figure 2.7).

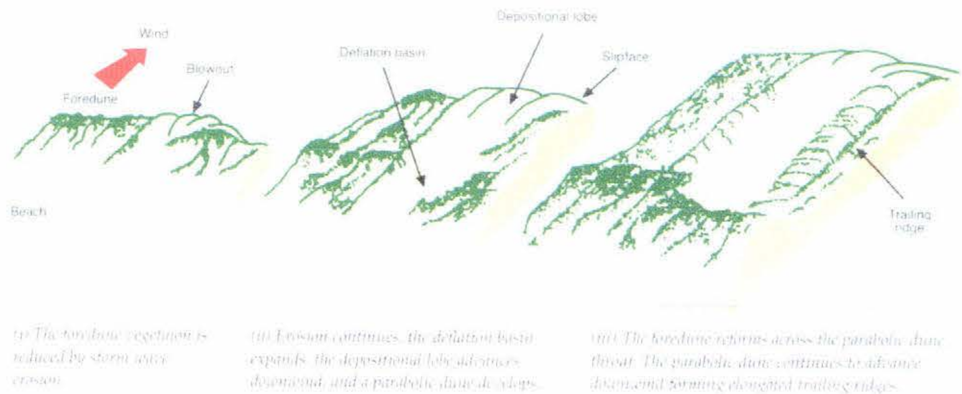


Figure 2.7 Three stage model of Parabolic Dune development from Hesp. 2000.

Pye (1982) produced a six stage model on the evolutionary development of elongate parabolic dunes based on his work at Cape Flattery, North Queensland, Australia. Stage 1 is a small parabolic dune consisting of mainly bare sand with an unvegetated slip face. The slip face subsequently becomes vegetated, an undercut windward knife edge forms upwind of the slip face and a small lake forms in the deflation basin. The second stage sees an incipient elongate parabolic dune form as the dune pushes beyond the apex and the slip faces reactivates. The third stage is a mature elongated parabolic with vegetated slip face and larger lake in the deflation basin. The fourth stage sees diverging arms of sand develop and push toward and eventually beyond the dune apex. In the fifth stage the trailing arms begin to converge once more and the dune decreases in height. During this stage Gegenwalle ridges may be present, and the lake becomes swamp. In the final stage a low sand tongue breaks through the apex of the dune. Pye does make the point that the development sequence may stop at any stage and that not all active parabolic dunes develop into elongate parabolic dunes.

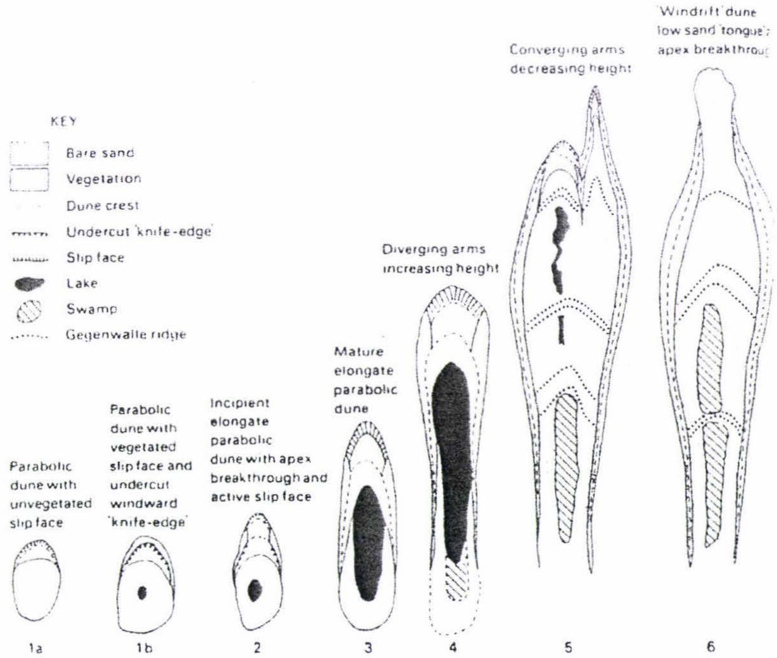


Figure 2.8 Model of stages in the evolutionary development of elongate parabolic dunes from Pye, 1982.

Vegetation may also influence the type of parabolic dune which forms. Along the northern coast of Quebec where the vegetation is composed of forest tundra, the parabolic dunes display a multi-lobate form. Due to the multi-directional winds of the area, normal incident dunes, dunes in opposition and hemicyclic dunes are all found. Further to the north the vegetation is composed of forest and shrub tundra, here the wind is unidirectional rather than multi-directional and the dunes display either imbricate or en echelon form (Filion & Morisset, 1983).

2.6 Rates of Migration

Rates of migration in parabolic dunes are highly variable from one location to another and are largely related to wind direction and wind energy, with rates of migration being slower where wind direction is more variable and wind energy is low. Hesp (2000) also identifies terrain and vegetation as important factors in migration rates, with dunes moving through pine forest, scrub, and bushland having much lower rates of migration than when moving across pasture. Cooper (1958) describes an example from the Oregon Washington coast where tall dense forest impedes the inland advance of coastal dunes. The forest vegetation causes the surface air currents to lose velocity and sand is deposited at the forest edge. The advance of the dunes is then much slower, as they progress by forward creep of the slip face of the dune. The rate of creep of the slip face continues to slow as the dune becomes more massive and the slip face gets higher. Due to this dunes along the Oregon Washington coast have only penetrated inland to a maximum of 4.5 km (Cooper, 1958). Slope appears not to have a significant affect on rates of migration, however where vegetation and slope combine, slope substantially increases the effects imposed by vegetation (Cooper, 1958).

In Europe and Britain rates of migration tend to be slow due to the lower average wind speeds (Landsberg, 1956), while in North Queensland Australia, rates of up to five to six metres per year have been measured by Pye (1983). Story (1982) recorded a much slower rate in the Northern Territory of Australia, of only five centimetres per year. In the Manawatu coastal area migration rates from one metre per year right through to 200 metres per year have been documented (Hesp, 2000), while Holland (1983) has also recorded rates of up 100 metres per month in some cases.

2.7 Gaps in the Literature

The large proportion of the literature relating to parabolic dunes is related to research conducted overseas with very little being available on parabolic dunes in New Zealand. What research there is from New Zealand deals mainly with distances and rates of migration. There is no literature relating to the morphological development of parabolic dunes nor is there any literature relating parabolic dune development to the wind regime of the area. There have been no detailed studies of morphological change of dunes conducted along the Manawatu Coast.

Of the research conducted overseas very little of it deals with morphological change over time and the wind regime of the area of study. Most studies are limited to distances and rates of migration with only a small mention of morphological development over time. Many studies also do not deal specifically with parabolic dunes but instead discuss all sand features of a selected area.

The models for parabolic dune development have been derived from research carried out overseas, mainly in the Netherlands, the U.S.A and Australia, with the exception of Hesp (2000) whose model is based largely on research carried out along the Manawatu Coast. This model however relates only to the development of a parabolic dune from a blowout and does not go on to describe morphological development over a longer time period.

Given the gaps in the literature the goals of this research are as follows:

- Examine morphological change of parabolic dunes over time;
- Compare morphological change to wind regime;
- Identify distance and rates of migration;
- Compare distance and rates of migration to wind regime;
- Produce a model of parabolic dune development relevant to the Manawatu Coast.

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Chapter Three: Methodology

3.1 Introduction

This chapter examines the research methods utilised in this thesis research. All equipment, data collection, methods and data manipulation are discussed. Errors which occurred during the research are also identified.

Survey benchmarks using warratah stakes (see Figure 3.1) were established on the four parabolic dunes to provide permanent lines of survey and to double as benchmarks and points at which measurements could be made to identify points of surface change.

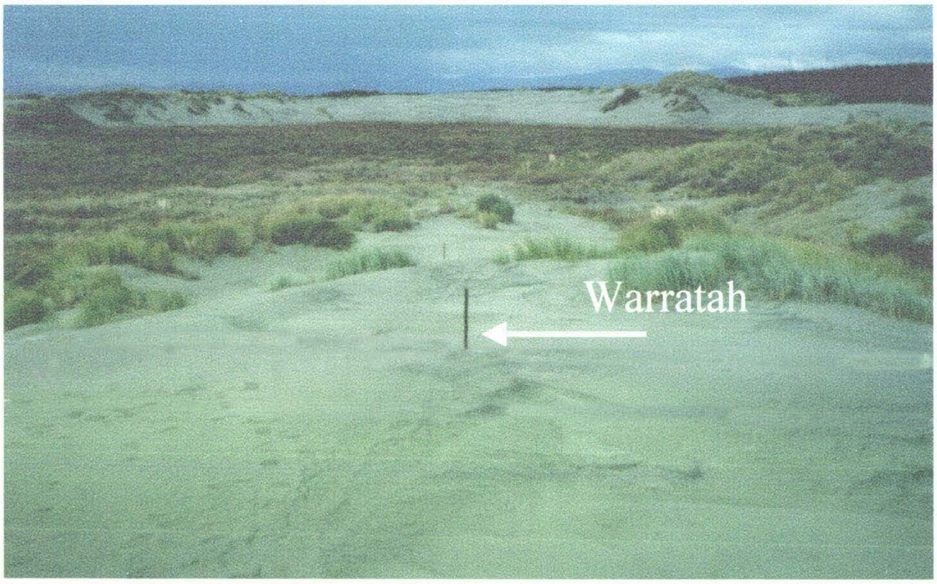


Figure 3.1: An example of the warratah stakes used on the parabolic dunes.

Surveying of the parabolic dunes was conducted using a Trimble RTK Global Positioning System (GPS) on two occasions and with a GTS-701 Total Station for the other surveys.

The survey data was then used to create Digital Terrain Models (DTMs) of the dunes. The DTMs were then used to assess morphological and volumetric changes in the dunes over time. The DTMs were created using the SURFER package.

Vertical aerial stereo photographs of the area were obtained, and geomorphic mapping of the aerial photos was carried out. By reviewing older aerial photographs changes in the dunes could be identified and measured over time.

Raw wind data from Ohakea was obtained courtesy of NIWA and entered into a Microsoft Excel spreadsheet. Wind roses were created using the Lakes Environmental Software WRPLOT View, which was obtained from the http://www.lakes-environmental.com/lakewrpl.html website.

Human error has been identified as a potential source of error within the study. Errors may have arisen from incorrect site setup, use of the Total Station and reflector staff, the incorrect recording of the data collected from the Total Station, use of the GPS system, as well as errors in the recording and manipulation of the wind data, and errors in mapping the aerial photos.

3.2 Site setup

For the purposes of this study the parabolic dunes are described as parabolic dunes one to four (PD 1-4), with PD1 being the southern most dune and PD4 being the northern most dune (see Figure 3.2).

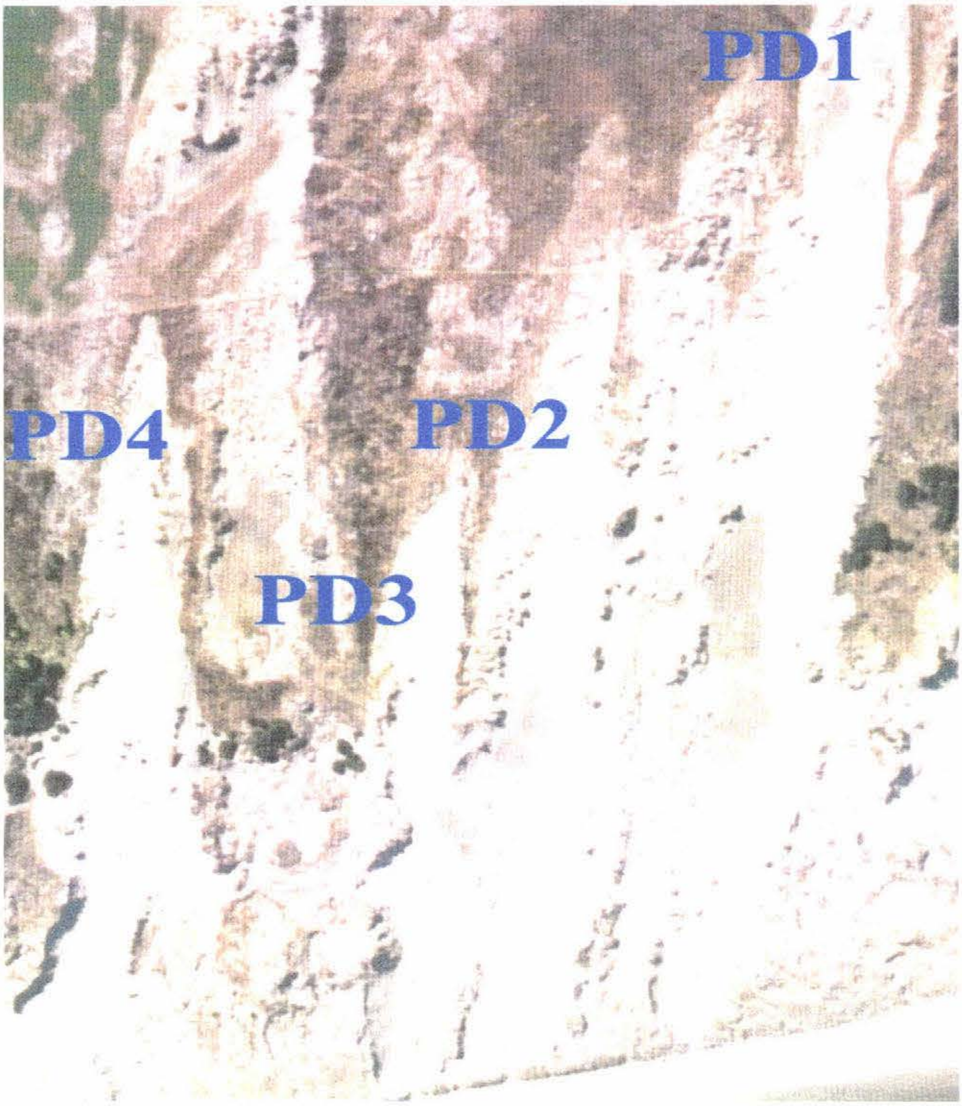


Figure 3.2: 2002 aerial photograph of the study area showing the four parabolic dunes.

The four parabolic dunes chosen for study were covered with survey benchmarks to establish lines of survey. These benchmarks also provided points of measurement (erosion rods) to determine whether sand was being deposited or being removed from a point on the dune. The metal waratahs which were used as benchmarks, were driven into the ground until approximately 0.70 metres was left exposed, and the height remaining above the surface of the sand was measured and recorded. This height above the level of sand was then subsequently measured in order to establish surface elevation changes in the area surrounding the benchmarks.

Two benchmarks were established down the approximate centerline of PD1. Seventeen benchmarks were established on PD2 with seven down the approximate center line of the dune, five on the northern edge and five on the southern edge. Fifteen benchmarks were established on PD3 with seven through the approximate center line of the dune, four on the northern edge and four on the southern edge. Seventeen benchmarks were established on PD4 with seven along the approximate center line of the dune, five on the northern edge and five on the southern edge.

Errors may have arisen within the subsequent measurements by incorrect reading or recording of the height, disturbance of the warratahs by human activity, or warratahs being eroded or buried by wind action.

3.3 Survey Methods

The dunes were surveyed using a GTS-701 Total Station and a Trimble RTK Global Positioning System (GPS).

The GPS surveying was carried out using a GPS system mounted on a four-wheeled motorbike. The motorbike was then ridden over the majority of the dune, although some areas were too steep, unstable or heavily vegetated to ride over. Areas of young vegetation were also avoided, as an effort was made to minimize further destabilizing the dune. The GPS then recorded X, Y, Z co-ordinates for each point. These points were recorded in Latitude, Longitude and the height in metres above sea level. The data from the GPS was then converted into the Easting and Northing co-ordinate system using the ArcMap programme by ESRI, which has an in built converter.

The Total Station was set up over a benchmark on each of the parabolic dunes from which the majority of the dune could be seen. The reflector staff was then placed at locations along and across the dune and a measurement of Eastings, Northings, and height taken for each location.

Once the surveys were completed X, Y, Z coordinate files were created by the GPS and the Total Station. These files were then able to be manipulated within a Geographic Information System (GIS) package.

The Trimble RTK GPS system, allows each point on the ground to be recorded within one centimeter of the co-ordinates. For any point in the survey it will be within one centimeter of the Northing, Easting or Height given for that point.

The GTS-701 Total Station used for surveying has an accuracy of +/-(2mm + 2ppm) at mean sea level. Errors may arise in the data as a result of incorrect set up of the instrument, settling during the survey which will affect the level of the instrument, and accidental changes to the staff height.

3.4 Digital Terrain Modeling

The surveys of the dunes provided data which could then be used to create a Digital Terrain Model (DTM). There are many (GIS) packages available which could be used to produce DTMs, including Idrisi, and ARC Info, however for this study the SURFER DTM package was used. The SURFER DTM offered two display options (contour map and wireframe map) which were best suited to displaying the data for analysis.

A DTM is a three dimensional image which is created using X, Y, Z co-ordinates, which in this case use the Eastings, Northings and Height values for the points surveyed.

The X, Y, Z data for each parabolic survey was entered into a SURFER worksheet, and the data was then processed.

By using the features of the SURFER programme a DTM can be produced for each dune from each survey. The DTMs from the different survey dates can then be compared and changes in length, volume and morphology can be measured, to allow a comparison of changes over time.

3.5 Aerial Photographic Mapping

Vertical aerial stereo photographs for the area were available from 1990, 1995, 2000, 2001 and 2002. The photos span a twelve-year period and clearly show the initiation and migration of the parabolic dunes over this time.

The different morphological areas of each parabolic dune were mapped for each of the aerial photographs to create geomorphic maps and these geomorphic maps were then used to estimate initiation, development, changes in position and distances of migration.

The aerial photos were enlarged onto A3 sheets to make identification of morphological features more easily following methods outlined by Compton (1962). The dunes were mapped for each of the years and the different morphological features, such as the terminal lobe, the trailing arms and the deflation basin were identified. Once the size and shape of the morphological features were mapped for each dune for each year, comparisons between years could be made. The maps also allowed for some estimation to be made of yearly rates of advance and of parabolic dune behavior under varying climatic conditions.

Errors may arise in the mapping of the aerial photographs and the measurements made from the photos. Possible errors include incorrect identification of the morphological features, incorrect measurement or conversion of the scale, and incorrect measurements of features. Errors may exist within the aerial photographs themselves due to factors such as warp and stretch during photography. Differences in scale may also occur within a photograph due to differing heights of the land's surface. This may be due to the different heights between the trailing arms, depositional lobe, deflation basin and the surrounding land. Tilt of the aircraft, which causes stretching to parts of the photograph, also affects scale. Usually tilt is less than five degrees and so is not a significant problem. The curvature of the Earth may also affect the photo, by bringing the centre of the photograph closer to the camera lens, however by using specially ground lenses this error is reduced. Changes in barometric pressure will affect the altimeter of the plane and may be recorded as changes in altitude when in fact they are changes in barometric pressure. Altimeter readings are therefore only approximate and may contain significant error under certain conditions (McArthur, 1998).

3.6 Wind Data

Hourly wind speed and direction data from Ohakea Air Force Base was used to identify relationships between wind direction and speed and the rate of dune migration. By using Lakes Environmental Software WRPLOT View computer programme the raw data was used to produce wind roses identifying the dominant wind direction and speed classes for sand movement. This allowed for an assessment of the movement of the parabolic dunes in years of different wind regimes.

Chapter Four: Parabolic dune development as identified from aerial photographs.

4.1 Introduction

Parabolic dune development along the Manawatu coast begins with the development of a blowout in the foredune which then develops into a parabolic dune (Hesp, 2000; Hesp 2001). From an analysis of the aerial photos and work by previous authors (Hesp, 2001) several blowouts in the foredune were identified which subsequently developed into the parabolic dunes which were studied in this research. The morphology of parabolic dunes is controlled by a number of factors, these are strength and variation in direction of the wind in the area, the quantity and source of the sand available, and type of terrain and vegetation over which the dunes are moving (Pye & Tsoar, 1990). This chapter examines the morphological changes, the distance of migration of the four parabolic dunes over a 12-year period from 1990 to 2002. The wind regime over this time period is analysed and discussed as is its relationship to parabolic dune development.

Aerial photographs of the area were available over a 12-year period and these were broken down into four periods. The first period is from 1990 to 1995, the second period is form 1995 to 2000, the third period is from 2000 till 2002 and the four and final period is from February 2002 to December 2002.

4.2 Development and migration of Parabolic Dune 1 (PD.1)

4.2.1 Changes to the former blowout and deflation basin of PD.1 between 1995 and 2000

In the aerial photograph from 1990, the former blowout in the foredune of PD.1 can still be clearly seen, even though sufficient time for further dune development to occur had elapsed since the blowout formed. The narrow former blowout gap in the foredune widens approximately 5.0 metres behind the foredune into the back of the former blowout and then into the deflation basin. By 1995 there had been no obvious change in the former blowout shape apart from an increase in the width at the landwards end of the blowout of approximately 4.0 metres.

Landwards of the former blowout, a substantial deflation basin had formed by 1990. The deflation basin was approximately 115 metres in length and 25 metres in width. By 1995 the deflation basin had increased in length by approximately 45 metres and by approximately 5.0 metres in width. There were no other significant changes. It is also probable that the deflation basin had decreased in height. The amount of decrease is difficult to assess but is unlikely to have been greater than 0.5 metres.

4.2.2 Changes to the former blowout and deflation basin of PD.1 between 1995 and 2000

Since 1995 there had been a huge amount of development of PD.1. The landwards portion of the former blowout, and seaward portion of the deflation basin eroded seawards approximately 5.0 metres, and had eroded right back to the back of the foredune. This usually occurs in the Manawatu region during strong offshore easterly winds which occur occasionally during the year (Burgess, 1983). The former blowout and seaward portion of the deflation basin had also expanded laterally to be approximately 15 metres wide. The deflation basin had also expanded in size. There had been approximately 12 metres of lateral expansion since 1995, mainly along the southern side of the deflation basin. The length of the deflation basin had increased by approximately 15 metres, but there had been no obvious or measurable change in height.

4.2.3 Changes to the former blowout and deflation basin of PD.1 between 2000 and 2002

The former blowout and seawards portion of the deflation basin of PD.1 had undergone only minor changes during the two-year interval. There had been a slight lateral enlargement in the back of the former blowout by approximately 5.0 metres to the north and 3.0 metres to the south, but the length had remained unchanged. The deflation basin had been enlarged laterally by approximately 2.0 metres along the northern and southern edges, and there had been an increase in length of approximately 27 metres.

4.2.4 Changes to the former blowout and deflation basin of PD.1 during 2002

During the 2002 period there were very few changes which occurred on the deflation basin and no changes to the former blowout portion of PD.1. The changes which did occur were at the landward end of the deflation basin. There had been a small lateral expansion on both sides of the deflation basin at the landwards end by approximately 4.0 - 5.0 metres. The length of the deflation basin had also increased by approximately 12 -15 metres.

4.2.5 Changes to the trailing arms of PD.1 between 1990 and 1995

The trailing arms of PD.1 are small features in the 1990 aerial photograph. The southern arm of the dune extended approximately 40 metres from the seawards end of the depositional lobe. It was still well formed and did not show much sign of erosion, other than a slight thinning in the trailing arm toward its seawards end. The northern trailing arm was approximately 30 metres long, and extended less than half the length of the deflation basin. Both arms were well vegetated and were approximately 1.5 - 2.0 metres in height. By 1995 the trailing arms had continued to evolve and increase in length. At the seawards end the northern arm had lost approximately 10 metres in length while the southern arm had lost approximately 30 metres of length. At the landwards end both trailing arms had developed approximately 18 metres of new trailing arm. What appear to be two remnant knobs had also formed seawards of the southern trailing arm where the trailing arm used to be, and were approximately 2.0 metres in height.

4.2.6 Changes to the trailing arms of PD.1 between 1995 and 2000

The trailing arms of PD.1 had been heavily eroded since 1995. They appeared to be narrower and less well formed than in previous photographs. The northern trailing arm had been eroded by approximately 10 metres while the southern trailing arm had been eroded by approximately 40 metres. At the landwards end there had been approximately 30 metres of new trailing arm development. Parts of both the trailing arms which were present in 1995 remained as remnant knobs.

4.2.7 Changes to the trailing arms of PD.1 between 2000 and 2002

Changes to the trailing arms of PD.1 obviously were not as great as during the last interval given the shorter temporal interval. There had been no obvious changes to the southern trailing arm, although it is likely that some small amount of erosion had occurred but this was probably less than 2.0 metres in any direction. The northern trailing arm showed more signs of erosion. The seawards end of the trailing arm and the remnant knobs show signs of small amounts of erosion, but these were less than 2.0 metres. The trailing arms were largely unchanged since 2000.

4.2.8 Changes to the trailing arms of PD.1 during 2002

The trailing arms of PD.1 were not strongly eroded during 2002. Any erosion of the seawards ends of the trailing arms was not sufficiently large to be seen on the aerial photographs. The remnant knobs which were present in February were still present ten months later in December, and there did not appear to have been a large amount of erosion on the remnant knobs. There had been no trailing arm development on the landwards end of either trailing arm.

4.2.9 Changes to the depositional lobe of PD.1 between 1990 and 1995

In 1990 the depositional lobe was approximately 35 metres in length extending beyond the deflation basin. The width of the depositional lobe was approximately 15 metres at its widest point. The depositional lobe had a gentle unvegetated slope up from the deflation basin with unvegetated slip faces on the sides and the landwards end. It is difficult to tell the height of the depositional lobe but it was significantly higher than both the deflation basin and the surrounding land, so it was probably somewhere between 1.5 - 2.0 metres in height. By 1995 the depositional lobe had migrated approximately 55 - 60 metres further inland increasing in length by approximately 15 - 20 metres. The width had increased by approximately 5.0 - 7.0 metres. Height changes are more difficult to assess, however using stereo aerial photograph pairs and based on other changes to the depositional lobe, an attempt had been made to give approximate height changes. These changes appear to be an increase of a further 1.5 - 2.0 metres.

4.2.10 Changes to the depositional lobe of PD.1 between 1995 and 2000

The depositional lobe of PD.1 had both increased in size and migrated inland since 1995. It had increased in width by approximately 10 - 15 metres, and had migrated approximately 25 - 30 metres inland. This had produced an increase in the length of approximately 10 - 15 metres. The aerial photograph indicated that the height of the depositional lobe had increased during this interval, and this increase is likely to have been somewhere between 1.0 - 1.5 metres.

4.2.11 Changes to the depositional lobe of PD.1 between 2000 and 2002

The depositional lobe of PD.1 had not changed in size dramatically nor had it migrated a long distance inland since 2000. Most of the changes to the depositional lobe were so small they are difficult to identify from the aerial photograph. There had been a small lateral increase of approximately 4.0 metres along the northern edge, and a similar amount of expansion along the southern edge. There had been approximately 5.0 metres of inland migration, which had seen the length reduced by approximately 22 metres due to deflation basin expansion. There had not been any obvious increase in height.

4.2.12 Changes to the depositional lobe of PD.1 during 2002

During 2002 there was an increase in the width, length and height of PD.1. The depositional lobe migrated inland by approximately 15 metres and in a slightly more northerly direction. An increase in width of approximately 3.0 metres occurred with most of the increase in width occurring along the northern edge, rather than the southern edge. The distance of inland migration minus the decrease in length due to deflation basin expansion saw a decrease in length of approximately 2.0 metres. It is difficult to assess increases in height from aerial photographs, however there does appear to have been an increase in the order of approximately 0.90 metres and this is supported by observations made in the field.

4.2.13 Changes to the surge lobe of PD.1 between 1990 and 1995

In 1990 there was no evidence of a surge lobe developing beyond the nose of the dune. A surge lobe is a lobe of sand which extends inland and downwind beyond the apex of the main depositional lobe of a parabolic dune. They are slightly narrower and significantly lower than the depositional lobe. When formed, they move at a much higher rate than the depositional lobe (Hesp, pers.comm, 2002). The sand features in front of the depositional lobe in 1990 appear to be older dune formations rather than a surge lobe from the parabolic dune. By 1995 there was still no evidence of a surge lobe from either aerial photograph, see Figure 4.1.

4.2.14 Changes to the surge lobe of PD.1 between 1995 and 2000

Between 1995 and 2000 a surge lobe had developed beyond the main depositional lobe of PD.1. The surge lobe was approximately 155 metres in length and approximately 33 metres in width. Previous field observations by P. Hesp indicate that the height of this feature was 0.2 - 0.3 metres.

4.2.15 Changes to the surge lobe of PD.1 between 2000 and 2002

The surge lobe had increased in size since 2000. In the 2000 aerial photograph the surge lobe was slightly narrower in width than the depositional lobe and was approximately the same width along its entire length. By 2002 there had been an increase in the width mainly through the middle and landwards end of the surge lobe, with the expansion being approximately 5.0 metres. There had not been a significant increase in height, however some mounds or hummocks of sand with vegetation growing on them appear to have developed during the interval. The distance of inland migration was approximately 8.0 metres.

4.2.16 Changes to the surge lobe of parabolic dune one during 2002

The surge lobe of PD.1 had migrated inland by approximately 27 metres during 2002, although its height and width did not change significantly during 2002. An anomaly which developed during 2002 was a deflated area immediately downwind of the depositional lobe. In February 2002 the surge lobe covered this area, however by December this area was significantly lower than the rest of the surge lobe and at times standing water was present. This indicates the surge lobe was becoming a separate entity and moving away and downwind of the main parabolic dune (Hesp, per.comm, 2002).

4.2.17 Summary of the major changes to PD.1 between 1990 and 2002

Between 1990 and 2002 there had been further erosion of the former blowout of PD.1. Erosion had caused a substantial increase in the width of the portion of the former blowout landwards of the foredune. The overall increase in width between 1990 an 2002 was approximately 17 metres. The length of the former blowout decreased during the interval as the deflation basin expanded seawards.

Between 1990 and 2002 there was substantial development of the deflation basin of PD.1. The deflation basin increased in length by approximately 100 metres, in width by approximately 24 metres and decreased in height by approximately 1.0 metre. The changes to the deflation basin can be seen in Figure 4.1.

Between 1990 and 2002 there had been significant creation and erosion of the trailing arms of PD.1. Erosion at the seawards end had caused a substantial decrease in length of both trailing arms. The northern arm had been eroded by approximately 20 metres, while the southern trailing arm had been eroded by approximately 70 metres. There had been approximately 48 metres of new trailing arm created landwards between 1990 and 2002. Erosion had also caused a thinning in the width of the trailing arms at the seawards end.

Between 1990 and 2002 there had been significant migration and change to the depositional lobe of PD.1. The depositional lobe was very active over this period and developed and moved dramatically. During this interval the depositional lobe migrated approximately 104 metres inland, increased in width by approximately 30 metres, increased in length by approximately 5.0 metres and increased in height by approximately 4.0 metres.

Between 1990 and 2002 there had been significant migration and change to the surge lobe of PD.1. The surge lobe did not develop until after 1995, however, after this it was very active. Between 1995 and 2002 the surge lobe migrated approximately 190 metres inland, increased in width by approximately 33 metres, increased in length by approximately 155 metres and increased in height by approximately 0.3 metres.

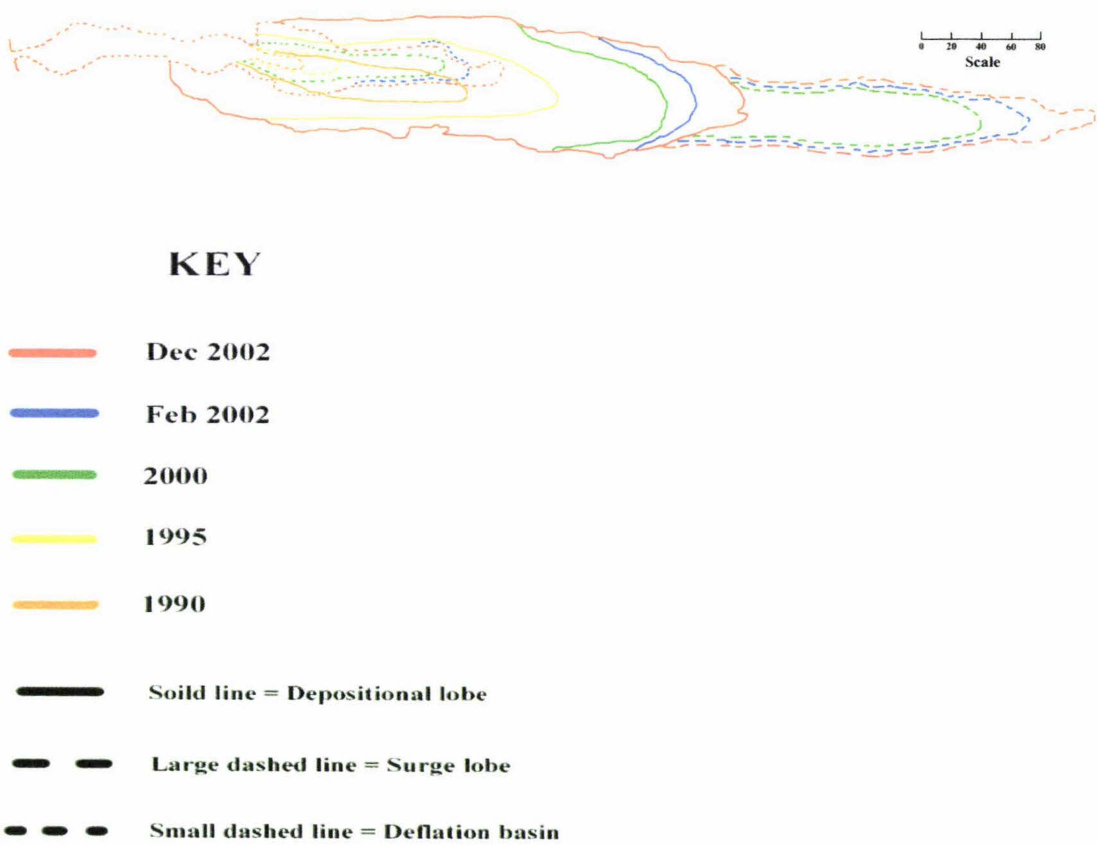


Figure 4.1 Diagram showing changes and development of PD.1 between 1990 and 2002. The different colours represent the position of the different morphological features at the dates of the aerial photographs. The different lines represent different morphological features. The development of each feature can easily be seen. The trailing arms are not shown as the diagram then becomes too complex.

4.3 Development and migration of Parabolic Dune 2 (PD.2)

4.3.1 Changes to the former blowout and deflation basin of PD.2 between 1990 and 1995

PD.2 formed approximately 40 metres north of PD.1 prior to 1990 by which stage it had developed into a small parabolic dune. In 1990 the former blowout had an entrance approximately 1.5 - 2.0 metres wide in the foredune, opening out approximately 5.0 - 10 metres back into the deflation basin. By 1995 the former blowout had extended into the foredune by approximately 5.0 metres. There had been approximately 8.0 metres of lateral expansion at the landwards end of the former blowout substantially increasing the size of the blowout.

In 1990 the deflation basin was approximately 90 metres in length and 15 metres in width and was significantly lower than the surrounding land. By 1995 the deflation basin had lengthened inland by approximately 30 metres. The width increase was smaller at approximately 5.0 metres, with more expansion occurring to the north where the deflation basin opened into the deflation basin of parabolic dune three.

4.3.2 Changes to the former blowout and deflation basin of PD.2 between 1995 and 2000

By 2000 the former blowout had expanded, the mouth was approximately 1.0 - 1.5 metres wider, while the landwards section of the former blowout had also expanded by approximately 3.0 metres. Overall there had been a significant increase in the former blowout size.

The deflation basin increased in length by approximately 38 metres and approximately 8.0 metres in width, especially to the north where the gap between the deflation basins of PD.2 and PD.3 join widened.

4.3.3 Changes to the former blowout and deflation basin of PD.2 between 2000 and 2002

The former blowout showed no significant expansion since 2000. There had been some erosion along both the northern and southern margins of the former blowout, however this had not produced any large change.

The deflation basin had increased slightly in width by approximately 5.0 metres, with most of the erosion occurring along the northern margin of the deflation basin. There had also been an increase in the length of the deflation basin at the landwards end by approximately 15 metres.

4.3.4 Changes to the former blowout and deflation basin of PD.2 during 2002

The aerial photographs indicate only a very small amount of development occurred to the former blowout during 2002. The mouth of the former blowout had increased in width by approximately 0.5 metres during 2002. The area of the former blowout immediately behind the foredune had remained largely unchanged during 2002.

The deflation basin had expanded approximately 20 metres inland and approximately 6.0 metres laterally mainly to the south during 2002. No changes in height can be identified from the aerial photographs between February and December.

4.3.5 Changes to the trailing arms of PD.2 between 1990 and 1995

In 1990 the trailing arms of PD.2 are similar in length to those of PD.1. The southern trailing arm was approximately 40 metres in length, while the northern one was approximately 30 metres. The southern trailing arm was well formed and did not show signs of significant erosion. There were no remnant knobs at this stage. The northern trailing arm showed more signs of erosion especially at the seawards end and also lacked remnant knobs. A break in the arm appears to be caused by the lateral extension of the deflation basin into the former blowout from which Parabolic Dune 3 evolved.

By 1995 the seawards end of the northern trailing arm had been eroded due to the enlargement of the deflation basin of PD.2 and PD.3 (which was directly adjacent to PD.2). There had been approximately 8.0 metres of erosion. At the landwards end there had been substantial development of approximately 20 metres of new trailing arm. The southern arm had lengthened landwards by approximately 10 metres, and there appeared to be some erosion (less than 2.0 metres) at the seawards end.

4.3.6 Changes to the trailing arms of PD.2 between 1995 and 2000

The trailing arms had changed significantly between 1995 and 2000. The southern trailing arm in particular had been heavily eroded. All that remained of the trailing arm was a few remnant knobs near the foredune and a few sparse remnant knobs leading up to the depositional lobe. There had been some trailing arm development of approximately 30 metres during the interval at the landwards end, but much of this had also been eroded leaving approximately 15 - 20 metres of trailing arm intact. The northern trailing arm had not been as heavily eroded as the southern arm, with approximately 15- 20 metres of erosion at the seawards end and approximately 15 metres of development inland. This erosion had enlarged the opening gap between the deflation basins of PD.2 and PD.3.

4.3.7 Changes to the trailing arms of PD.2 between 2000 and 2002

Since 2000 the trailing arms of PD.2 have gone through very few changes. The northern trailing arm had been eroded at the seawards end and had been shortened by approximately 5.0 metres. Erosion had also caused the development of several remnant knobs, as well as further erosion to the remnant knobs which were present in 2000 at the seawards end of the trailing arm. There had been no significant development landwards. The southern trailing arm had not been eroded as heavily as the northern trailing arm, and was in a similar state to the 2000 aerial photograph. The remnant knobs present in 2000 were still present and while showing signs of being eroded during the two year interval had not been destroyed. There had been no significant development of trailing arm landwards.

4.3.8 Changes to the trailing arms of PD.2 during 2002

There were changes to both of the trailing arms during 2002. Along the northern trailing arm there had been substantial erosion at the upwind end, where it had been eroded landwards by approximately 4.0 metres. No remnant knobs were created along this arm. There had been a small amount of development approximately 2.0 metres at the downwind end of the trailing arm as the depositional lobe had migrated inland. The southern trailing arm had developed significantly during 2002 as the depositional lobe had migrated inland, and approximately 2.0 metres of new trailing arm had been formed. There had not been a large amount of erosion approximately 5.0 metres along the southern trailing arm. The only obvious signs came from the remnant knobs which appear to have been eroded, especially the most upwind knob which had been almost completely removed.

4.3.9 Changes to the depositional lobe of PD.2 between 1990 and 1995

The depositional lobe had developed prior to 1990 and was approximately 65 metres in length and approximately 10 - 15 metres in width. The depositional lobe had a gentle, unvegetated slope away from the deflation basin and had much steeper, unvegetated slip faces on the sides and front. It is difficult to tell the height of the depositional lobe but it was higher than the surrounding area at approximately 1.5 - 2.0 metres.

Since 1990 the depositional lobe had continued to develop and had increased slightly in length, and width as well as migrating inland. It had migrated approximately 30 metres inland and increased in width by approximately 10 - 15 metres. Due to the deflation basin lengthening inland, the depositional lobe had increased in length by only a few metres, but by 1995 the height of the depositional lobe had increased to be approximately 1.0 metres higher.

4.3.10 Changes to the depositional lobe of PD.2 between 1995 and 2000

The depositional lobe of PD.2 had both enlarged and migrated downwind since 1995. There have been increases in the length and width of the depositional lobe. The lobe had migrated approximately 30 metres inland and had increased in width by approximately 5.0 metres. The absolute length had remained fairly similar due to deflation basin expansion, and the height of the dune had also increased by approximately 0.5 - 1.0 metres.

4.3.11 Changes to the depositional lobe of PD.2 between 2000 and 2002

The depositional lobe had increased in width, length, height and migrated inland since 2000. There had been lateral expansion of the depositional lobe of approximately 5.0 metres mainly along the southern edge. There had also been approximately 25 metres of inland migration which was an increase in length of approximately 15 metres. With an increase in height of approximately 0.5 metres.

4.3.12 Changes to the depositional lobe of PD.2 during 2002

During this period there had been an increase in width of approximately 3.0 - 5.0 metres. There had been inland movement of approximately 40 metres which had resulted in an overall increase in length of approximately 20 metres. The height of the depositional lobe had increased by approximately 0.7 metres during 2002.

4.3.13 Changes to the surge lobe of PD.2 between 1990 and 1995

In 1990 there was no evidence of a surge lobe beyond the depositional lobe of PD.2, although there were some older sand formations unrelated to this parabolic dune in front of the depositional lobe. In 1995 there was also no evidence in either aerial photographs of a surge lobe beyond the depositional lobe.

4.3.14 Changes to the surge lobe of PD.2 between 1995 and 2000

In 2000 a small surge lobe approximately 13 metres long and 8.0 metres wide was present beyond the depositional lobe. The height of the surge lobe was difficult to determined but was likely to be approximately 0.2 - 0.3 metres in height.

4.3.15 Changes to the surge lobe of PD.2 between 2000 and 2002

Since 2000 the surge lobe had continued to develop and migrate beyond the depositional lobe of PD.2. It had migrated approximately 75 metres since 2000 and was approximately 65 - 70 metres in length. At its widest point near the depositional lobe the surge lobe was approximately 18 metres wide, and the height had increased by approximately 0.3 - 0.4 metres.

4.3.16 Changes to the surge lobe of PD.2 during 2002

The surge lobe of PD.2 had migrated a substantial distance inland during 2002, as well as increasing in width. It had migrated inland by a distance of approximately 70 metres with an increase in width of approximately 5.0 metres. A secondary tongue had formed on the southern side of the surge lobe and this extends 5.0 metres inland. The height of the surge lobe had increased by approximately 0.4 metres.

4.3.17 Summary of the major changes to PD.2 between 1990 and 2002

Between 1990 and 2002 there had been continued erosion of the former blowout of PD.2. During the 12 year period erosion had caused an increase in the width of the portion of the former blowout landwards of the foredune. The overall increase in the width was approximately 17 metres. The length of the former blowout decreased during the interval as the deflation basin expanded seawards.

Between 1990 and 2002 there was continued development of the deflation basin of PD.2. The deflation basin increased in length by approximately 103 metres, in width by approximately 24 metres and decreased in height by approximately 0.5 metres

The trailing arms of PD.2 underwent significant change between 1990 and 2002. Erosion at the seawards end had caused a substantial decrease in the length of both trailing arms. The northern arm had been eroded by approximately 57 metres, while the southern trailing arm had been eroded by approximately 26 metres. There had been approximately 52 metres of new trailing arm created landwards between 1990 and 2002 on the northern, and 27 metres on the southern trailing arms. Erosion had also caused a thinning in the width of the trailing arms especially at the seawards end.

Between 1990 and 2002 the depositional lobe of PD.1 had been altered substantially. By 2002 the depositional lobe had migrated approximately 125 metres inland, increased in length by 37 metres, in width by 27 metres and height by 3 metres.

Between 1990 and 2002 there had been significant migration and change to the surge lobe of PD.2. The surge lobe did not develop until after 1995, however, after this it was very active. By 2002 the surge lobe had migrated approximately 158 metres inland, increased in width by approximately 31 metres, increased in length by approximately 93 metres and increased in height by approximately 0.1 metres.

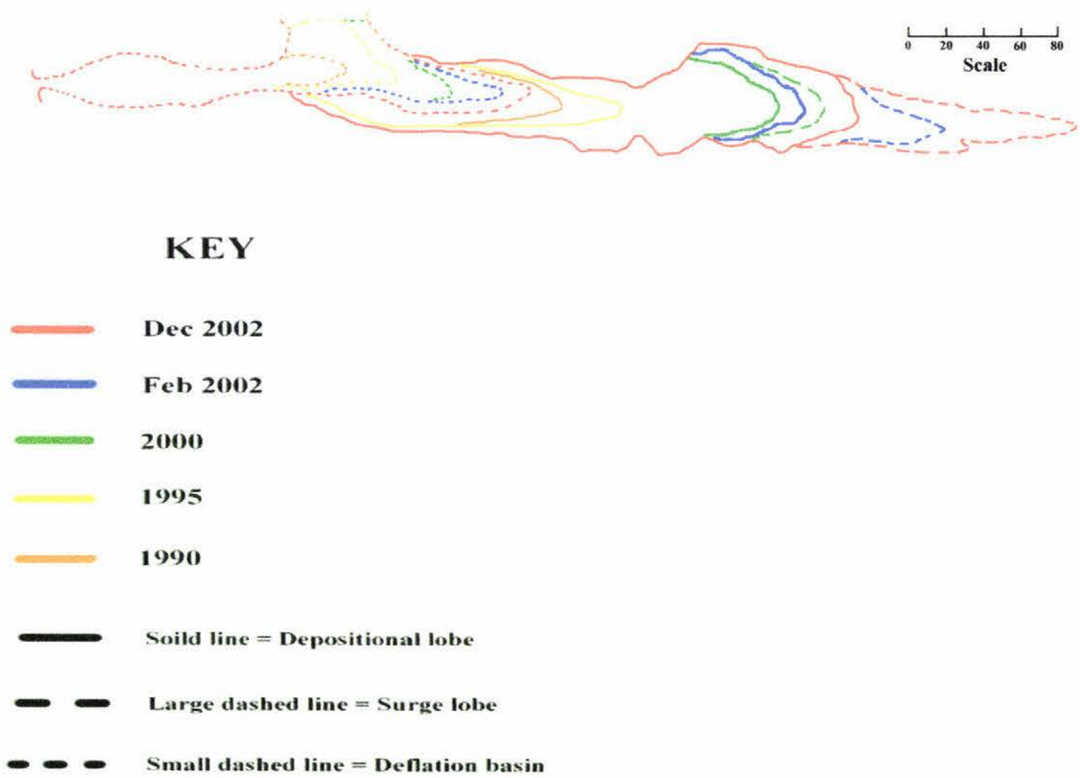


Figure 4.2 Diagram showing changes and development of PD.2 between 1990 and 2002. The different colours represent the position of the different morphological features at the dates of the aerial photographs. The different lines represent different morphological features. The development of each feature can easily be seen.

4.4 Development and migration of Parabolic Dune 3 (PD.3)

4.4.1 Changes to the former blowout and deflation basin of PD.3 between 1990 and 1995

In 1990 the blowout which eventually evolved into parabolic PD.3 can be identified. The mouth of the former blowout can be seen in the foredune and is approximately 2.0 - 3.0 metres in width. Approximately 7.0 metres landwards the back of the former blowout opens out into the deflation basin. By 1995 there had been some lateral expansion at the landwards end of the former blowout of approximately 5.0 - 8.0 metres.

In 1990 the open area behind the former blowout could be identified as a deflation basin. While this area may not actually have been a deflation basin at this time, had it developed into this by 1995. The deflation basin in 1990 was approximately 60 metres in length and 10 metres in width. The height of deflation basin was similar to that of PD.2 but have been up to 0.4 metres higher. By 1995 it had increased by approximately 20 metres in length and in width by approximately 5.0 metres. The height had remained similar and was unlikely to have changed by more than 0.5 metres.

4.4.2 Changes to the former blowout and deflation basin of PD.3 between 1995 and 2000

Since 1995 the former blowout had enlarged slightly. The deflation basin had increased in length by approximately 10 metres, and in width by approximately 10 metres at the seawards end and by 5.0 metres at the landwards end. Most of the increase had been along the southern edge of the basin. The height had not changed significantly and any changes were likely to be less than 0.3 metres.

4.4.3 Changes to the former blowout and deflation basin of PD.3 between 2000 and 2002

By 2002 the former blowout had been enlarged laterally by approximately 3.0 - 5.0 metres with more erosion along the northern edge than the southern. The deflation basin had also enlarged at its seawards end by approximately 8.0 metres, while at the landwards end the increase was much smaller at approximately 2.0 - 4.0 metres. The increase in length was approximately 10 metres. Along the southern wall where the deflation basins of PD.2 and PD.3 joined, the gap had increased in size by approximately 5.0 metres at the landward end.

4.4.4 Changes to the former blowout and deflation basin of PD.3 during 2002

During 2002 the former blowout had expanded noticeably. The mouth had enlarged substantially and was now approximately 2.0 metres, which was more than twice as wide as it was in February. The area behind the foredune had also expanded with substantial erosion in behind the foredune especially along the northern side of the former blowout. There had been approximately 3.0 metres of lateral erosion along this side.

The deflation basin had not changed in size significantly but there had been a noticeable change in shape. At the landwards end of the deflation basin there was only 1.0 - 2.0m increase in length and no significant change in width. The deflation basin had however shifted towards the south and was noticeably south of where it had been in February. A further change in the deflation basin was the large volume of sand which had been deposited at the downwind end of the deflation basin. A significant volume of sand now extended through approximately 90 metres through the deflation basin and extended up to the depositional lobe. This sand feature may be somewhat similar to that seen in the deflation basin of Parabolic Dune 4.

4.4.5 Changes to the trailing arms of PD.3 between 1990 and 1995

The northern trailing arms of PD.3 had not developed by the time the aerial photograph was taken in 1990 but developed sometime between then and 1995. By

1995 the northern trailing arm was approximately 70 metres, and was largely unaffected by erosion, with no evidence of any remnant knobs. The southern trailing arm, (which was also the northern trailing arm of PD.2) had developed before the northern trailing arm and the rest of PD.3. In 1990 it was approximately 30 metres in length, and by 1995 it was approximately another 8.0 metres longer.

4.4.6 Changes to the trailing arms of PD.3 between 1995 and 2000

By 2000 the northern trailing arm had been heavily eroded leaving only a few remnant knobs. The trailing arm was now approximately reduced to 20 metres in length. There had been some new development of approximately 10 metres at the landwards end. The southern trailing arm had had 15- 20 metres of erosion at the seawards end and approximately 15 metres of development inland.

4.4.7 Changes to the trailing arms of PD.3 between 2000 and 2002

The trailing arms of PD.3 were largely unaffected during this time. There had been some erosion of the upwind end of the southern trailing arm and this had moved inland by approximately 5.0 metres. There had also been erosion to several of the remnant knobs which are seawards of the main trailing arm. The northern trailing arm did not show any sign of significant erosion from the aerial photograph. There was no obvious extension of the trailing arms downwind, which may be because there did not appear to have been much inland migration of PD.3.

4.4.8 Changes to the trailing arms of PD.3 during 2002

There were some minor changes to the trailing arms of PD.3 during 2002. At the upwind end of the southern arms there had been approximately 4.0 metres of erosion, although there had been no remnant knob formation. There had been development of 2.0 metres of new trailing arm. The northern trailing arm appeared to have suffered only minor erosion at the seawards end. The large remnant knob up wind of the trailing arm had been eroded slightly as had the main trailing arm. At the downwind end approximately 2.0 metres of the trailing arm had been destroyed as the depositional lobe had expanded laterally to the north.

4.4.9 Changes to the depositional lobe of PD.3 between 1990 and 1995

The depositional lobe had not formed by the time of the 1990 photograph but formed sometime between then and 1995. By 1995 the depositional lobe was a small feature, significantly smaller than the depositional lobes of PD1 and PD.2 were in 1990. The depositional lobe was approximately 50 metres in length and 15 metres in width, and approximately 0.5 - 0.8 metres in height.

4.4.10 Changes to the depositional lobe of PD.3 between 1995 and 2000

Between 1995 and 2000 the depositional lobe had continued to develop and migrate. By 2000 it had migrated approximately 30 metres inland and increased in width by approximately 10 metres. The length of the lobe had substantially increased by approximately 20 metres during this time. The height had also increased since 1995 by approximately 0.5 -1.0 metres.

4.4.11 Changes to the depositional lobe of PD.3 between 2000 and 2002

Since 2000 there had been only small changes to the depositional lobe of PD.3 with slight increases in width and the length. The width had increased by approximately 3.0 metres and the length by an insignificant amount. There had been approximately 10 metres of inland migration. The height of the depositional lobe had also increased by an small amount during this period.

4.4.12 Changes to the depositional lobe of PD.3 during 2002

The depositional lobe of PD.3 had been altered during 2002 with increases in the width, length and height. An increase in the width had occurred on both sides of the depositional lobe. Along the southern side there had been an increase of approximately 2.0 metres especially at the downwind end, while along the northern side there had been an increase of approximately 5.0. During 2002 there was approximately 5.0 metres of inland migration by the depositional lobe and an increase in length by the same amount. It was now approximately 5.0 - 6.0 metres longer than it had been in February. The height of the depositional lobe had increased by approximately 0.5 metres.

4.4.13 Changes to the surge lobe of PD.3 between 2000 and 2002

At no time prior to February 2002 did a surge lobe appear present on any aerial photograph. Therefore its evolution will be discussed from February 2002 onwards. In February 2002 the surge lobe was very small in size being approximately 5.0 metres in width and length, and approximately 0.20 to 0.30 metres in height.

4.4.14 Changes to the surge lobe of PD.3 during 2002

By December 2002 the surge lobe had increased in length by approximately 30 metres and was now approximately 15 metres wide. The height had increased by approximately 1.0 metre during 2002.

4.4.15 Summary of the major changes to PD.3 between 1990 and 2002

Between 1990 and 2002 there had been continued erosion of the former blowout of PD.3. During the 12 year period erosion had caused a significant increase in the width of the portion of the former blowout landwards of the foredune. The overall increase in the width was approximately 15 metres. The length of the former blowout decreased during the interval as the deflation basin expanded seawards.

Between 1990 and 2002 there was continued development of the deflation basin of PD.3. The deflation basin increased in length by approximately 42 metres, in width by approximately 16 metres and decreased in height by approximately 1.0 metres. The increases are significantly less than those for PD.2 in the same period.

The trailing arms of PD.3 had undergone significant change between 1990 and 2002. Erosion at the seawards end had caused a substantial decrease in length of both trailing arms. The northern arm had been eroded by approximately 53 metres, while the southern trailing arm had been eroded by approximately 27 metres. There had been approximately 80 metres of new trailing arm created landwards between 1990 and 2002 on the northern trailing, and 25 metres on the southern trailing arm. Erosion had also caused a thinning in the width of the trailing arms especially at the seawards end.

Between 1990 and 2002 the depositional lobe of PD.3 had increased substantially. By 2002 the depositional lobe had migrated approximately 95 metres inland, increased in length by 76 metres, in width by 35 metres, and in height by 2.0 metres.

Between 1990 and 2002 there had been significant migration and change to the surge lobe of PD.3. Unlike the surge lobes of the other parabolic dunes the surge lobe did not develop until after 2000, and it was not as active as the other surge lobes. By 2002 the surge lobe had migrated approximately 35 metres inland, increased in width by approximately 15 metres, increased in length by approximately 35 metres and increased in height by approximately 1.25 metres.

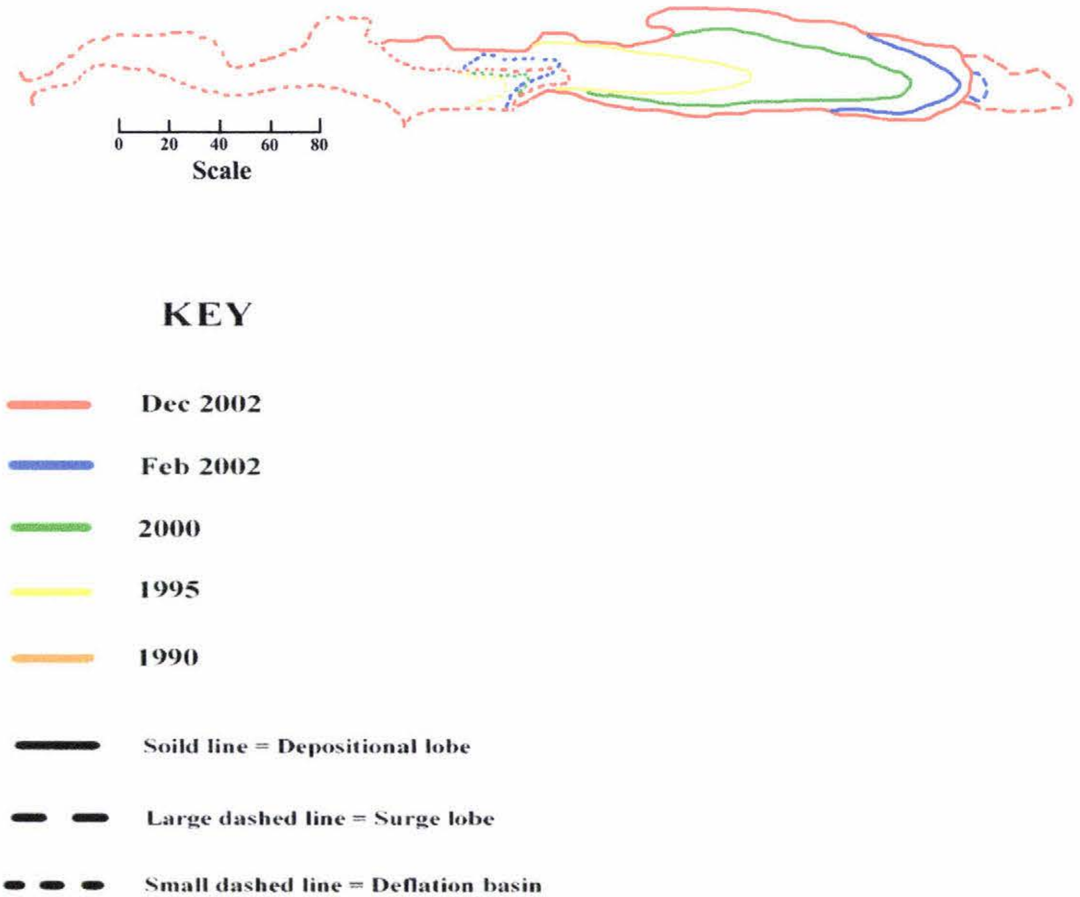


Figure 4.3 Diagram showing changes and development of PD.3 between 1990 and 2002. The different colours represent the position of the different morphological features at the dates of the aerial photographs. The different lines represent different morphological features. The development of each feature can easily be seen.

4.5 Development and migration of Parabolic Dune (PD.4)

4.5.1 Changes to the former blowout and deflation basin of PD.4 between 1990 and 1995

From the aerial photograph taken in 1990 the former blowout and the area landwards which becomes deflation basin can be identified. The mouth of the former blowout can be seen and was approximately 1.0 - 2.0 metres wide. Landwards of this the former blowout was approximately 10 metres in width. By 1995 there had been little change to the size of the former blowout, and although it is likely that some erosion would have occurred it was too small to show up on the aerial photograph.

In 1990 the area identified as deflation basin was approximately 70 metre long and 10 - 15 metres wide. The area was significantly lower than the rest of the area, and although the actual difference is unknown, it may be in the order of 2.0 metres lower. By 1995 the deflation basin had expanded in size, with an increase in width of approximately 5.0 metres and an increase in length of approximately 10 metres. To the north of the deflation basin substantial erosion had joined the deflation basin of PD.4 to the deflation basin of another parabolic dune. A tongue of sand which extended from the back of the foredune complex right through the deflation for approximately 45 metres had formed. This tongue was approximately 2.0 metres high at its highest point and 3.0 metres wide.

4.5.2 Changes to the former blowout and deflation basin of PD.4 between 1995 and 2000

Since 1995 the former blowout had increased in width by approximately 5.0 metres landwards of the foredune and the mouth had also enlarged by approximately 1.5 -2.0 metres.

The deflation basin had also increased in size with an increase in length of approximately 15 metres while the width had increased by approximately 5.0 metres. The tongue of sand which extended from the foredune complex through the deflation basin had also enlarged since 1995. It had increased in height by approximately 1.0 metres, in width by approximately 2.0 - 3.0 metres, and in length by approximately 15 metres. The tongue had also moved slightly more to the south.

4.5.3 Changes to the former blowout and deflation basin of PD.4 between 2000 and 2002

The former blowout and deflation basin had remained largely unchanged between 2000 and 2002. Any changes which have occurred were insignificant and did not appear on the aerial photograph. The tongue of sand which ran through the deflation basin had extended inland by approximately 10 metres and increased in width at the landward end by approximately 1.0 - 2.0 metres. The height, especially at the seaward end, had increased by approximately 0.5 metres.

4.5.4 Changes to the former blowout and deflation basin of PD.4 during 2002

During 2002 the former blowout and the deflation basin had not changed to any major extent, with the deflation basin having increased by approximately 4.0 metres only. Changes in its width and height were also insignificant. During 2002 the tongue of sand showed varied increases in height of approximately 0.5 metres in some place but otherwise it did not change significantly.

4.5.5 Changes to trailing arms of PD.4 between 1990 and 1995

The trailing arms of PD.4 were absent in 1990 and developed sometime between then and 1995. In 1995 the southern arm was approximately 10 metres long, and it is possible that it was originally longer but had since been eroded. There was no evidence of remnant knob formation. In 1995 the northern trailing is approximately 50 metres long and there was also no evidence of remnant knob development.

4.5.6 Changes to trailing arms of PD.4 between 1995 and 2000

By 2000 the southern trailing arm was approximately 30 metres in length. There had been no significant erosion and approximately 20 metres of development. The northern arm had approximately 2.0 - 4.0 metres of erosion at the seaward end while at the landwards end of the arm lateral expansion of the depositional lobe had covered approximately 10 metres of the trailing arm.

4.5.7 Changes to trailing arms of PD.4 between 2000 and 2002

The trailing arms of PD.4 did remained largely unchanged since 2000, with both arms having been unaffected by erosion in any significant way. There had been only insignificant trailing arm development at the landwards end.

4.5.8 Changes to trailing arms PD.4 during 2002

The trailing arms of PD.4 did not alter significantly during 2002. The southern trailing arm show no signs of significant erosion nor was there any significant new trailing arm developing at the landwards end of the arm.

The northern trailing arm did show evidence of a small amount of erosion during 2002, mainly along the southern margin of the trailing arm. At the landwards end of the trailing arm there was erosion and lateral expansion by the depositional lobe which removed part of the trailing arm, which resulted in no new trailing arm development.

4.5.9 Changes to depositional lobe of PD.4 between 1990 and 1995

In 1990 there was either no depositional lobe present or one which was too small to show up on the aerial photograph. By 1995 a depositional lobe had formed and begun to develop and migrate inland from its original position. The depositional lobe was approximately 120 metres in length and approximately in 10 metres in width. The height was less easily determined but was approximately 1.5 - 2.0 metres.

4.5.10 Changes to depositional lobe of PD.4 between 1995 and 2000

The depositional lobe of PD.4 had undergone significant change and development since 1995. The depositional lobe had expanded laterally by approximately 15 metres, and had migrated by approximately 15 - 20 metres, although the length had remained approximately the same. The changes in height are more difficult to identify, but had increased by approximately 1.0 metre.

4.5.11 Changes to depositional lobe of PD.4 between 2000 and 2002

By 2002 the depositional lobe had migrated a further 15 - 20 metres inland, but had not increased in length. The width had increased by approximately 5.0 - 10 metres, while the height had increased by approximately 0.5 metres only.

4.5.12 Changes to depositional lobe of PD.4 during 2002

The depositional lobe had changed significantly since February 2002, with substantial increases in the length, width and height of the depositional lobe. The depositional lobe had migrated approximately 15 metres and increased in length by approximately 12 metres. Increases in width were greatest at the landward end of the depositional lobe, and were approximately 5.0 - 6.0 metres. The height of the depositional lobe had increased by approximately 1.0 metre.

4.5.13 Changes to surge lobe of PD.4 between 1995 and 2000

In 1995 no surge lobe was evident beyond the depositional lobe although by 2000 one had developed. The surge lobe was approximately 40 metres in length and approximately 15 metres wide, and approximately 0.3 metres in height.

4.5.14 Changes to surge lobe of PD.4 between 2000 and 2002

By 2002 the surge lobe had migrated approximately 55 metres inland and increased in length by approximately 40 metres. The increase in width at the seawards end was minimal, and the landward end was now narrower than in 2000 at approximately 10 metres. The height of the surge lobe increased during this time by approximately 0.2 - 0.3 metres.

4.5.15 Changes to surge lobe of PD.4 during 2002

The surge lobe of PD.4 was active again during 2002 and had migrated approximately 20 metres further inland since February. The length and the width had not changed significantly during 2002, but the height increased significantly during this period by approximately 0.3 - 0.4 metres.

4.4.16 Summary of the major changes to PD.4 between 1990 and 2002

Between 1990 and 2002 there was continued erosion of the former blowout of PD.4. During the 12 year period erosion had caused a slight increase in the width of the portion of the former blowout landwards of the foredune. This overall increase in width was approximately 5.0 metres. The length of the former blowout decreased slightly during the interval as the deflation basin expanded seawards.

Between 1990 and 2002 there was continued development of the deflation basin of PD.4. The deflation basin increased in length by approximately 29 metres, in width by approximately 10 metres and decreased in height by approximately 0.5 metres. The increases of PD.4 are significantly less than for the other three parabolic dunes. Unlike the other dunes, a tongue of sand developed in the deflation basin after 1995 and continued to grow and develop after that.

The trailing arms of PD.4 had undergone several changes between 1990 and 2002. Erosion at the seawards end had caused a slight decrease in length of both trailing arms. The northern arm had been eroded by approximately 6.0 metres, while the southern trailing arm had been eroded by approximately 4.0 metres. There had been approximately 57 metres of new trailing arm created landwards between 1990 and 2002 on the northern trailing, and 32 metres on the southern trailing arm. Erosion had also caused a thinning in the width of the trailing arms especially at the seawards end.

Between 1990 and 2002 the depositional lobe of PD.4 had increased substantially. By 2002 the depositional lobe had migrated approximately 170 metres inland, increased in length 134 metres, in width by 37 metres and in height by 4.0 metres.

Between 1990 and 2002 there had been significant migration and change to the surge lobe of PD.4. The surge lobe did not develop until after 1995, however, after this it was very active. By 2002 the surge lobe had migrated approximately 115 metres inland, increased in width by approximately 25 metres, increased in length by approximately 80 metres and increased in height by approximately 0.85 metres.

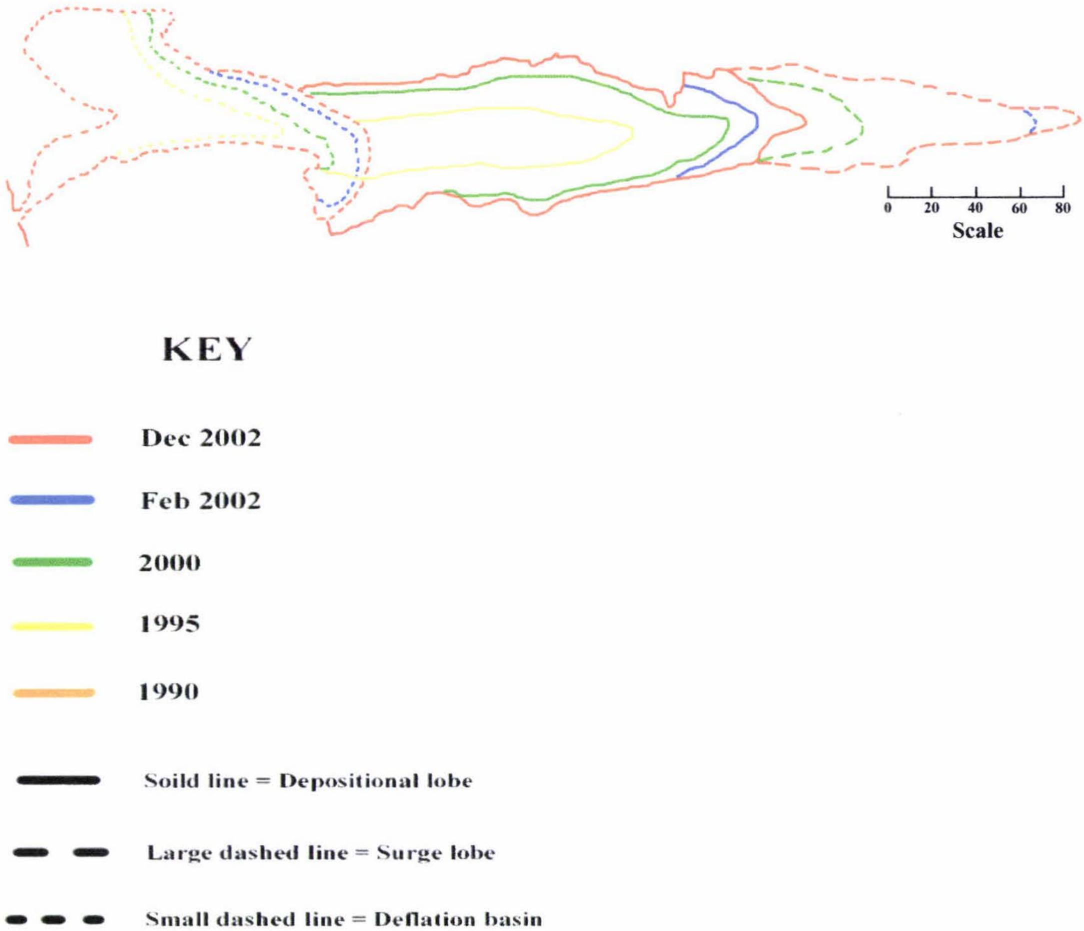


Figure 4.4 Diagram showing changes and development of PD.4 between 1990 and 2002. The different colours represent the position of the different morphological features at the dates of the aerial photographs. The different lines represent different morphological features. The development of each feature can easily be seen.

4.6 Wind regime

4.6.1 Wind regime between 1990 and 1995

The first photograph period is from the 2nd of July 1990 to the 14th of May 1995. Wind data collected by National Institute of Water and Atmosphere (NIWA) had been analysed and used to produce information on the wind regime during this period. The information on wind regime will be discussed here with respect to parabolic dune movement and development. The factors relevant to parabolic dune development are:

- Dominant wind direction;
- Frequency of dominant wind direction;
- Average speed from dominant direction;
- Other high frequency (greater than 6%) wind directions;
- Other high frequency average wind speeds;
- Calm wind frequency;
- Average wind speed;

From the wind data, it is then possible to produce figures for the potential movement of sand and produce a sand rose following methods derived by Fryberger (1978 and 1979). The classifications for the figures for sand movement are

- Resultant Drift Potential (the higher this vector unit is, the greater the potential amount of sand movement);
- Resultant Drift Direction (the direction that the sand is moving towards)

The Resultant Drift Potential (RDP) and the Resultant Drift Direction (RDD) are two resulting factors of the wind regime which explain the potential for sand movement and can impact on parabolic dune development.

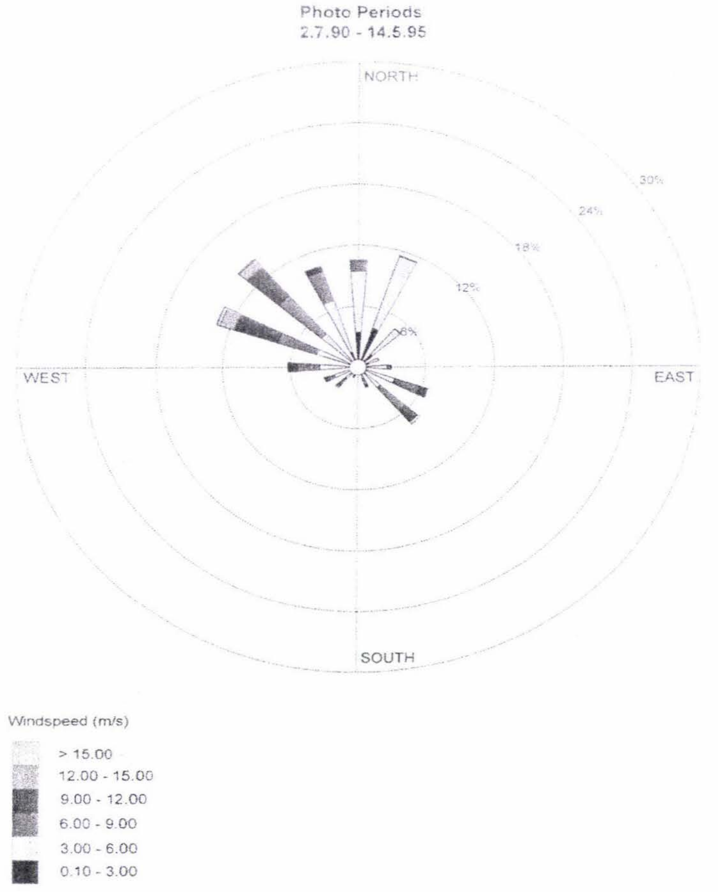


Figure 4.5 Wind rose for the Manawatu coastal zone between 2/07/90 - 14/05/95.

A break down of the wind rose data for the first photograph period is shown in Table 4.1.

Table 4.1 Wind regime for Photograph Period 1 (2/07/90 - 14/05/95)

Dominant wind direction	Northwest
Frequency of dominant direction	36.80%
Most common range of wind speeds from dominant direction	6-12 m/s
Other high frequency wind directions	West (6.2%)
	North (10.8%)
	Northeast (18%)
	Southeast (14%)
Other high frequency winds most common speeds	West (3-9 m/s)
	North (3-6 m/s)
	Northeast (3-6 m/s)
	Southeast (3-9 m/s)
Calm wind frequency	8.00%
Average wind speed	5.62 m/s

The wind data for photograph period 1 indicates that the dominant wind direction is from the north-west. The wind from this direction occurs more than twice that of any other direction. Winds from the northwest are also higher speed winds than those from the west and southeast, which are in turn higher than those from the north and northeast. The average wind speed for this period is 5.62 m/s and calm conditions occur only 8% of the time.

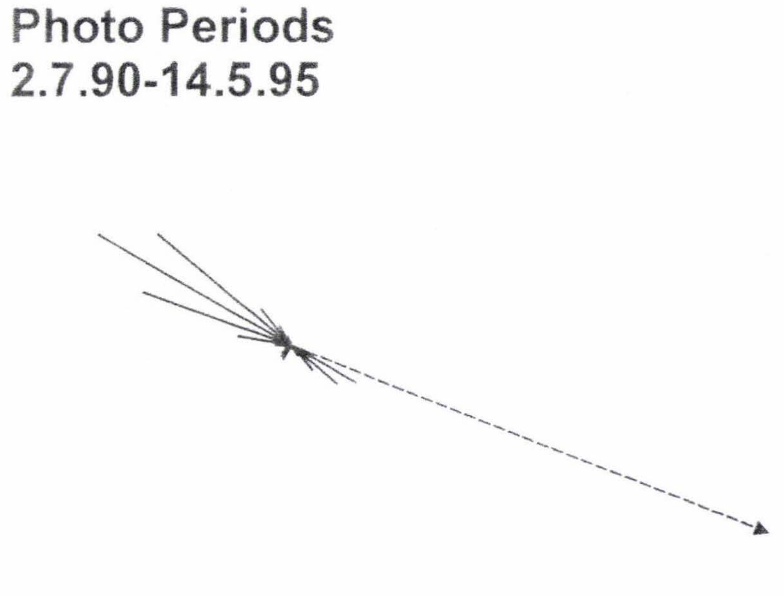


Figure 4.6 Sand rose for the Manawatu coastal zone between 2/07/90 - 14/05/95.

A break down of the sand rose data for the first photograph period is shown in Table 4.2.

Table 4.2 Sand rose data for Photograph Period 1 (2/07/90 - 14/05/95)

Resultant Drift Potential (RDP)	67.84
Resultant Drift Direction (RDD)	-68.2

The sand rose data for photograph period 1 produces figures for the amount of potential sand movement and the dominant direction to which the sand will move. The sand rose clearly shows a dominant sand moving direction to the south-east. The potential of sand to be moved in this direction is more than twice that of any other direction.

4.6.2 Wind regime between 1995 and 2000

The second photograph period is from the 21st July 1995 to the 28th of February 2000. The data for this period had been analysed as for the first period. The information on wind regime will be discussed here with respect to parabolic dune movement and development during this period.

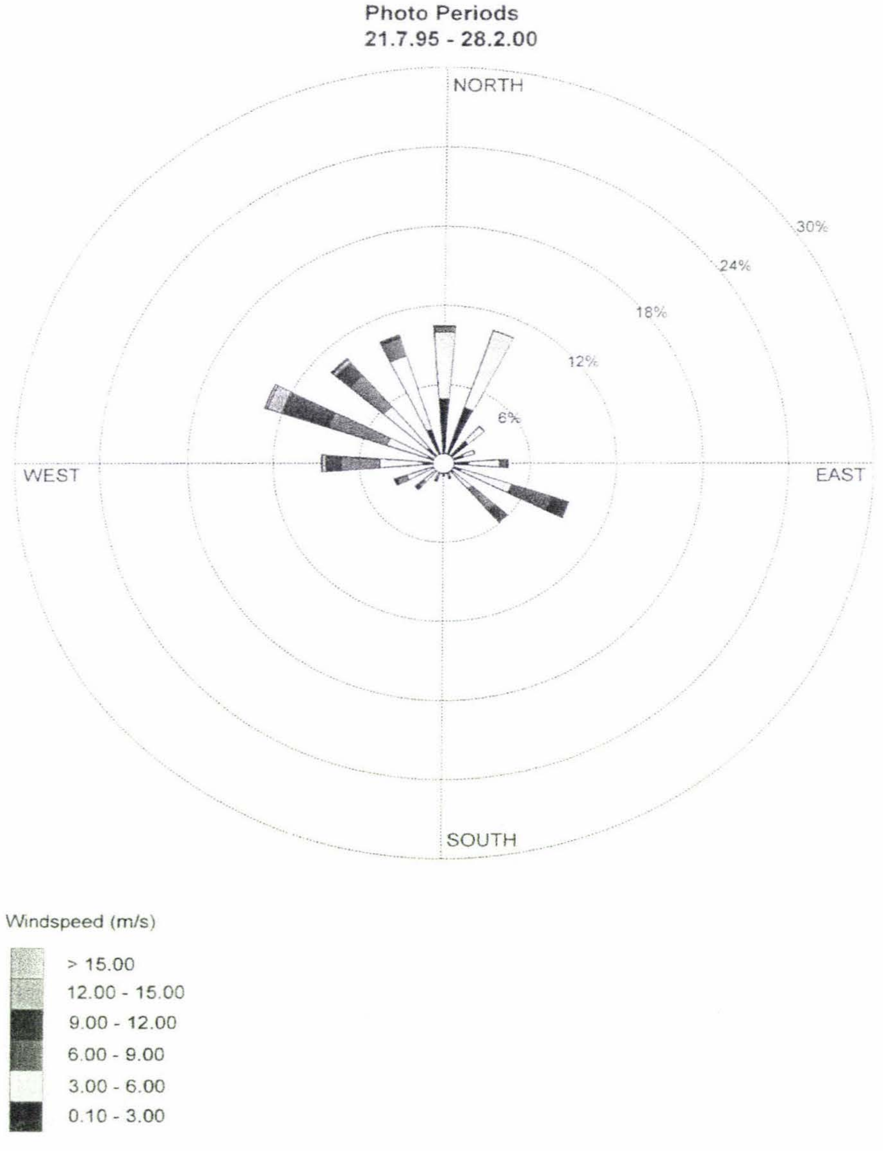


Figure 4.7 Wind rose for the Manawatu coastal zone between 21/07/95 - 28/02/00.

A break down of the wind rose data for the first photograph period is shown in Table 4.3.

Table 4.3 Wind regime for Photograph Period 2 (21/07/95 - 28/02/00)

Dominant wind direction	Northwest
Frequency of dominant direction	35.00%
Most common range of wind speeds from dominant direction	6-12 m/s
Other high frequency wind directions	West (8.5%)
	North (10.5%)
	Northeast (15.8%)
	Southeast (15.8%)
Other high frequency winds most common speeds	West (3-9 m/s)
	North (3-6 m/s)
	Northeast (3-6 m/s)
	Southeast (3-9 m/s)
Calm wind frequency	2.81%
Average wind speed	4.49 m/s

The wind data for Photograph Period 2 indicates that the dominant wind direction is from the north-west. The wind from this direction occurs more than twice as often as wind from any other direction. Wind speed frequency from the dominant direction was lower than during the first period, while the other directions remained mostly the same. The wind speeds vary across the different directions during this period, whereas during photograph period 2 wind speeds were similar across all the high frequency wind directions for this period. Wind speeds were lower from the west, north and north-east. The average wind speed of 4.49 m/s during this period is significantly lower than the average wind speed of 5.62 m/s recorded for the first period. Calm conditions during this period were also substantially less common during this period down to 2.81% from 8% during the first period. The second period was significantly windier than the first period, however, average wind speed was lower. The wind speed from the dominant direction was however similar over both periods.

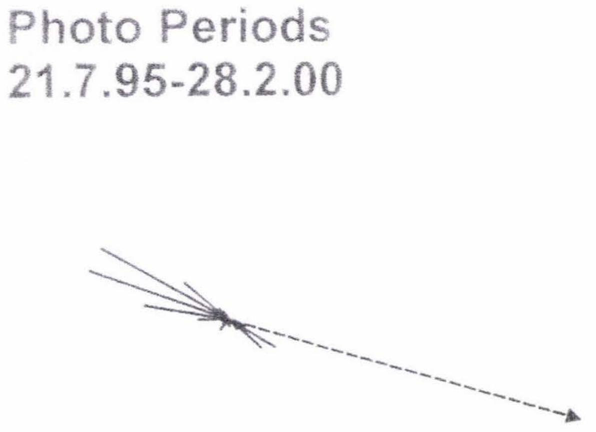


Figure 4.8 Sand rose for the Manawatu coastal zone between 21/07/95 - 28/02/00.

A break down of the wind rose data for the first photograph period is shown in Table 4.4.

Table 4.4 Sand rose for Photograph Period 2 (21/7/95 - 28/02/00)

Resultant Drift Potential (RDP)	48.68
Resultant Drift Direction (RDD)	-73.98

The sand rose for Photograph Period 2 clearly shows a dominant sand moving direction of south-east. However the direction of dominant sand movement is slightly further to the east than during the first period. The potential of sand to be moved in this direction is more than twice that of any other direction. The RDP for the second period is substantially lower than for the first period.

4.6.3 Wind regime between 2000 and 2002

The third photograph period is from February/March 2000 to the 21st of February 2002, but there is no actual date supplied for the 2000 photograph. Therefore the wind data for the third photograph period will begin on the 28th of February 2000. The information on wind regime will be discussed here with respect to parabolic dune movement and development during this period.

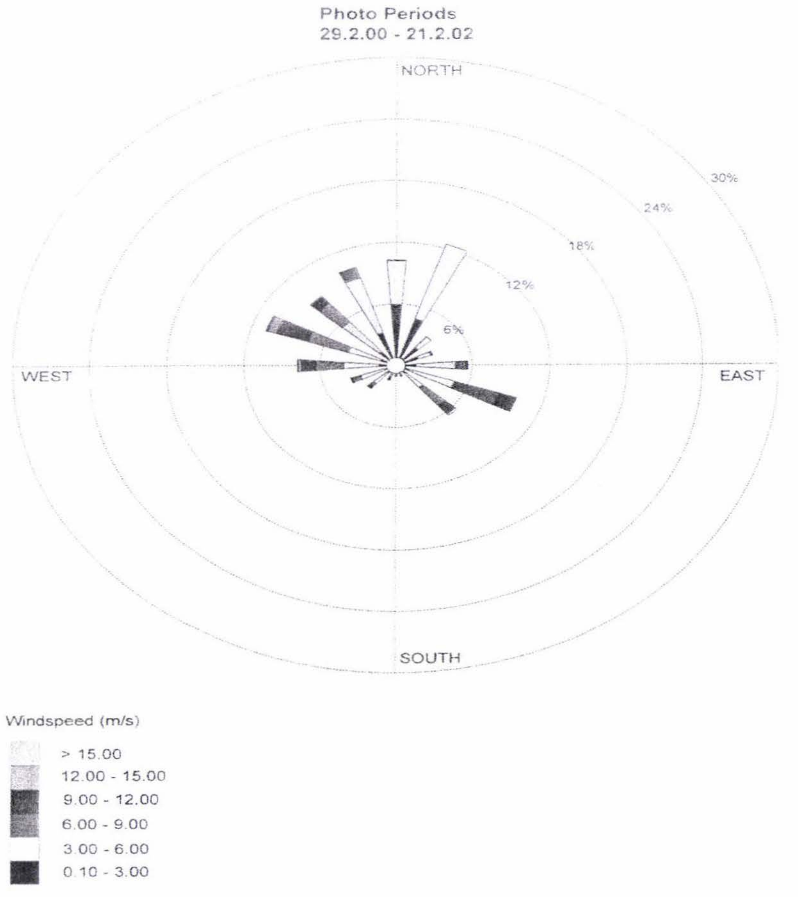


Figure 4.9 Wind rose for the Manawatu coastal zone between 29/02/00 - 21/02/02.

A break down of the wind rose data for the first photograph period is shown in Table 4.5.

Table 4.5 Wind regime for Photograph Period 3 (29/02/00 - 21/0202)

Dominant wind direction	Northwest
Frequency of dominant direction	30.70%
Most common range of wind speeds from dominant direction	6-12 m/s
Other high frequency wind directions	West (8%)
	North (10%)
	Northeast (18.3%)
	Southeast (16.8%)
Other high frequency winds most common speeds	West (3-9 m/s)
	North (3-6 m/s)
	Northeast (3-6 m/s)
	Southeast (3-9 m/s)
Calm wind frequency	0.69%
Average wind speed	4.66 m/s

The wind data for Photograph Period 3 indicates that the dominant wind direction (as for the first two periods) is from the north-west. The wind from this direction is slightly less than for the last period, which in turn was lower than the previous period. Wind from the dominant direction was twice as common during the previous periods, however this is not the case for this period 3. Winds from the other direction increased in frequency especially from the north-east and south-east although wind speeds remained largely the same across the different directions during this period. The only direction to have changed was from the west where wind speeds increased. The average wind speed of 4.66 m/s during this period is slightly higher than the average wind speed of 4.49 m/s recorded for the last period. Calm conditions during this period were also substantially less common and were down to 0.69% from 2.81% during the last period. The third period was significantly windier than the first two periods recording another large drop in calmness frequency, however average wind speed remained fairly constant. The wind speed from the dominant direction was however similar over both periods, although the frequency decreased.

Figure 4.10 Sand rose for the Manawatu coastal zone between 29/02/00 - 21/02/02.

A break down of the wind rose data for the first photograph period is shown in Table 4.6.

Table 4.6 Sand rose for Photograph Period 3 (29/02/00 - 21/02/02)

Resultant Drift Potential (RDP)	26.33
Resultant Drift Direction (RDD)	-88.28

The sand rose for Photograph Period 3 shows a dominant sand moving direction of almost directly east. This is a significant shift from the first two periods where the direction of movement was south-east. The potential of sand to be moved in this direction is still more than twice that of any other direction. However the RDP for the third period is substantially lower than for the first two period and is less than half that of the first period.

4.6.4 Wind regime during 2002

The fourth photograph period is from the 21st of February 2002 to the 20th of December 2002. The information on wind regime will be discussed here with respect to parabolic dune movement and development during 2002.

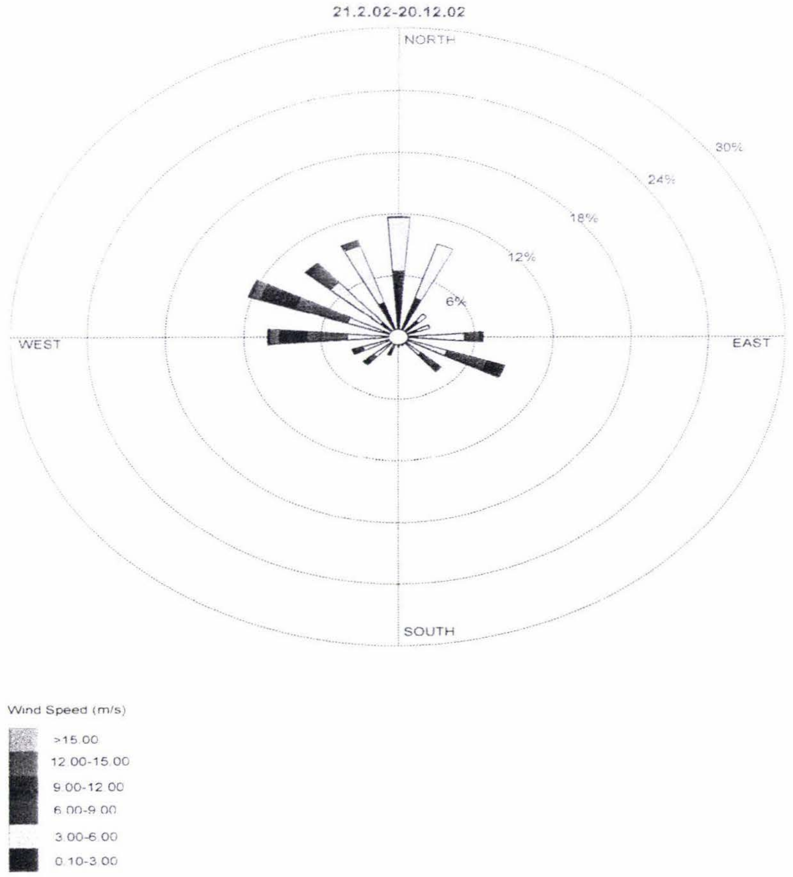


Figure 4.11 Wind rose for the Manawatu coastal zone between 21/02/02 - 20/12/02.

A break down of the wind rose data for the first photograph period is shown in Table 4.7.

Table 4.7 Wind regime for Photograph Period 4 (21/02/02 - 20/12/02)

Dominant wind direction	Northwest
Frequency of dominant direction	32.60%
Most common range of wind speeds from dominant direction	6-12 m/s
Other high frequency wind directions	West (10.2%)
	North (11.7%)
	Northeast (15.6%)
	Southeast (14.2%)
Other high frequency winds most common speeds	West (3-9 m/s)
	North (3-6 m/s)
	Northeast (3-6 m/s)
	Southeast (3-9 m/s)
Calm wind frequency	0.60%
Average wind speed	4.83 m/s

The wind data for Photograph Period 4 indicates that the dominant wind direction is from the north-west. The wind from this direction is again slightly less than for the last period, which was lower than the previous period. During this period wind from the dominant direction is no longer twice as common as it was during the first two periods. Winds from the west and north increased in frequency, however, wind from the north-east and south-east decreased in frequency. Wind speeds across the other high frequency wind directions remained the same during this period. The average wind speed of 4.83 m/s during this period is slightly higher than the average wind speed of 4.66 m/s recorded for the last period. Calm conditions during this period were also slightly less common during this period down to 0.60% from 0.69% during the last period. The wind speed from the dominant direction remained similar over both periods, however, the frequency decreased slightly.

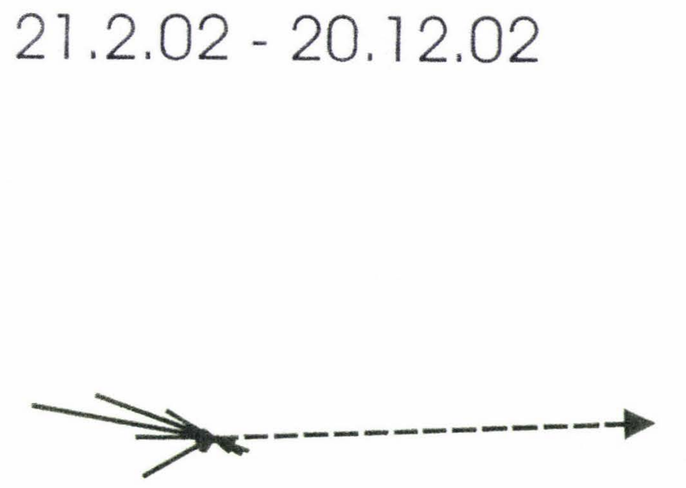


Figure 4.12 Sand rose for the Manawatu coastal zone between 21/02/02 - 20/12/02.

A break down of the wind rose data for the first photograph period is shown in Table 4.8.

Table 4.8 Sand rose for Photograph Period 4 (21/02/02 - 20/12/02)

Resultant Drift Potential (RDP)	58.05
Resultant Drift Direction (RDD)	87.62

The sand rose for Photograph Period 4 shows a dominant sand moving direction of slightly north of east which is a shift away from that which occurred during the other photograph periods where the direction was always to the south of east. It has subsequently been discovered however that the sand rose and RDD for this period are incorrect. This error was the result of a calculation error in the figures which were used to create the sand rose. Due to the original data being no longer available this error was unable to be fixed. However, as the wind rose is similar to that for period 3 the sand resultant is likely to be similar. The RDP for the fourth photograph period had increased and is now more than twice what it was during the third period, is higher than for the second period, and almost as high as the first period.

4.7 Wind regime and parabolic dune development

The direction of inland movement is a function of the dominant wind direction. As the dominant wind direction is north-west the direction of greatest sand moving potential is south-east. Given domination of wind from the northwest and the high speeds of these winds, high rates of parabolic dune development are unsurprising given a suitable sand supply, the low vegetation and the relatively flat topography. The relationship between parabolic dune development and inland migration with RDP and RDD is potentially the most important relationship between the parabolic dunes and wind regime.

The wind regime of this area is dominated by northwest winds mostly above 6 m/s. These winds give a strong sand moving potential towards the southeast, as illustrated by the RDP and RDD values.

The following tables show the migration rates for all the parabolic dunes and the RDP for each period.

Table 4.9 Rates of migration in metres per month for each dune between 1990 and 1995

PD1	0.254
PD2	0.508
PD3	0.847
PD4	2.034

RDP for the period 67.84

RDD for the period -68.20

The RDP for this period was the highest of all the periods. The RDD was also the most southerly for all the periods. Migration rates during this period varied from 0.25 metres per month up to just over 2.0 metres per month. The youngest dunes had the highest migration rates during this period. Younger dunes migrate faster as they are smaller and so are able to "roll over" at a higher rate than the more mature dunes.

Table 4.10 Rates of migration in metres per month for each dune between 1995 and 2000

PD1	0.482
PD2	0.536
PD3	0.536
PD4	0.304

RDP for the period 48.68

RDD for the period -73.98

The RDP for this period is considerably less than it was for the previous period. The RDD is also more easterly than for the previous period. The range of migration rates varies from just over 0.3 metres per month up to over 0.5 metres per month. It should be noted that during this period the surge lobes of PD.1 and PD.2 developed and began migrating, and that surge lobes migrate at higher rates. PD.4, which is a younger dune, had the lowest migration rate and while the rates of migration of the other dunes, are similar.

Table 4.11 Rates of migration in metres per month for each dune between 2000 and 2002

PD1	0.208
PD2	1.042
PD3	0.417
PD4	0.708

RDP for the period 26.33

RDD for the period -88.28

The RDP for this period is lower than previous period and is the lowest for any period. The RDP however is even further east than for the previous period. The rates of migration vary from 0.2 metres per month to 1.0 metre per month. The parabolic dune with the lowest migration rate is PD.1, which is one of the older dunes, however the other oldest dune had the highest migration rate. The surge lobe of PD.2 developed significantly during this period, as did the surge lobe of PD.4.

Table 4.12 Rates of migration in metres per month for each dune during 2002

PD1	1.5
PD2	4
PD3	0.5
PD4	1.5

RDP for the period 58.05

RDD for the period 87.62

The RDP for this period is significantly higher than for the last period and is nearly as high as for the first period. The RDD had now moved slightly north of east. The lowest rate of migration is 0.5 metres per month and this is higher than for the previous periods. This rate is for PD.3 which is one of the younger dunes. The highest migration rate is 4.0 metres per month for PD.2, one of the older dunes. The surge lobes of all dunes were particularly active during this period.

Figure 4.13 Parabolic Dune Migration Rates vs RDP for each Photograph Period

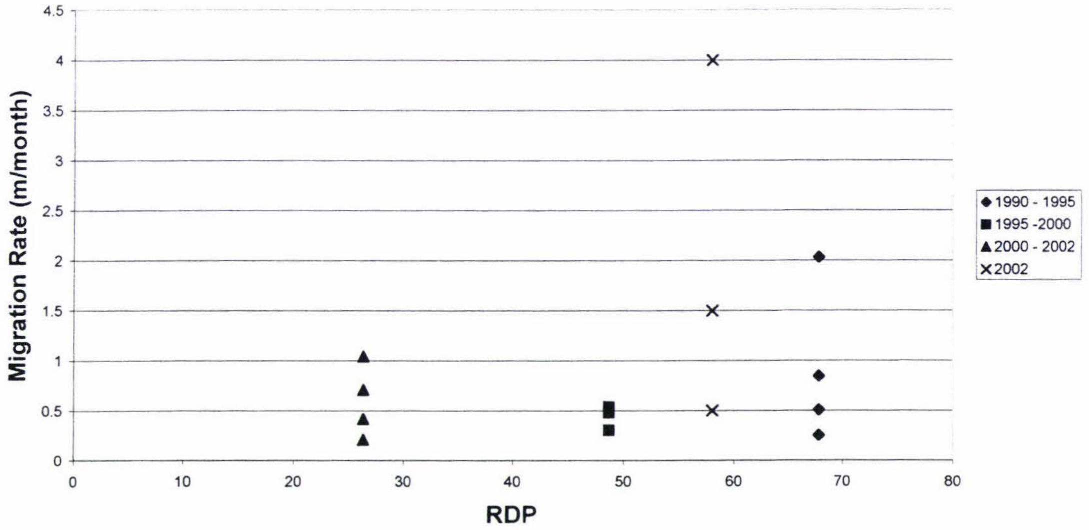


Figure 4.13 shows the rates of migration for each parabolic dune versus RDP for each period. It can be seen that the periods 1990 to 1995 and 2002, which had the highest RDP also had the highest migration rates. The period 2000 to 2002, which had the lowest RDP, is an anomaly as the migration rates are higher than for 1995 to 2000, which had a higher RDP.

Figure 4.14 Average migration rate vs RDP for each period

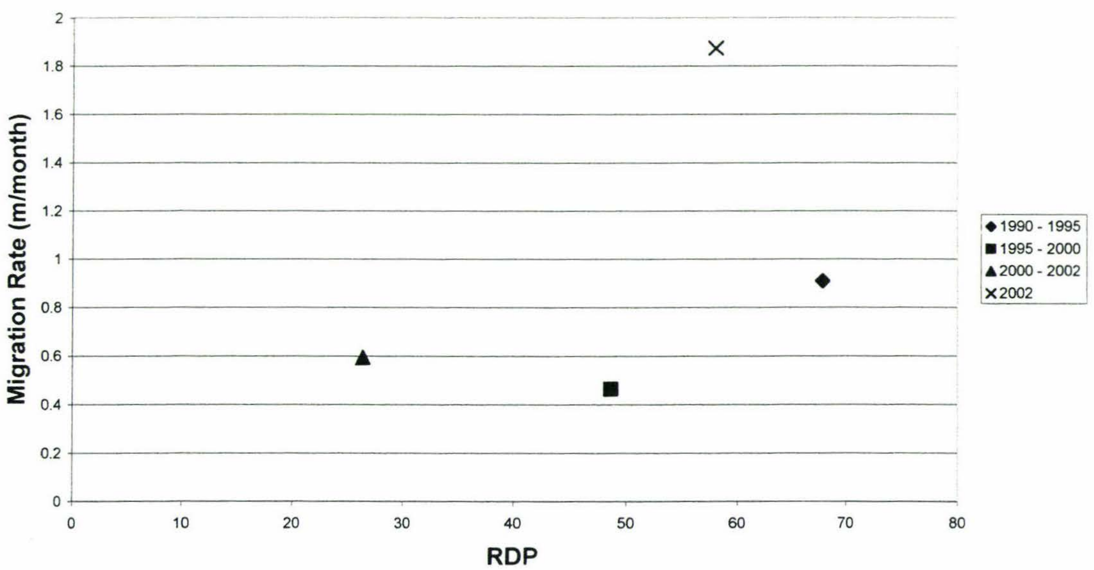


Figure 4.14 shows the average rate of migration for each period versus the RDP for that period. This supports the hypothesis that the periods of higher RDP had higher rates of migration.

4.8 Comparison of parabolic dunes during the four photograph periods

The changes, development and migration of all four parabolic dunes occurred at different rates during each photograph period and over all the periods. The differences are the result of height, length, exposure to wind, sand supply, topography and vegetation.

4.8.1 The importance of wind regime, resultant drift direction and resultant drift potential on development and migration

The wind regime is the driving force behind the development and migration of parabolic dunes. The resulting factors of wind regime of particular importance to parabolic dune development are the resultant drift direction (RDD) and resultant drift potential (RDP). Therefore changes in wind regime, will cause changes to the RDD and RDP, and will result in changes in parabolic dune behaviour.

The most important aspect of wind regime for parabolic dune behaviour is the dominant wind direction, followed by the average wind speed from that direction. Important changes to the wind regime of importance are changes to dominant wind frequency and wind speed, frequency of calm periods, and the frequency of other wind directions particularly wind from the opposite direction of the dominant direction.

Increases in the frequency of dominant wind direction and wind speed will increase RDP, as will decreases in calmness frequency and the frequency of winds from other directions. Increases in the frequency of calm periods and the frequency of winds from other wind directions (particularly from the opposite direction of the dominant wind direction) will result in a lower RDP and a more variable RDD.

Changes in RDP may have significant impacts on parabolic dune development and migration. Under conditions of a lower RDP there is less potential for sand movement, and as a result the parabolic dune may develop and migrate more slowly. Under conditions of a higher RDP when there is more potential for sand movement, parabolic dune development and migration may be faster.

Changes to the dominant wind direction will result in changes to the RDD. Changes in the RDD may affect parabolic dune development and migration as the parabolic dune is aligned in a particular direction and a shift closer to or further from this direction will affect the parabolic dune. The change in dominant direction does not need to be particularly large (e.g. a change from northwest to north) for a significant change in RDD to occur. Along the Manawatu coast the dominant direction is from the northwest, however, between 1990 and 2002 the RDD changed from a southeasterly direction to almost directly east.

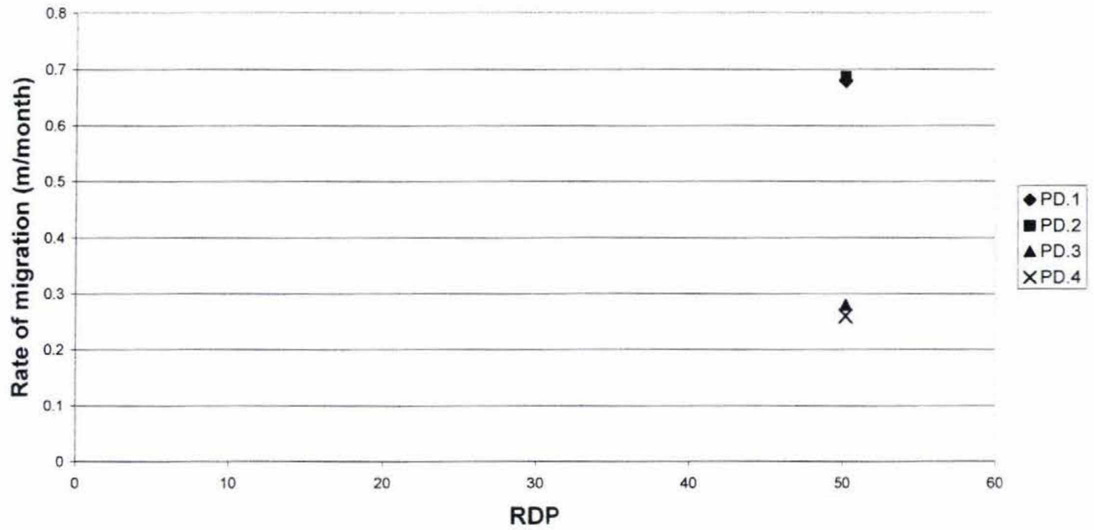
Any change to the wind regime, RDD and RDP will potentially affect the development and migration rate of the parabolic dunes. The nature of these will depend on the change to the wind regime and the morphological features of the parabolic dune. The constructional features of the parabolic dune are the depositional lobe, the surge lobe and the landward end of the trailing arms. A higher RDP and an RDD which is closer to the direction of the features will give the potential for a higher rate of development and migration. A decrease in RDP may decrease the rate of migration, while an increase in RDP may increase the rate of migration.

The effects of changes to the RDD are not as simple. A shift in direction toward the parabolic dune may increase the rate of development and migration, while a shift away may decrease the rate or the direction of the dune may shift to compensate. The erosional features, which are the blowout, deflation basin and seawards end of the trailing arms, may be affected differently. Changes in the direction of RDD may cause more erosion at the landwards end, or increase the rate of erosion if the shift is closer to the direction of the dune. If the change in direction is further from the direction of the parabolic dune, then erosion may decrease or become more concentrated at one part of the parabolic dune. Changes in RDD may also affect the lateral development of the dunes.

4.8.2 Comparison of rates of migration between 1990 and 2002

The migration rates of the parabolic dunes are different even though the RDP is the same. Rates of deflation basin migration are plotted against the RDP for 1990 - 2002 in Figure 4.15.

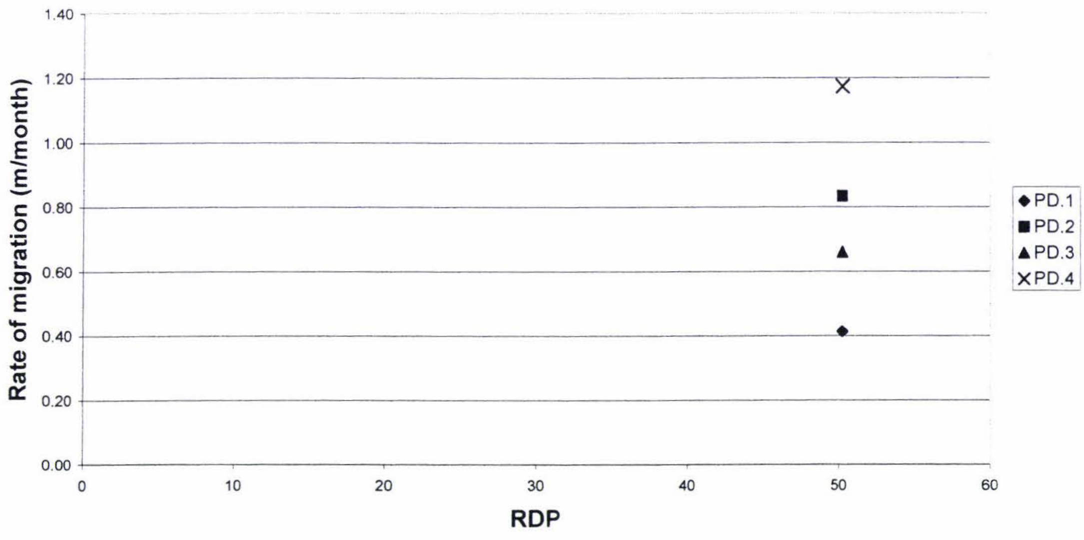
Figure 4.15 Rate of deflation basin migration vs RDP between 1990 - 2002



The rates of migration of the deflation basins of PD.1 and PD.2 are higher than those of PD.3 and PD.4. PD.1 and PD.2 are older parabolic dunes and the deflation basins formed before PD.3 and PD.4. The deflation basin of PD.1 and PD.2 are bigger in size and are concentrated along the northern margin of the parabolic dune. The deflation basins of PD.3 and PD.4 are smaller in size, and have had tongues of sand developed through them. PD.1 and PD.2 are more open at the seawards end and have larger blowouts. These factors may increase the exposure of the deflation basin to the wind which would then increase the rate of migration. It is also possible that deflation basin advance or migration is faster as the dune becomes bigger, and that there is a threshold which, once crossed, allows for an accelerated rate of migration.

The rate of migration of the depositional lobes for all four parabolic dunes is plotted against RDP for 1990 to 2002 in Figure 4.16.

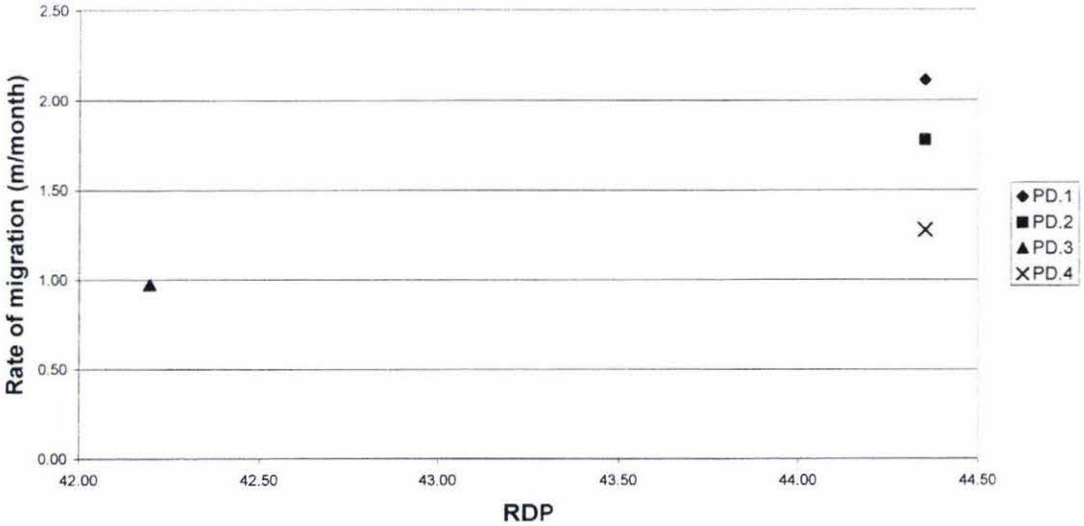
Figure 4.16 Rate of depositional lobe migration vs RDP between 1990 - 2002



There is some variation of the average migration rates of the depositional lobes, however this difference is not substantial. PD.1, which is one of the oldest parabolic dunes, had the lowest migration, while PD.4 which is one of the younger parabolic dunes had the highest migration rate. PD.2 and PD.3 have similar migration rates. Differences in depositional lobe migration rate may be related factors, such as the age of the parabolic dune, the height, the length, the width, and exposure to wind, as well as the topography and vegetation in front the depositional lobe. Older parabolic dunes migrate at a slower rate than younger ones because they have a smalller volume of sand to "roll-over" as they migrate downwind. Migration rates are often very high following initial development of the depositional lobe. The larger the size of the depositional lobe the slower it will migrate, and length in particular may slow the rate. Increases in height while increasing the size also increase the exposure of the top of the depositional lobe to wind, which may in turn accelerate the rate of migration. Topography and vegetation in front of the migrating depositional lobe may have a significant effect. Uneven topography and tall, thick vegetation slow wind speeds, and slow sand movement as the sand had to build up before it can continue migrating (Filion & Morisset, 1983; Thompson, 1983).

The rate of migration of the surge lobes for PD.1, PD.2, and PD.4 is plotted against RDP for 1995 to 2002, while the migration rate of the surge lobe for PD.3 is plotted for the RDP for 2000 to 2002 as it formed after the other parabolic dunes (Figure 4.17).

Figure 4.17 Rate of surge lobe migration vs RDP between 1995 - 2002



The migration rates of surge lobes of all four parabolic dunes are very similar. PD.1 and PD.2 have higher rates of surge lobe migration than the younger parabolic dunes PD.3 and PD.4. The surge lobes of PD.1, PD.2, and PD.4 are older than the surge lobe of PD.3, and all have higher rates of migration. The RDP for the period over which PD.3 developed is slightly lower than the RDP for other three parabolic dunes. Factors which affect the migration rate are the age of the parabolic dune, the height, the length, the width, exposure to wind and the topography and vegetation in front the surge lobe. The older surge lobes migrate at a faster rate than younger surge lobes. PD.1 and PD.4 had its greatest distance of migration following its initiation, while PD.2 and PD.3 had greater rates of migration well after initiation. The larger the size of the surge lobe, the slower the rate of migration. After initial high rates once the surge lobe is significantly large in size the rate of migration decreases. An increase in height can potentially increase the rate of migration as wind speeds are higher further from the ground and vegetation which disturbs wind flow. Uneven topography and high, thick vegetation also may slow migration rates due to the low height and small volume of surge lobes, which may take time to be able to build up sufficient height to move over uneven topography or tall, thick vegetation.

Chapter Five: Parabolic dune development as identified during 2002.

5.1 Introduction

Parabolic dune development can vary from year to year depending on factors such as wind regime and sediment supply. This chapter examines the morphological development of the four parabolic dunes over a one-year period. By identifying changes and wind patterns over shorter time periods, it is hoped that a clearer pattern of the relationship between wind regime and parabolic dune development will emerge. During 2002 a series of ground surveys and measurements, as well as photographs, were taken to identify morphological changes occurring during the year. The morphological changes which occurred during the year, are then identified and discussed. The wind data for the year will also be analyzed and discussed in relation to parabolic dune development. The different morphological units will be examined and the changes discussed in the format used during the previous chapter.

5.2 Parabolic Dune One

PD.1 is the southern most dune of the four and is the oldest of the four dunes. In the aerial photograph from 1990 it would appear that PD.1 was already well established by this date. The dune developed rapidly from a blowout after 1990 (Hesp, pers comm.). It was the largest of two blowouts, with the other becoming PD2. Therefore, the rate of development of PD.1 over one year will potentially be different when compared with that of the younger dunes. Due to financial and time constraints no ground surveys were conducted on PD.1, however changes can still be identified.

5.2.1 Changes to former blowout during 2002

The former blowout of PD.1 was observed during the research period. The changes which occurred during 2002 can be identified based on aerial and ground photographs as well as site observations. The series of photographs taken during 2002 illustrate a number of changes which occurred during the year. The ground photographs are taken from the back of the beach looking up toward the foredune and former blowout, while the aerial photographs provide details of the changes occurring behind the foredune. The photographs of the former blowout show that very little has changed to the actual break in the foredune. Wave action during the winter months caused some erosion to the foredune and the removal of some of the vegetation. This created a steeper front to the foredune as it slopes up to the crest and the former blowout. The erosion and the vegetation loss make the foredune less stable, which may mobilise sand from the foredune and the backshore. This sand may then be blown through the former blowout and become part of the parabolic dune. The actual height of the gap in the foredune did not change during the year. It is likely that the vegetation will recolonise the lower parts of the foredune during spring and summer when high seas are less common.

The main part of the former blowout is located in behind the foredune. Changes here are assessed based on the two aerial photographs taken in 2002, as well as observations made during 2002. The area of the blowout behind the foredune did not undergo any large changes during the year. The changes which did occur are small scale and do not show up on the aerial photographs. There was some erosion in the former blowout, with some lateral erosion of the blowout walls, and this erosion expanded the width of the former blowout slightly. During the year sand appeared to be moving through the former blowout and was piled up in different areas at different times. The amount of sand moving through the former blowout was not examined during this study.

5.2.2 Changes to the deflation basin during 2002

Using the aerial photographs, a series of ground photographs and observations made during 2002 it is possible assess the changes to the deflation basin of PD.1. The aerial photographs show that overall there has been a small lateral expansion on both sides of the deflation basin at the landwards end. This increase is quite small, approximately 5.0 metres, and does not show up well on the aerial photograph. There has been a larger increase in the length at the landwards end where the deflation basin has lengthened by approximately 12 - 13 metres. The ground photographs show smaller changes have also been occurring. The margins of the deflation basin appeared to fluctuate during the early part of the year as sand moved along the margins. In the middle of the year the margins appeared to be slowly expanding. The photographs also show an increase in the length of the deflation basin which would appear to be in the order of 3.0 - 4.0 metres over five months. There have not been any changes in the height of the deflation basin which had standing water present during July. This is an indicator that the height of the deflation basin is already at the height of the winter water table.

5.2.3 Changes to the trailing arms during 2002

Changes to the trailing arms of PD.1 are also assessed through the aerial and ground photographs. Both remained largely unchanged during the year, however, there was erosion along both arms. The erosion was confined to the seaward portion of the trailing arms and the remnant knobs. The aerial photographs show no significant erosion, although it can be seen on the ground photographs. Overall, the decreases are less than 1.0 metre. The height of the trailing arms was reduced by less than half a metre in places while the height and size of several of the remnant knobs was also reduced by less than a metre. No remnant knobs were completely removed during 2002 and the overall erosion was not as significant as had been observed during the longer periods.

5.2.4 Changes to the depositional lobe during 2002

The changes to the depositional lobe of PD.1 during 2002 are assessed by aerial and ground photographs, as well as by using warratah stakes as points of reference for changes in height. During 2002 there was an increase in the width, length and height of the depositional lobe of PD.1. The increase in width of approximately 3.0 metres, was mainly concentrated at the landwards end of the lobe, with the increase along the northern margin being greater than along the southern margin. The end of the lobe had also migrated slightly further to the north as it moved inland. This has accentuated the increase in the width along this margin. The distance of inland migration is approximately 15 metres. Rates of inland movement were quite rapid, as is shown by the complete burying of a warratah stake which was placed at the front of the depositional lobe in early March and was completely buried by late June. Due to the substantial increase in the length of the deflation basin the depositional lobe did not increase in length, in fact it decreased by approximately 2.0 metres.

It is difficult to assess increases in height from aerial photographs, however, by using stereo aerial photograph pairs and a stereoscope an estimate has been made. There does appear to have been an increase in height and this is supported by observations made in the field. The increase in height between February and December is in the order of approximately 0.90 metres. Measurements of the warratah stake during the first half of the year showed the height of the depositional lobe was actually decreasing by approximately 0.50 metres. However from August onwards this trend was reversed and the height of the depositional lobe increased to be over half a metre higher than at the start of the year. Small scale changes on the aerial photographs are difficult to identify. An increase in height of approximately 0.30 metres occurred between August and December, with the height in December being about 1.00 metre higher than the previous February.

5.2.5 Changes to the surge lobe during 2002

The aerial photographs show that the surge lobe has migrated approximately 27 metres inland during 2002. This resulted in an overall increase in length of approximately twelve metres. A series of ground photographs taken during 2002 from the top of the depositional lobe shows changes to the surge lobe over time. The photographs show that by July the vegetation (mainly marram grass) growing along the margins of the surge lobe had been buried by the migration of the surge lobe. In February 2002 the surge lobe covered the area from the landwards edge of the depositional lobe to its landwards limits and was approximately all the same height. However, by May the southern side of the surge lobe at the seawards end had been lowered relative to the rest of the surge lobe and by July this area contained standing water. The area was still lower at the end of 2002 relative to the rest of the surge lobe. There were no apparent increases in height from the aerial or ground photographs.

5.2.6 Summary of change to PD.1 during 2002

During 2002 PD.1 developed in significant areas. The blowout and deflation basin remained largely unchanged apart from an increase of approximately 12 -13 metres in the length and an increase of approximately 5.0 metres in the width of the deflation basin. The trailing arms showed little change either, with no significant erosion at the seawards end or development of new trailing arms at the landwards end of either trailing arm. The depositional lobe migrated approximately 15 metres inland, and showed small increases in width and height of 3.0 and 0.9 metres respectively. The surge lobe migrated inland approximately 27 metres but showed no significant increases in height or width.

5.3 Parabolic Dune Two

PD.2 is the next most southerly dune and is connected to PD.3 along its northern trailing arm and the northern edge of the deflation basin. PD.2 is the second oldest dune and became a parabolic dune after 1990. Aerial photographs, ground photographs, GPS surveys and Total Station surveys were carried out on PD.2 to assist in identifying morphological change and migration during 2002.

5.3.1 Changes to the former blowout during 2002

The aerial photographs and ground photographs indicate only a very small amount of development occurred to the former blowout during 2002. The ground photographs of the former blowout gap in the foredune indicate that there was some removal of vegetation and sand from the foredune during the early winter months similar to that which was observed at the former blowout of PD.1. There does appear to have been a decrease in height of approximately 0.20 metres, as well as a similar increase along the sides of the former blowout in June following high seas. The aerial photographs show that the area of the former blowout immediately behind the foredune is largely unchanged during 2002.

5.3.2 Changes to the deflation basin during 2002

The aerial photographs, ground photographs and surveys indicate substantial development of the deflation basin during 2002. The aerial photographs of PD.2 suggest that the deflation basin has expanded approximately 20 metres inland and approximately 6.0 metres laterally to the south during 2002. The GPS survey conducted in December 2003 (Figures 5.1 and 5.5) also shows a significant shift in the deflation basin to the south from that which was observed in April. The ground photographs taken of the deflation basin support this. Between April and August it can be seen that there was an expansion of approximately 5.0 metres in length and approximately 2.0 metres in width of the deflation basin. The height of the deflation basin has remained fairly constant throughout the year, especially at the seawards end where there was only slight fluctuation. At the landwards end however deflation caused the height to be lowered by 0.15 metres between April and August. No changes can be identified from the aerial photographs between February and December.

5.3.3 Changes to the trailing arms during 2002

The trailing arms of PD.2 have been eroded more than they have developed during 2002. The seawards end of the northern trailing arm, has been eroded approximately 4.0 metres inland during 2002. The DTMs created from the survey data (Figures 5.1, 5.2, 5.3 and 5.4) indicate this erosion to the northern arm was between April and December. The benchmarks and the survey data indicate that erosion has lowered the height of the trailing arm by up to 0.13 metres in places between March and August. Survey data also indicates that by December the trailing arm had been further lowered by up to 0.20 in places. New trailing arm development was approximately 2.0 metres during 2002, and there were no remnant knobs created. Erosion occurred to the remnant knobs between February and December, however, only the most seaward remnant knob was completely eroded.

The southern trailing arm developed approximately 2.0 metres of new arm during 2002, and there was approximately of erosion of at the seaward end. Changes to the height of the trailing arms were far larger, with the seaward end eroding faster than the landward end. At the seaward end there was 1.08 metres of erosion between March and May, but this was much reduced after May. The December (Figure 5.5) survey indicates erosion towards the middle of the arm. A decrease in height of 0.22 metres was recorded here between July and August. At the seawards end however, a decrease of 0.52 metres was recorded between March and August. Erosion of the remnant knobs appears to have been considerable during 2002, especially the most seawards knob which has almost been completely eroded away. From the aerial photographs changes in height were undetectable so changes of height appear to have been less than a metre for 2002.

5.3.4 Changes to the depositional lobe during 2002

The depositional lobe of PD.2 has been active during 2002, increasing in width, length, and height, as well as migrating inland. There has been an increase in width along the length of both sides of the depositional lobe, however most of the increase has occurred through the middle section. Along the northern edge of the depositional lobe the increase is approximately 2.0 metres at it's maximum. Along the southern edge, the increase appears to have been less than the northern edge and is approximately 1.0 metre. The terminal edge of the depositional lobe has migrated approximately 40 metres during 2002. This increase in length, minus the loss at the seawards end due to deflation basin expansion, has produced an overall increase in the length of the depositional lobe of approximately 20 metres. The height of the depositional lobe fluctuates during the year, but shows a decrease in height between March and August of between 0.20 metres and 0.58 metres.

5.3.5 Changes to the surge lobe during 2002

The surge lobe of PD.2 was particularly fast moving in 2002, migrating a substantial distance inland, as well as increasing in width. By the 20/12/02 the surge lobe had migrated inland approximately 68 metres. This resulted in an overall increase in length of 28 metres. The increase in width has been approximately ten metres with expansion of 6.0 metres occurring along the northern side of the lobe and 4.0 metres along the southern side. The height of the surge lobe increased by 0.07 metres between March and July, and overall the increase in height of the surge lobe was negligible. However, the December survey (Figures 5.1, 5.2, 5.3, 5.4) indicates one area in the middle of the surge lobe where an increase of approximately 0.40 - 0.50 metres has occurred.

Table 5.1 Cumulative distance of PD.2 surge lobe migration during 2002

Date	Distance (m)
5-March	0
9-April	7
21-May	12.94
20-June	35.3
9-July	42.2
30-July	45.1
18-November	65.2

5.3.6 Summary of changes to PD.2 during 2002

PD.2 has continued a high rate of development during 2002. While no significant changes occurred to the blowout, the deflation basin increased in length by approximately 20 metres and in width by approximately 6.0 metres. The northern trailing arm decreased in length by approximately 2.0 metres while the southern arm increased by approximately 3.0 metres. The height of the trailing arms decreased by up to 0.5 metres in places. The depositional lobe migrated inland by approximately 40 metres but had only small increases in width and height of 3.0 and 0.5 metres respectively. The surge lobe has migrated inland 68 metres and increased in width by approximately 10 metres.

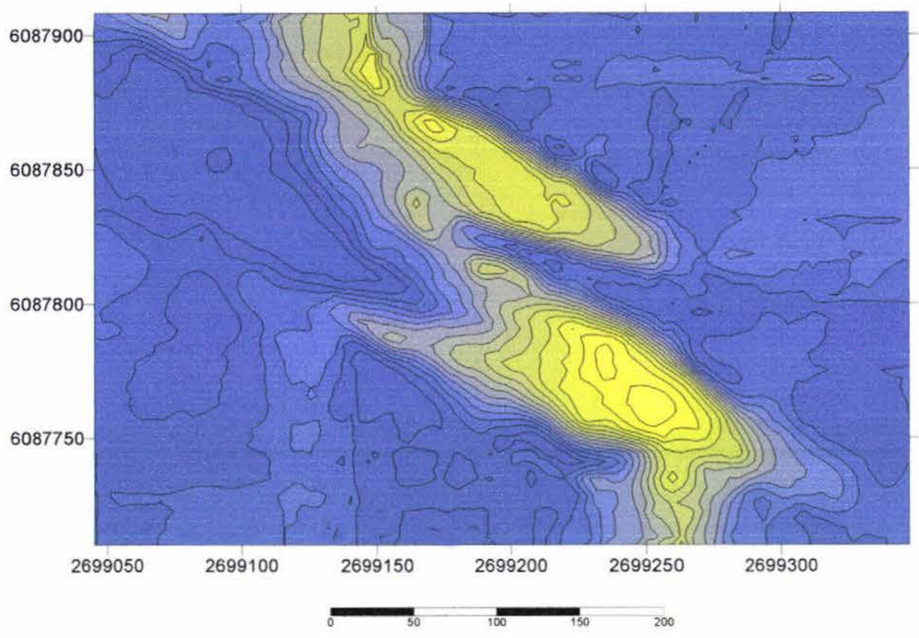


Figure 5.1 Contour Map of PD.2 and PD.3 produced using SURFER from data collected by GPS on 8/04/2002. The high yellow areas are the depositional lobes and trailing arms while the lower surge lobes can be seen extending beyond the depositional lobe and are the greyer areas.

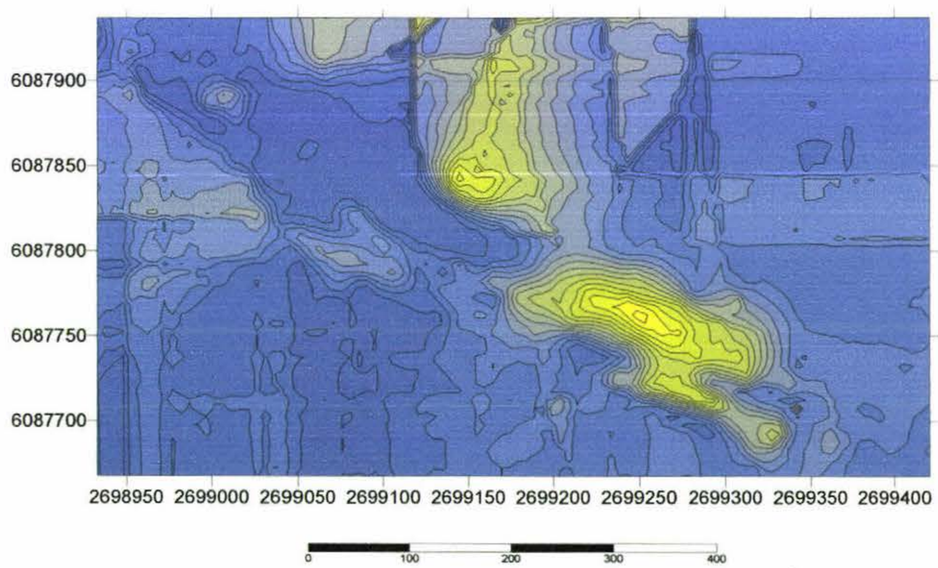


Figure 5.2 Contour Map of PD.2 produced using SURFER from data collected by GPS on 7/12/2002. The high yellow areas are the depositional lobe and trailing arms while the lower surge lobe can be seen extending beyond the depositional lobe and are the greyer areas.

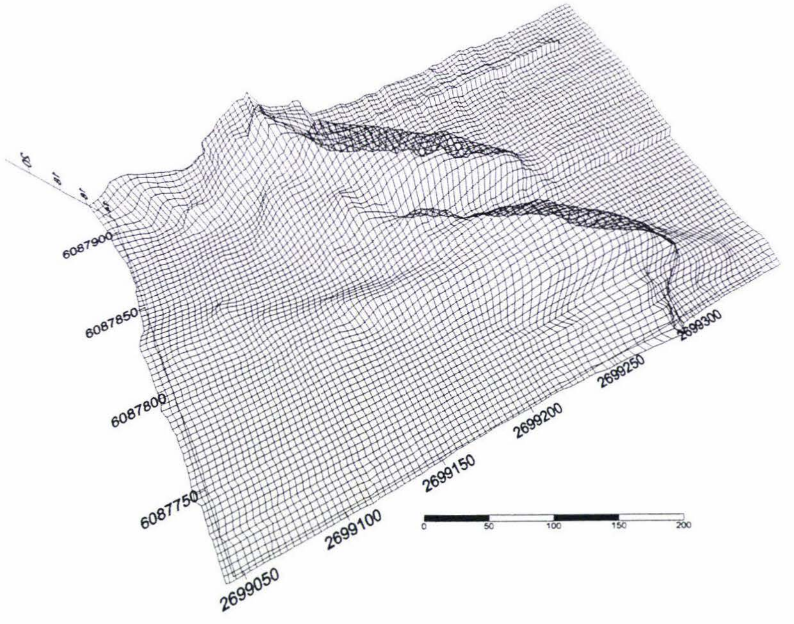


Figure 5.3 Wireframe Map of PD.2 and PD.3 produced using SURFER from data collected by GPS on 8/04/2002. The higher areas represent the depositional lobe, trailing arms and surge lobes.

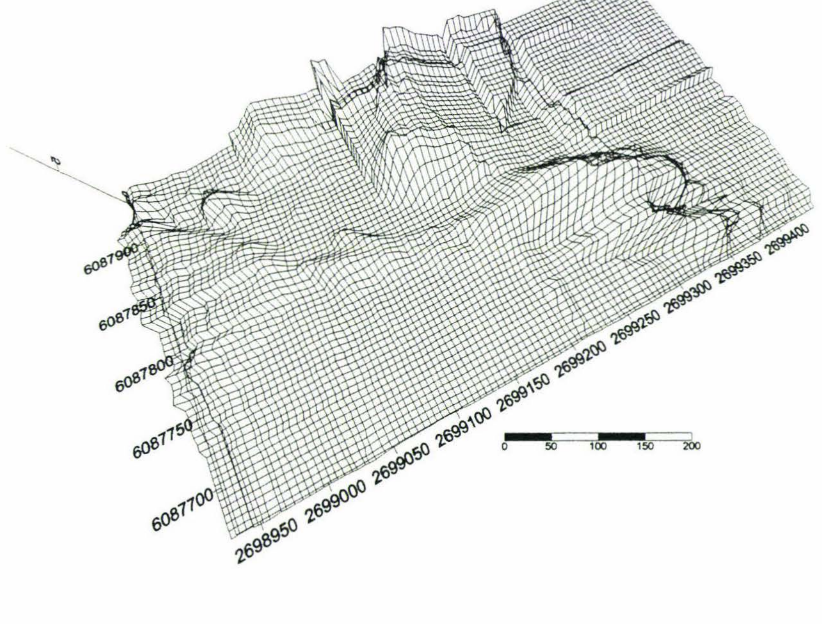


Figure 5.4 Wireframe Map of PD.2 produced using SURFER from data collected by GPS on 7/12/2002. The higher areas represent the depositional lobe, trailing arms and surge lobes. The high region to the left of the depositional lobe is unrelated to PD.2.

5.4 Parabolic Dune Three

PD.3 is just to the north of PD.2 and despite it's close proximity to PD.2 had not formed in 1990, although the blowout and what later became the deflation basin had developed. However by 1995 PD.2 had developed into a full parabolic dune although it was not particularly large in size. The time of development occurred sometime between 1990 and 1995, and given the level of development in 1990 it is likely that development occurred after 1991. The age of PD.3 is likely to be in the order of approximately ten years or less.

5.4.1 Changes to the former blowout during 2002

The former blowout of PD.3 has expanded significantly during 2002. Ground photographs of the break in the foredune show that between May and June there was substantial erosion of the foredune especially on the northern side. The width of the former blowout increased by approximately 1.5 metres during this period. The aerial photographs show that the area of the blowout behind the foredune has had only small increases in size. There has been approximately 2.0 metres of lateral expansion along the southern margin of the former blowout. The northern margin remained largely unaffected by erosion. The rest of the former blowout also remained largely unchanged during 2002.

5.4.2 Changes to the deflation basin during 2002

The deflation basin, like the former blowout of PD.3, did not increase substantially during 2002. There has been a negligible amount of lateral expansion and only approximately 1.5 to 2.0 metres of expansion landwards as indicated by both the aerial photographs and the December survey. More noticeable was a shift in the landwards edge of the deflation basin from the northern margin to a more central, slightly southern position. A second significant change during 2002 was the accumulation of a significant volume of sand along the southern margin of the deflation basin. This sand extends through approximately 25 metres of the landwards end of the deflation basin and into the depositional lobe. The height of the deflation basin increased by 0.18 metres at the seawards end, however at the landwards end it decreased by 0.12 metres between March and August.

5.4.3 Changes to the trailing arms during 2002

Erosion has caused changes to the trailing arms of PD.3. The seawards ends of the trailing arms have been eroded, especially the southern trailing arm. Erosion at this end has removed approximately 4.0 metres of trailing arm, and there has been no remnant knob formation. At the landwards end approximately 1.0 metre of new trailing arm has been created. The height of the trailing arm varied during the year, however between March and August it decreased by 1.09 metres at the seawards end and by 0.36 metres at the landwards end. The aerial photograph indicates that by December a decrease of 1.0 metre was likely.

The northern trailing arm has suffered only minor erosion at the seawards end. At the landwards end approximately 2.0 metres of the trailing arm has been destroyed as the depositional lobe has expanded laterally to the north. The large remnant knob up wind of the trailing arm has been eroded only slightly. The northern arm did not decrease in height as much as the southern arm, losing only 0.12 metres at the seawards end and 0.03 metres at the landwards end. The aerial photographs show that the northern arms had not changed significantly between February and December.

5.4.4 Changes to the depositional lobe during 2002

During 2002 there have been increases in the width, length and height of the depositional lobe of PD.3. A lateral increase has also occurred on both sides of the depositional lobe. The increase along the southern side has been approximately 4.0 metres, with an increase in the width along the northern margin of approximately 5.0 metres. The lateral increase buried the two warratah stakes, which were located on either side of the depositional lobe between March and June of 2002. There has also been variation in the height of the depositional lobe where the seawards end recorded decreases of between 0.66 metres and 1.55 metres, while the landwards end increased in height by 0.328 metres. The aerial photographs and survey from December (Figure 5.1, 5.2, 5.5 and 5.6) indicate a decrease in height at the landwards end of approximately 1.5 metres, and an increase of 0.5 metres at the seawards end. Inland migration of the depositional lobe was considerably less than that of the other parabolic dunes as it was approximately 5.0 metres. This resulted in an overall increase in length of 4.0 metres.

5.4.5 Changes to the surge lobe during 2002

By December 2002 the surge lobe of PD.3 had more than doubled it's length in February 2002. The surge lobe which was approximately 15 metres long in February had migrated approximately 35 metres inland by December. The width had also increased by approximately 10 metres during 2002 and was now approximately 15 metres wide. The height of the surge lobe had increased markedly by between 0.93 metres and 0.82 metres between March and August 2002. The surge lobe did not appear well on the DTM of the survey data, however a noticeable increase in height can be observed from the aerial photographs.

Table 5.2 Cumulative distance of PD.3 surge lobe migration during 2002

Date	Distance (m)
5-March	0
9-April	0.15
21-May	0.3
20-June	14.05
9-July	19.8
30-July	19.8
18-November	34.1

5.4.6 Summary of changes to PD.3 during 2002

The amount of development which occurred on PD.3 was less than that which was recorded for the other three parabolic dunes. The blowout increased in width by approximately 3.5 metres but was otherwise unchanged. The deflation basin, however, did not change in any significant way. Both of the trailing arms decreased in length by approximately 2.0 metres. The northern trailing arm decreased by up to 1.0 metre in places while the southern trailing arm decreased by 0.10 metres in places. The depositional lobe only migrated 5.0 metres inland and showed both increases and decreases in height of 1.55 metres and 0.3 metres respectively. The width of the depositional lobe increased by up to 5.0 metres. The surge lobe was the feature which showed the largest changes during 2002, with 35 metres of inland migration, increases in height of up to 1.0 metre and an increase in width of approximately 3.0 metres.

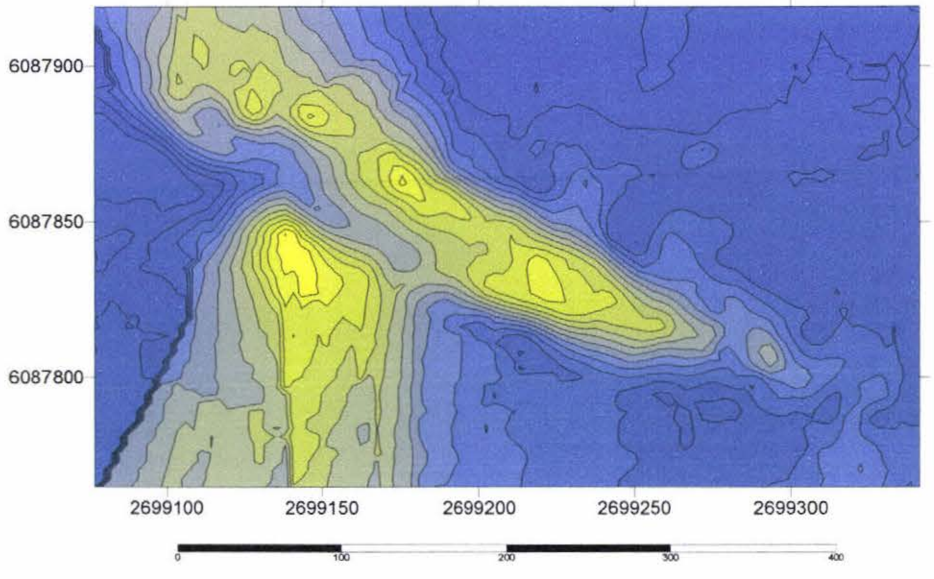


Figure 5.5 Contour Map of PD.3 produced using SURFER from data collected by GPS on 7/12/2002. The high yellow areas are the depositional lobe and trailing arms while the lower surge lobe can be seen extending beyond the depositional lobe and are the greyer areas

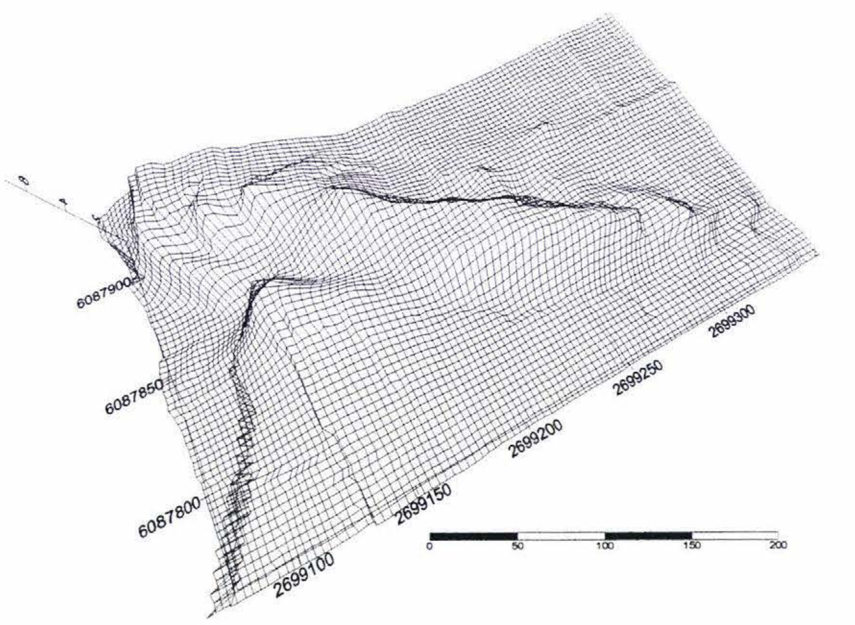


Figure 5.6 Wireframe Map of PD.2 produced using SURFER from data collected by GPS on 7/12/2002. The higher areas represent the depositional lobe, trailing arms and surge lobes.

5.5 Parabolic Dune Four

PD.4 is the northern most of the four parabolic dunes. In 1990 PD.4 was similar to PD.3 in that only the blowout and deflation basin were identifiable. In 1995 the development and size of PD.3 and PD.4 were similar to each other. The age of PD.4, therefore is likely to be similar to that of PD.3 at approximately ten years.

5.5.1 Changes to the former blowout during 2002

Aerial and ground photographs of the former blowout of PD.4 show that there has been very little change during 2002. Ground photographs taken between March and August show that there was very little change to the former blowout in the foredune. High wave action during May and June has not affected the former blowout or the vegetation to the extent observed on the blowouts of the other three parabolic dunes. The aerial photographs also indicate that there was very little erosion or expansion of the area of the former blowout behind the foredune. The former blowout has remained stable during 2002.

5.5.2 Changes to the deflation basin during 2002

Aerial and ground photographs indicate very little change to the deflation basin of PD.4 during 2002. There is no indication of any large increases in the width from the photographs, nor do the measurements of the warratahs indicate major changes in the height of the deflation basin. The deflation basin has, however, lengthened by approximately 4.0 metres on the northern side of the tongue of sand and by approximately 2.0 metres on the southern side. The December survey (Figures 5.8 and 5.9) also indicates an increase in deflation basin length and no change in the width. The tongue of sand extending through the centre of the deflation basin does, however, appear to have been more active. Measurements of the warratahs indicate that the tongue shrank along its northern margin at the seawards end although by less than 0.5 metres. The height of the tongue also decreased at the seawards end by 1.32 metres between March and August. At the landwards end of the tongue there were no large changes to the margins or any major changes in height. There was however some variation in height: between March and June the tongue increased in height by 0.58 metres, while between June and August the tongue decreased in height by 0.54 metres giving an overall gain in height of 0.04 metres. The December survey (Figures 5.8 and 5.9) also indicates an increase in the height of the tongue especially at the landward end.

5.5.3 Changes to the trailing arms during 2002

The trailing arms of PD.4 have not changed significantly during 2002, with only small amounts of erosion and development occurring. The southern trailing arm shows no signs of major erosion from the ground or aerial photographs nor has there been any significant new trailing arm developing at the landwards end of the arm. The height of the trailing arm at the seawards end remained fairly constant between March and August increasing in height by 0.09 metres during this time. The landwards end of the southern trailing arm increased in height by 0.45 metres between March and August. No changes were indicated from the aerial photographs.

The northern trailing arm does show evidence of a small amount of erosion during 2002. Ground photographs show that erosion occurred along the margin of the trailing arm between March and August and that some of the vegetation was removed. The aerial photograph taken in December also shows that erosion occurred along the southern margin of the trailing arm. From the aerial photograph it can also be seen that there was erosion and lateral expansion by the depositional lobe which removed part of the landwards end of the trailing arm. As a result of this there was no new trailing arm development. The height of the northern trailing arm had increased slightly in height between March and August. At the seawards end the height increased by 0.12 metres, with most of this increase occurring between March and April. At the landwards end, the trailing arm increased slightly between March and May before decreasing by 0.22 metres between May and June. However between June and August the height increased by 0.29 metres with most of the increase occurring between July and August. Overall the net increase in height between March and August was 0.08 metres.

5.5.4 Changes to the depositional lobe during 2002

The depositional lobe of PD.4 has been altered significantly in length, width and height since February 2002. It has also migrated inland by approximately 15 metres between February and December, which has resulted in an overall increase in length of approximately 12 metres. The increases in the width of the depositional lobe have been mainly through the middle and toward the landwards end of the depositional lobe. There have been approximately 4.0 metres of increase along the northern margin and 2.0 metres along the southern margin.

Changes to the height of the depositional lobe have been quite varied. At the seawards end there was a decrease in height of 0.25 metres between March and August with the majority of the change occurring between March and April. Toward the landwards end of the lobe the height of the dune varied greatly but by August had decreased in height by approximately 0.09 metres. Increases in height are shown by both the aerial photographs as well as the December survey (Figures 5.8 and 5.9), and are significantly greater than those identified during the early part of the year. An increase of up to 1.0 metre occurred between August and December 2002.

5.5.5 Changes to the surge lobe during 2002

The surge lobe of PD.4 migrated the least distance of any of the four parabolic dunes during 2002. The surge lobe was approximately 70 metres long in February but had migrated only another 17.8 metres during 2002. The December survey also indicates an increase in surge lobe length. There were no large increases in the width of the surge lobe, but the height increased during 2002. Between March and August it had increased by 0.22 metres at the seawards end, and by 0.29 metres at the landwards end.

Table 5.3 Cumulative distance of PD.4 surge lobe migration during 2002

Date	Distance (m)
5-March	0
9-April	0.4
21-May	3.13
20-June	14.2
9-July	15
30-July	17.4
18-November	17.8

5.5.6 Summary of changes to PD.4 during 2002

The amount of change to PD.4 is significant. There were no changes to the blowout, but the deflation basin did change noticeably, as it increased in length by approximately 4.0 metres. There were, however, no significant changes to it's width or height. The tongue of sand which extends through the deflation basin did show significant increases in height and volume. The trailing arms of PD.4 remained unchanged during 2002 neither shrinking nor growing in length, while the height did increase by up to 0.5 metres in places. The depositional lobe migrated 15 metres inland, increased in width by approximately 6.0 metres and increased in height by approximately 1.0 metre. The surge lobe has migrated approximately 18 metres inland and increased in height by approximately 0.3 metres.

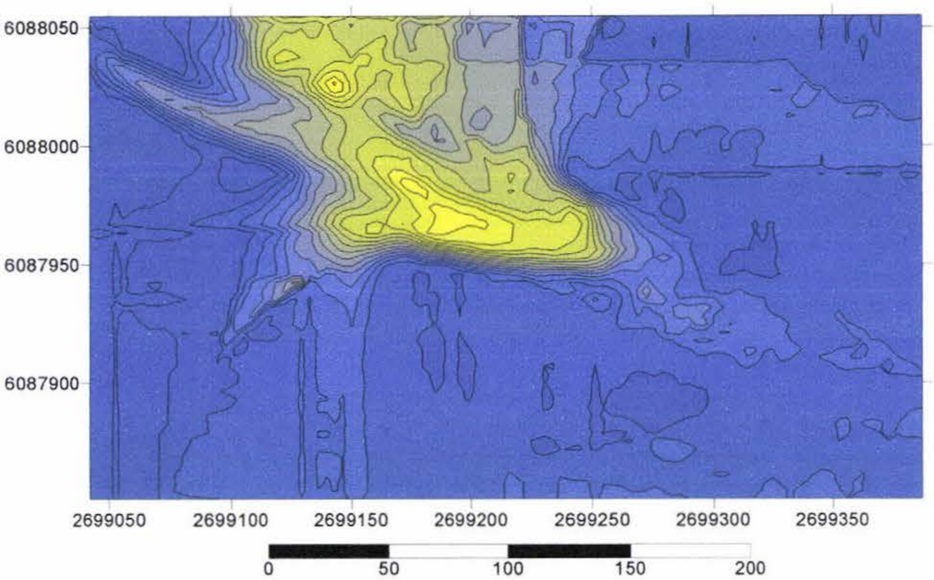


Figure 5.7 Contour Map of PD.4 produced using SURFER with data collected by GPS on 8/04/2002. The high yellow areas are the depositional lobe and trailing arms while the lower surge lobe can be seen extending beyond the depositional lobe and is represented by the greyer areas. The tongue of sand which extends back into the deflation basin can be seen to the left of the depositional lobe.

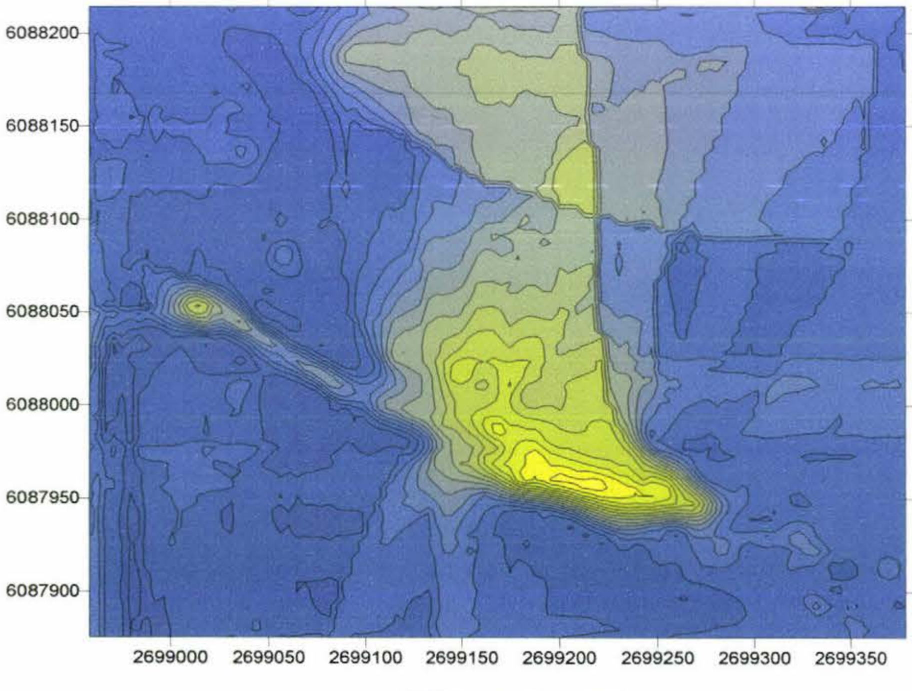


Figure 5.8 Contour Map of PD.4 produced using SURFER with data collected by GPS on 7/12/2002. The high yellow areas are the depositional lobe and trailing arms

while the lower surge lobe can be seen extending beyond the depositional lobe and is represented by the greyer areas. The tongue of sand which extends back into the deflation basin can be seen to the left of the depositional lobe.

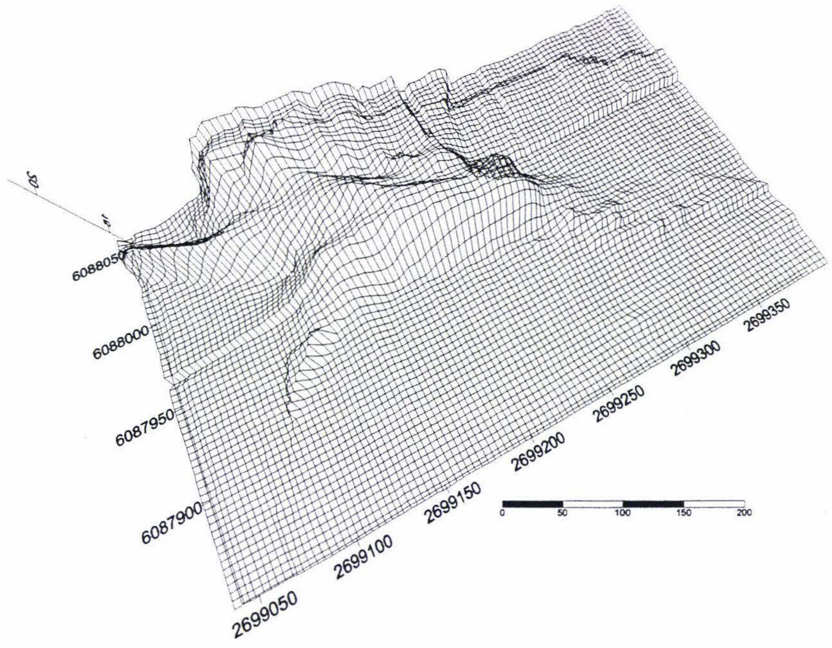


Figure 5.9 Wireframe Map of PD.4 produced using SURFER with data collected by GPS on 8/04/2002. The higher areas represent the depositional lobe, trailing arms and surge lobes.

Figure 5.10 Wireframe Map of PD.4 produced using SURFER with data collected by GPS on 7/12/2002. The higher areas represent the depositional lobe, trailing arms and surge lobes.

5.6 Wind regime and sand rose data for entire survey period

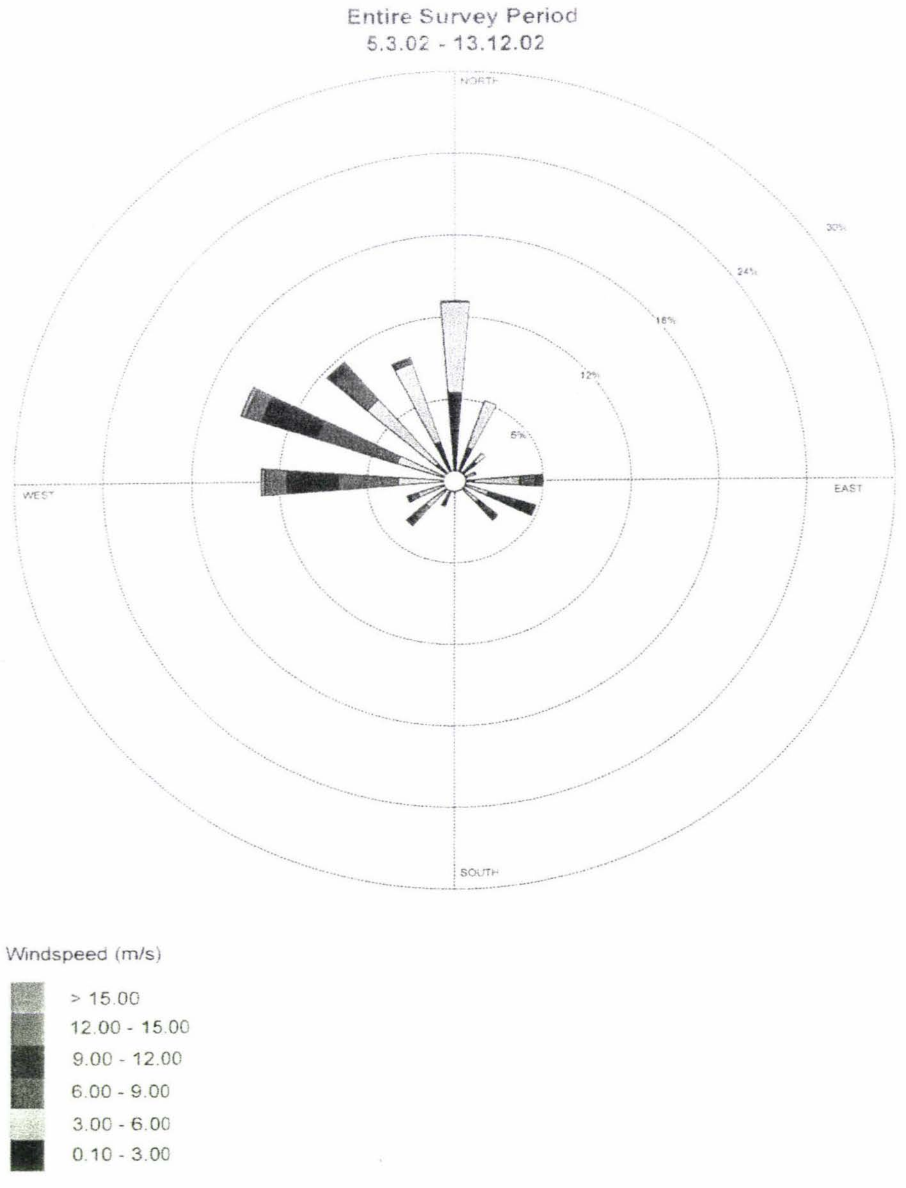


Figure 5.11 Wind rose for the Manawatu coastal zone between 5/03/02 - 13/12/02.

A break down of the wind rose data for the first photograph period is shown in Table 5.4.

Table 5.4 Wind regime for survey period (5/03/02 - 13/12/02)

Dominant wind direction	Northwest
Frequency of dominant direction	36.50%
Most common range of wind speeds from dominant direction	6-12 m/s
Other high frequency wind directions	West (13%)
	North (12.5%)
	Northeast (9.5%)
	Southeast (9%)
Other high frequency winds most common speeds	West (6-12 m/s)
	North (3-6 m/s)
	Northeast (3-6 m/s)
	Southeast (6-12 m/s)
Calm wind frequency	0.58%
Average wind speed	5.37 m/s

The wind data between 5/03/02 and 13/12/02 indicates that during this period the dominant wind direction is from the northwest. The wind from this direction is more than twice as frequent as from any other direction. Winds from the northwest, west and southeast have higher average wind speeds than those from the north and northeast. The average wind speed for this period is 5.37 m/s and calm conditions occur only 0.58% of the time.

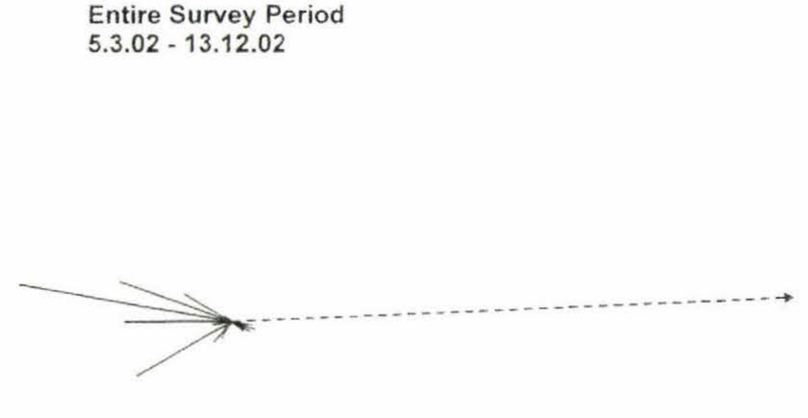


Figure 5.12 Sand rose for the Manawatu coastal zone between 5/03/02 - 13/12/02.

A break down of the sand rose data for the first photograph period is shown in Table 5.5.

Table 5.5 Sand rose data for entire survey period (5/03/02 - 13/12/02)

Resultant Drift Potential (RDP)	106.23
Resultant Drift Direction (RDD)	87.53

The sand rose data for the period from 5/03/02 to 13/12/02 shows that the dominant sand moving direction was just slightly north of east. It has subsequently been discovered however that the sand rose and RDD for this period are incorrect. This error was the result of a calculation error in the figures which were used to create the sand rose. Due to the original data being no longer available this error was unable to be fixed.

5.7 Parabolic Dune development and the relationship to wind regime

The wind regime for 2002 shows a predominance of winds from the northwesterly direction and that these winds usually blew at a speed greater than 6 m/s. Corrected sand rose data would probably show that potential for sand to be moved in an east to southeasterly or inland direction is significantly greater than any other direction.

During 2002 PD.1 experienced significant development. The former blowout and deflation basin remained largely unchanged apart from an increase of approximately 12 -13 metres in the length and an increase of approximately 5.0 metres in the width of the deflation basin. The trailing arms showed little change either, with no significant erosion at the seawards end or development of new trailing arms at the landwards end of either trailing arm. The depositional lobe migrated approximately 15 metres inland, and showed small increases in width and height of 3.0 and 0.9 metres respectively. The surge lobe migrated inland approximately 27 metres but showed no significant increases in height or width. The migration rate for PD.1 during 2002 was 1.5 metres per month.

The high rate of inland movement of PD.1 and the depositional and surge lobes illustrates the high potential for the inland movement of sand. While the rate of development for PD.1 is high when compared with the rates recorded elsewhere, given the high potential for sand to be moved inland, the development and direction of development of PD.1 is not unusual.

There was significant inland development of PD.2 during 2002. The deflation basin increased in length by approximately 20 metres and in width by approximately 6.0 metres. The northern trailing arm decreased in length by approximately 2.0 metres while the southern arm increased by approximately 3.0 metres. The height of the trailing arms decreased by up to 0.5 metres in places. The depositional lobe migrated inland by approximately 40 metres but had only small increases in width and height of 3.0 and 0.5 metres respectively. The surge lobe has migrated inland 68 metres and increased in width by approximately 10 metres. The rate of migration for PD.2 was 4.0 metres per month for 2002.

The high rate of inland migration and the significant inland migration of the deflation basin, depositional lobe and surge lobe all show how this high potential for the inland movement of sand has affected the rate of development. While the rate of inland migration is high even when compared with the other parabolic dunes, given the high potential for inland sand movement, the height, age and exposure of PD.2 and a large enough sand supply these high rates of inland movement are not unusual.

The development of PD.3, while not at the rate seen on PD.2 was still high when compared with rates recorded elsewhere. The former blowout and deflation basin did not change in any significant way. Both of the trailing arms decreased in length by approximately 2.0 metres. The depositional lobe only migrated 5.0 metres inland and showed both increases and decreases in height of 1.55 metres and 0.3 metres respectively. The width of the depositional lobe increased by up to 5.0 metres. The surge lobe was the feature which showed the largest changes during 2002, with 35 metres of inland migration, increases in height of up to 1.0 metre and an increase in width of approximately 3.0 metres. The rate of inland migration for PD.3 was 0.5 metres per month during 2002.

The rate of inland migration and the inland migration of the deflation basin, depositional lobe and surge lobe are not as great as for the other parabolic dunes and the rate of inland migration is more in line with rates recorded elsewhere. The differences between PD.3 and the other parabolic dunes are the result of the differences in age, height, exposure and sand supply between the parabolic dunes.

The amount of change to PD.4 is significant. There were no changes to the former blowout, but the deflation basin increased in length by approximately 4.0 metres. The tongue of sand which extends through the deflation basin did show significant increases in height and volume. The depositional lobe migrated 15 metres inland, increased in width by approximately 6.0 metres and increased in height by approximately 1.0 metre. The surge lobe migrated approximately 18 metres inland and increased in height by approximately 0.3 metres. The rate of inland migration for PD.4 was 1.5 metres per month during 2002.

The rate of inland migration of the deflation basin, depositional lobe and surge lobe is significant and approximately the same as PD.1. Although the rate of inland migration is approximately the same between PD.1 and PD.4, PD.4 is significantly younger than PD.1, so factors like height and exposure must influence their rates of development rather than age.

The frequency of northwesterly winds produces a high RDP along this coast. This in turn provides a high potential for sand to be moved in the RDD. The high rates of inland migration and significant development of the parabolic dune are evidence of the substantial sand moving potential of the northwesterly winds along this coast. Given the high RDP and the RDD along the coast the behavior of the parabolic dunes is not surprising.

5.8 Comparison of changes on the four parabolic dunes and relationship to RDP

The changes and migration rates of the four parabolic dunes are quite different from each other. While wind regime and drift potential play an important role in parabolic dune development, the stage of maturity, size, wind exposure, sand supply, topography and vegetation also play a role. The differences in the development are the result of a combination of these factors.

5.8.1 Former blowout

The former blowouts of all four parabolic dunes showed only relatively small changes during 2002. The largest changes were on the former blowout of PD.3 with smaller changes on PD.2 and PD.4 and almost no change on PD.1. The mouths of all four former blowouts are similar in size and exposure, but do differ in age with the former blowouts of PD.1 and PD.2 being older. Beyond the mouth of the former blowout behind the foredune differences in size and exposure are more noticeable. The former blowouts of PD.1 and PD.2 are larger in size than PD.3 and PD.4. The former blowout of PD.1, PD.3 and PD.4 are all curved in behind the foredune slightly, PD.2 however is much straighter. This increases the exposure of the blowout as a whole to wind, while the other former blowouts are exposed much more along one part only. This may explain the smaller amount of erosion along the former blowout of PD.1, as it is older in age and curved, while the younger and straighter former blowouts are more prone to erosion.

5.8.2 Deflation basin

The deflation basins of all four parabolic dunes all changed differently throughout the year. Despite the same RDP and RDD, both distances and rates of migration differed. As is shown in Figure 5.1, the distance of migration of the deflation basin of all four parabolic dunes was different. PD.3 and PD.4 migrated similar distances and were less than the distance migrated by PD.1 and PD.2, with PD.2 having migrated the greatest ditance. The migration rates are also significantly different for each dune, see Figure 5.2.

Figure 5.13 Total distance of deflation basin migration vs RDP for each parabolic dune over survey period (5/03/2002 - 13/12/2002)

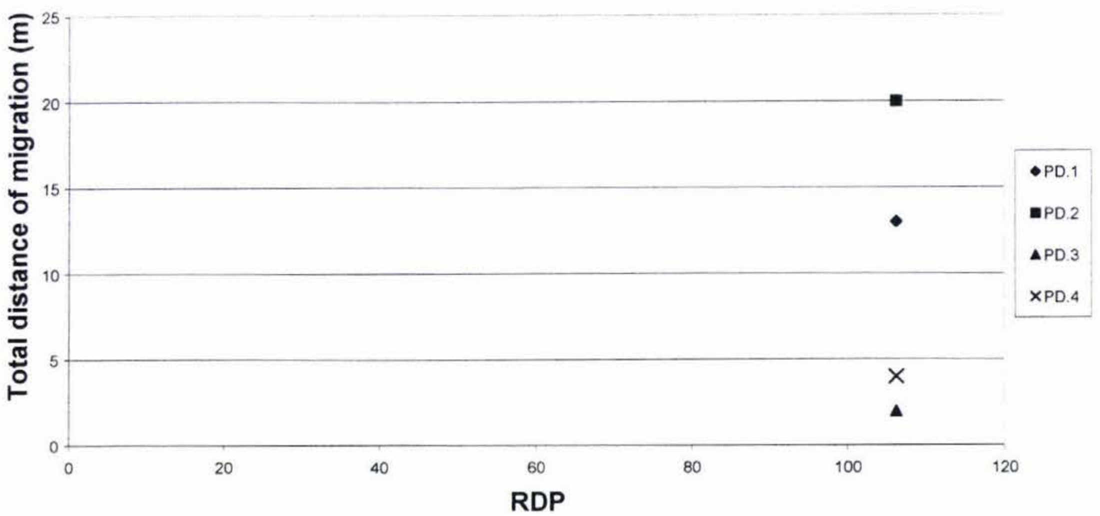
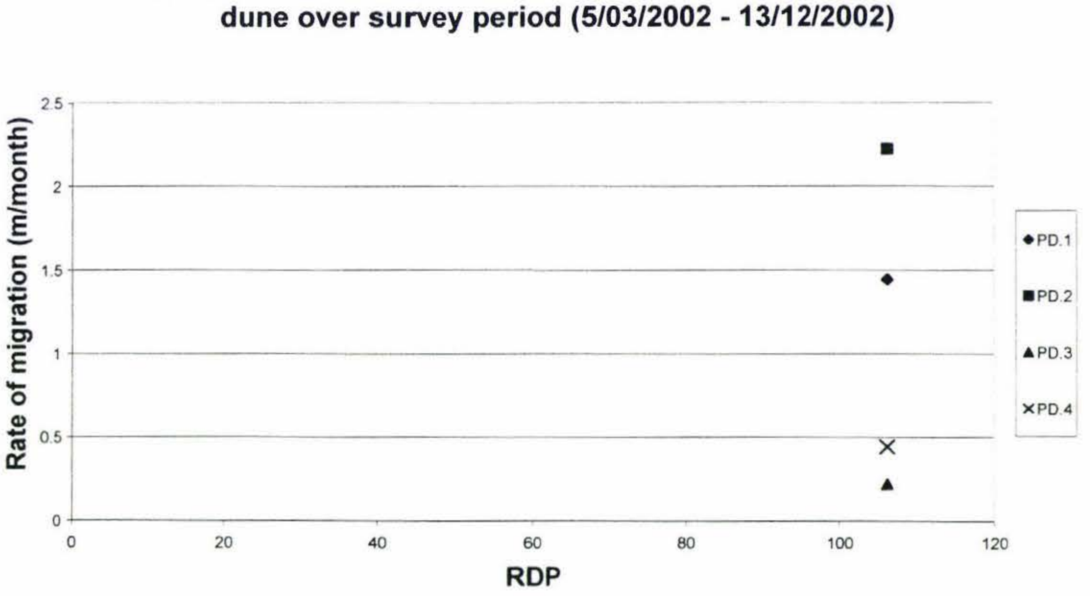


Figure 5.14 Rate of deflation basin migration vs RDP for each dune over survey period (5/03/2002 - 13/12/2002)



The deflation basins of PD.1 and PD.2 are bigger and older than the deflation basins of PD.3 and PD.4. Age and maturity of the deflation basin may affect the amount of deflation basin migration, however it is more likely that the size of the deflation basin is important. A larger deflation basin is likely to be more exposed to the wind and therefore be more prone to erosion. The straighter deflation basins may also have increased exposure to wind which increases the chance of erosion. The deflation basins of PD.1 and PD.2 are significantly straighter, especially at the upwind end, and this may contribute to their increased erosion.

5.8.3 Trailing arms

During 2002 there was only a small amount of change on the trailing arms of all four parabolic dunes. The largest amount of change was seen on the northern trailing arm of PD.2, which is also the southern trailing arm of PD.3. The biggest factor affecting erosion of the trailing arms is exposure to wind; other important factors are vegetation, size, age and compaction of the sand on the trailing arms. The trailing arms of PD.1 and PD.2 are more prone to erosion as a result of the larger deflation basins of these parabolic dunes. The trailing arm which is part of both PD.2 and PD.3 has the most exposure to wind as it is exposed on both sides as two deflation basins border it. The height of the trailing arm may also affect its exposure to wind however the trailing arms are all approximately the same height. The age and maturity of the trailing arms does not appear to have had an affect either. The compaction of sand on the trailing arms was approximately the same across all trailing arms. The other trailing arms are all well vegated, decreasing the effects of erosion.

The development of new trailing arm was not significant during 2002 with only a small amount occurring on all trailing arms. The development of new trailing arm occurs fastest during periods of slower inland migration when the trailing arms have more time to develop as the parabolic dune migrates inland. Vegetation development at the downwind end is slowed during periods of high inland migration. The behaviour of the depositional lobe also affects trailing arm development as lateral increases may cover the downwind end slowing development considerably.

5.8.4 Depositional lobe

There was a significant spread in the distance of migration of the depositional lobes between the four parabolic dunes during 2002 apart from PD.1 and PD.4, which were the same. PD.3 had the smallest distance of migration while PD.2 had the greatest distance. The distances and rates of migration of the depositional lobes are shown in Figures 5.3 and 5.4.

Figure 5.15 Total distance of depositional lobe migration vs RDP for each parabolic dune over survey period (5/03/2002 - 13/12/2002)

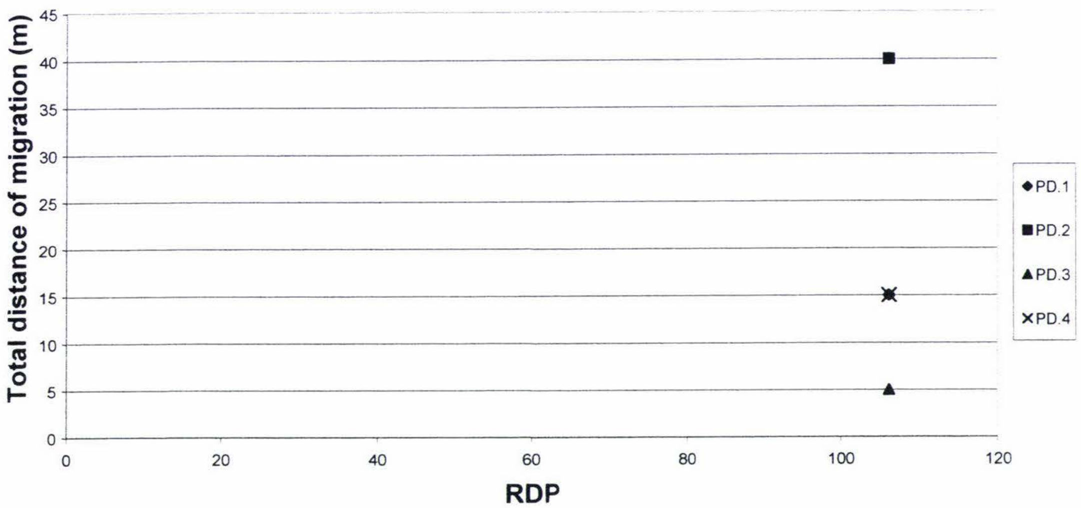
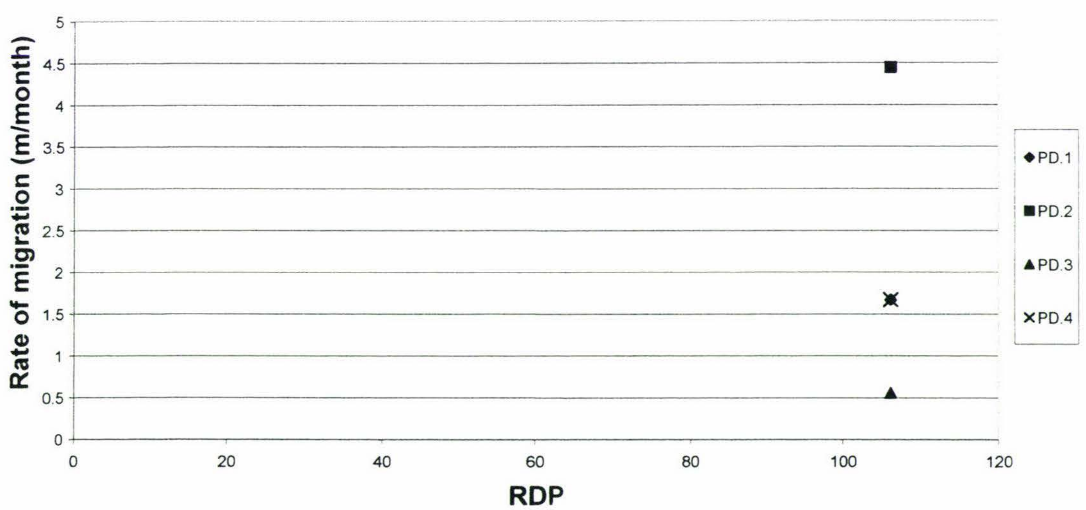


Figure 5.16 Rate of depositional lobe migration vs RDP for each dune over survey period (5/03/2002 - 13/12/2002)



The age of the parabolic dunes may play less of a role in terms of the migration of the depositional lobe, as the youngest depositional lobes had the smallest distance of migration. Other factors such as sand supply, size, height and exposure may be more important. PD.2 has migrated significantly further than the other parabolic dunes, and PD.1 has migrated further than PD.3. The rate of inland migration is affected by sand supply, so as the depositional lobes grew in volume they migrated. The depositional lobes of PD.1 and PD.4 are similar in size and are the biggest of the four. PD.2 is similar in length but not as wide, while PD.3 is significantly smaller. PD.1 and PD.2 are similar in height, while PD.4 grew in height considerably during the year to now be approximately the same height as well. This large increase in height may have slowed the rate of migration. PD.3 was significantly lower than the other three parabolic dunes. Topography and vegetation in front of a migrating depositional lobe may affect the rate of migration, however as the depositional lobes were migrating over the surge lobes this factor will have had no affect. The height of the depositional lobe and therefore exposure to wind may be the single most important factor, however a combination of all factors will affect the rate.

5.8.5 Surge lobe

The surge lobes show similar rates of movement between the four parabolic dunes during 2002, other than PD.2, which was the highest. The distances and rates of migration of the surge lobes are shown in Figures 5.5 and 5.6.

Figure 5.17 Total distance of surge lobe migration vs RDP for each parabolic dune over survey period (5/03/2002 - 13/12/2002)

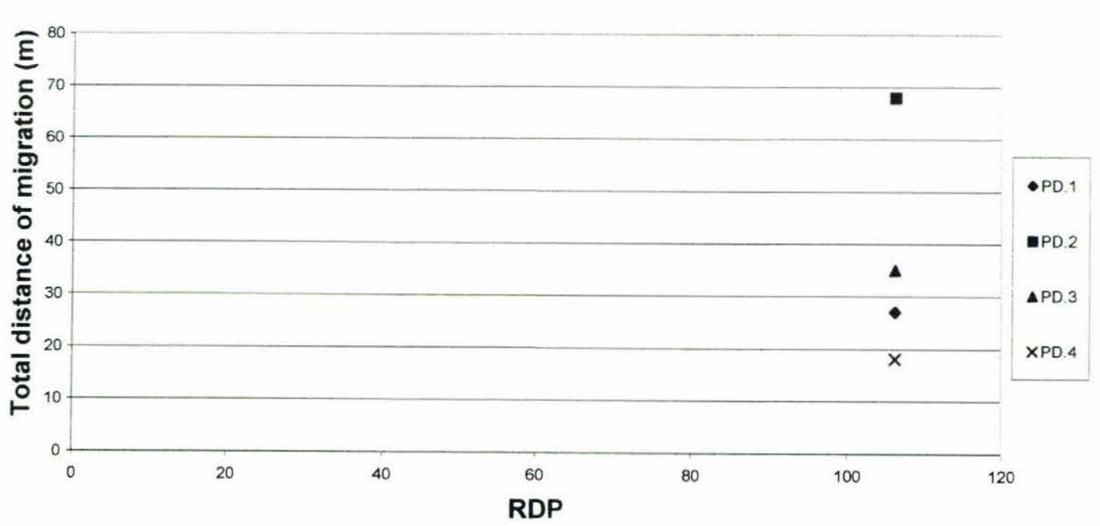
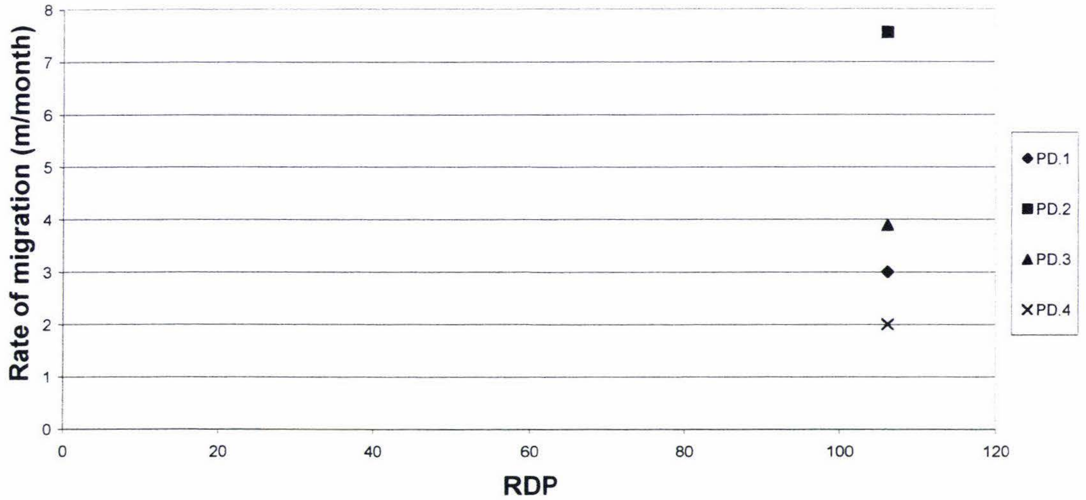


Figure 5.18 Rate of surge lobe migration for each parabolic dune over survey period (5/03/2002 - 13/12/2002)



The rate of surge lobe migration does not look to be strongly related to the age of the parabolic dune. Given the low height of the surge lobe the topography and vegetation over which the surge lobe is migrating is an important factor in migration rates. The surge lobe of PD.2 had the lowest vegetation and flattest topography. PD.3 had higher vegetation and very uneven topography initially, however once it moved over that the topography was flatter and the rate of migration increased. PD.1 had very flat topography and vegetation which was approximately 0.3 metres in height. The rate of surge lobe migration may therefore be related to the sand supply or age of the parabolic dune. The topography and vegetation in front of PD.4 was very flat and the vegetation was grass approximately 0.1 metres in height. However part of the surge lobe had been planted in marram grass and this has slowed the rate of migration. During 2002 it was observed that the marram grass was trapping sand and that the height of the surge lobe at this point was increasing significantly.

The migration rates for the older dunes are significantly higher than the younger dunes. PD.1 and PD.2 have developed larger blowouts and deflation basins. This increase in size increases exposure to the dominant northwest winds and subsequently increases the potential for erosion and inland migration of the deflation basin.

Chapter Six: Discussion

6.1 The morphological development of parabolic dunes

The morphological development of parabolic dunes is dependent on a number of factors. The development of the different morphological features may also be inter-related, as they do not develop in isolation. The development of the morphological features of a parabolic dune will be identified and discussed.

6.1.1 The morphological development of the former blowout

The development of a blowout from initiation has not been studied as a part of this research. However, consideration has been given to blowout development as part of the parabolic dune complex. A blowout begins in the foredune following the destabilisation of the foredune by wave action or other factors. Once the blowout mouth has expanded, and the back of the blowout has formed landwards of the foredune, the deflation basin of the parabolic dune then begins to form. Once the blowout reaches maturity the changes and developments are usually small. When the blowout has reached maturity and if a parabolic dune develops, it then becomes a former blowout. Changes to the mouth of the former blowout may occur following storm wave conditions, which remove vegetation and destabilise the foredune. High onshore winds may also erode the mouth of the former blowout causing it to increase in size. The back of the former blowout may also be eroded and increase in size. Depending on the wind direction and exposure to wind one side of the former blowout may be eroded more than the other. The relative height of the bottom of the blowout remains reasonably constant once the blowout has reached maturity. The relative height may increase or decrease as sand is moved from the back of the beach through the former blowout by the wind.

6.1.2 The morphological development of the deflation basin

The deflation basin develops once the blowout reaches maturity, and as long as the prerequisite conditions for parabolic dune development are suitable. Wind erosion at the landwards end of the former blowout initiates the deflation basin, and as erosion continues the deflation basin forms beyond the former blowout. Initially the deflation basin has similar proportions to the former blowout, however, as development continues the deflation basin expands beyond this. The length of the deflation basin initially grows beyond that of the former blowout, although, after time the width also begins to increase. The height remains fairly constant once the deflation basin has reached maturity with only small fluctuations as sand is blown through. The bottom of the deflation basin is eroded to approximately the winter water table level. Once the parabolic dune has matured the main increases in deflation basin size occur as increases in length at the landwards end of the deflation basin.

6.1.3 The morphological development of the trailing arms

The trailing arms of a parabolic dune develop once the depositional lobe has formed beyond the deflation basin and begun to migrate inland. The trailing arms form along the seawards margins of the depositional lobe and extend back into the deflation basin. As the depositional lobe migrates inland the trailing arms grow in the same direction. Wind erosion of the seawards end of the trailing arms may cause the destruction of part of the trailing arm, or lead to the formation of remnant knobs.

Over time the continued erosion and further development causes the inland movement of the trailing arms. The landwards end of the trailing arm is where new trailing arm forms as the depositional lobe migrates inland. The rate of development here is not as high as that of the depositional lobe. While the landwards end is the point of growth, destruction of the trailing arm may also occur at this point, possibly by wind action or more often by lateral increases of the depositional lobe which covers part of the trailing arm. The trailing arms are vegetated which helps them to resist erosion, so removal of this vegetation will result in their destruction. Wind erosion along the trailing arm occurs particularly at the seawards end and removes the sand surrounding the roots of the plants killing the vegetation thus mobilising the sand and destroying the trailing arm. In places where the vegetation is particularly resistant, part of the trailing arm may become separated from the main trailing arm. This resistant area then becomes a remnant knob.

6.1.4 The morphological development of the depositional lobe

Following the development of the deflation basin, continued sand movement through the blowout and deflation basin leads to the initiation of a depositional lobe. Depositional lobe initiation occurs from the approximate centre of the landwards edge of the deflation basin. Initially the depositional lobe forms as a long, narrow, low feature landwards of the deflation basin, and is significantly longer than it is wide. Following formation the depositional lobe begins developing, and increases in length, width and height as well as migrating inland. The rate of development is dependent on its length, width and height, as well as exposure to wind, sand supply, wind regime, and vegetation and topography in front of the depositional lobe. Depending on these factors the depositional lobe will continue to increase in size and migrate inland. Significantly the width increases over time to be approximately that of the deflation basin.

Once the width of the depositional lobe is approximately that of the deflation basin there is no significant change. The length and height are more changeable as the length may increase depending on the distance of inland migration by the depositional lobe and the increase in length of the deflation basin. Increases in deflation basin length greater than the distance of inland migration by the depositional lobe cause the depositional lobe to shorten in length. The height gradually increases over time as more sand enters the depositional lobe, however, large increases in length may reduce the height as sand is blown from the top down the slip face to increase the length. Periods of slow inland migration, or when the depositional lobe is moving over high vegetation or topography, may cause the depositional lobe to increase in height. Sand moving into the depositional lobe may build up the height due to the small increases in inland migration or to gain the height to clear the obstacle.

6.1.5 The morphological development of the surge lobe

Once the depositional lobe has developed sufficiently and reached maturity under a suitable wind regime a surge lobe is likely to develop beyond the main depositional lobe. A surge lobe is usually initiated in the approximate centre of the landwards end of the depositional lobe and begins as short, narrow, low lobe of sand extending a short distance beyond the end of the depositional lobe. Once the surge lobe has been initiated the rate of development and migration is very high, usually greater than for any other part of the parabolic dune. The rate of development is dependent upon factors such as length, width and height, exposure to wind, sand supply, wind regime, as well as vegetation and topography in front of the surge lobe. If these factors are suitable the surge lobe will continue to develop and migrate inland.

The surge lobe may continue developing and migrating so long as conditions are suitable. The width of the surge lobe increases until it is approximately that of the depositional lobe after which there is little change. The length and height are more changeable. As the surge lobe migrates inland it will increase in length so long as the rate is higher than that of the depositional lobe. The height steadily increases over time, although at a rate slower than the rest of the surge lobe. However, short term increases and decreases in height are caused by the same factors which affect the height of the depositional lobe, that is rate of migration as well as the topography and vegetation in front of the surge lobe.

6.1.6 Relationship between parabolic dune migration and changes in volume

Parabolic dune migration along the Manawatu coast appears to be related in part to changes in the volume of the parabolic dune, particularly the depositional lobe. The migration of parabolic dunes may be the result of the recycling of sand already present within the parabolic dune with little input of new sand or there may be significant input of new sand into the system or a combination of the two. In the parabolic dunes studied there have been significant increases in size and volume indicating input of new sand. New sand is moved from the back of the beach through the blowout and deflation basin onto the depositional lobe by wind action. This new sand, as well as the sand already on the depositional lobe, is then moved inland as the parabolic dune migrates. All the depositional lobes were observed to have migrated inland during 2002, and it was also noticed that increases in volume occurred. PD.2 and PD.4 (the dunes which migrated the furthest distance during 2002), also had the most significant increases in volume. It is likely that changes in the volume of the dune have an effect on the rate of migration, with increases in volume helping to increase the rate of migration.

6.2 The impact of wind regime on parabolic dune development

The wind regime is the driving force of the parabolic dunes of the Manawatu coast. Changes in wind strength and direction may have a significant effect on how the dune develops and migrates, while changes in wind regime may have a significant impact on the rate and style of development. The wind regime and its impact on the development of the different morphological features of a parabolic dune will be identified and discussed.

6.2.1 Former blowout and deflation basin development and wind regime

The former blowout and deflation basin comprise the upwind section of the dune and the parabolic dune behaviour is dependent on their development. The former blowout and deflation basin will be aligned with the dominant wind direction. Development of the former blowout and deflation basin will vary with changes to the RDP and RDD. A decrease in RDP will likely produce a decrease in the rate of development, while changes in RDD may produce increases or decreases in the rate of development depending on the change in direction and the attached part of the former blowout or deflation basin.

The rate of blowout development is affected by the wind regime of the area. Under suitable conditions on the Manawatu coast the dominant northwest winds cause a blowout to form. The rate of development will increase under conditions of a higher RDP, but changes to the RDD may have a different impact. A shift in the RDD to the south would increase the erosion of the blowout in that direction, while an increase to the north would cause an increase in that direction. These shifts may decrease the rate of development as the blowout may be less exposed to the wind under these conditions, however, a shift which is more beneficial to blowout development may increase the rate even under a lower RDP.

Once the blowout has developed and matured a deflation basin may form landwards. The deflation basin will align itself in the same direction as the blowout and behaves in a similar fashion under the changing wind regime, with similar effects from the changing RDP and RDD.

Sand is moved from the back of the beach through the former blowout and deflation basin and onto the depositional lobe. Changes in RDP, in particular, affect the amount of sand which is moved. Given sufficient sand supply, increases in RDP will allow more sand to be moved through to the depositional lobe. Changes in the RDD may reduce the effectiveness, however, as a shift away from the line of the former blowout and deflation basin may allow less sand to be moved into the former blowout, or for sand to be piled along one side of the deflation basin.

6.2.2 Trailing arm development and wind regime

The trailing arms form as the depositional lobe has developed and begun migrating inland. The trailing arms are aligned along the same direction as the depositional lobe which is the direction of the dominant wind direction. Trailing arm formation occurs as the depositional lobe migrates inland so RDP and RDD affect the formation of new trailing arms. The erosion of the trailing arms at the seawards end is less affected by RDP and RDD, as the direction and strength of the wind regime is more important.

Once the depositional lobe has begun migrating inland the trailing arms develop along the sides. New trailing arm is formed as the depositional lobe migrates inland so the rate of trailing arm development is partly dependent upon the rate of depositional lobe migration. A higher RDP may increase the rate of depositional lobe migration thereby increasing the rate of trailing arm development. However, a higher RDP may instead cause destruction of the trailing arm by increasing the rate of depositional lobe development which may then expand destroying part of the trailing arm. Changes to the RDD which reduce the rate of migration of the depositional lobe will reduce the rate of trailing arm development, while changes which alter the direction of migration may cause more development along the arm which is on the outer side of depositional lobe as it changes direction.

The seaward end of the trailing arm is the erosional end, and so is affected by changes to wind regime which affect erosion. A change in wind regime, which reduces erosion but not development, will allow the trailing arms to grow. A reduction in RDP may reduce the rate of erosion by decreasing the potential for sand to be removed, however, this may not always be the case. Depending on the direction of the seaward end of the trailing arms exposure to the wind, a change in RDD may have a larger impact than changes to the RDP.

6.2.3 Depositional lobe development and wind regime

Following the formation of the deflation basin the depositional lobe forms at it's landwards end. The rate of development of the depositional lobe may vary with changes to the RDP or RDD. Increases in RDP will potentially increase the rate of development, while shifts in direction of the RDD may increase or decrease the rate depending on the change in direction.

Once a depositional lobe has been initiated, it begins to develop and migrate inland. These processes are dependent upon the wind regime and in particular the RDP and RDD. The development and inland migration is dependent on the wind not only to move the sand already present on the depositional lobe but also to supply new sand from the beach through the blowout and deflation basin. The RDP therefore is important to both the development and migration of the depositional lobe with a high RDP likely to increase and a low RDP likely to decrease the rate at which these happen.

Changes to the RDD may also affect the rate of development and migration. Changes in the RDD from the line of the depositional lobe may reduce the rate as less sand enters through the blowout. Another potential effect is a shift in the direction of inland migration of the depositional lobe.

6.2.4 Surge lobe development and wind regime

Once the depositional lobe has reached maturity a surge lobe will form beyond landwards end of the depositional lobe given a suitable wind regime. The rate of its development and migration may vary with changes in RDP or RDD. A higher RDP may increase the rate of development and migration, while a change in the RDD may increase or decrease the rate depending on the change in direction.

Once the surge lobe has developed and begun growing and migrating, the rate at which this happens is affected by the wind regime and in particular the RDP and RDD. The development and inland migration is dependent on the wind not only to move the sand already present, but also to move sand from off the depositional lobe and on to the surge lobe.

Changes to the RDD also affect the rate of development and migration. Changes in RDD away from the line of the surge lobe may reduce the rate of migration as less sand may be added from the depositional lobe. Another potential effect is a shift in the direction of inland migration of surge lobe.

6.3 Impact of El Niño on dune development

The wind regime of the Manawatu coast is the driving force of parabolic dune development. As a result of this, factors which affect the climate and wind regime are important as they will influence parabolic dune development. The El Niño Southern Oscillation can produce significant changes in the climate and wind regime of New Zealand, which therefore may impact on parabolic dune development. During El Niño conditions there tends to be stronger, and more frequent winds from the west during summer, while during winter, winds from the south tend to be more frequent. Winds during autumn and spring are also affected with more frequent or stronger winds from the southwest. The opposite of El Niño is La Niña. During La Niña, winds from the northeast are more frequent (El Niño and Climate Forecasting Page NIWA. http://www.niwa.co.nz/rc/atmos/clivar/elnino).

El Niño events are therefore important as they often increase the frequency and strength of the northwest winds, which in turn may increase the RDP along the Manawatu coast. An El Niño event which produces a higher RDP value may cause high rates of development and migration during that period. Figure 6.1 shows the El Niño events over the last 22 years and these events can then be compared with dune development and migration and RDP.

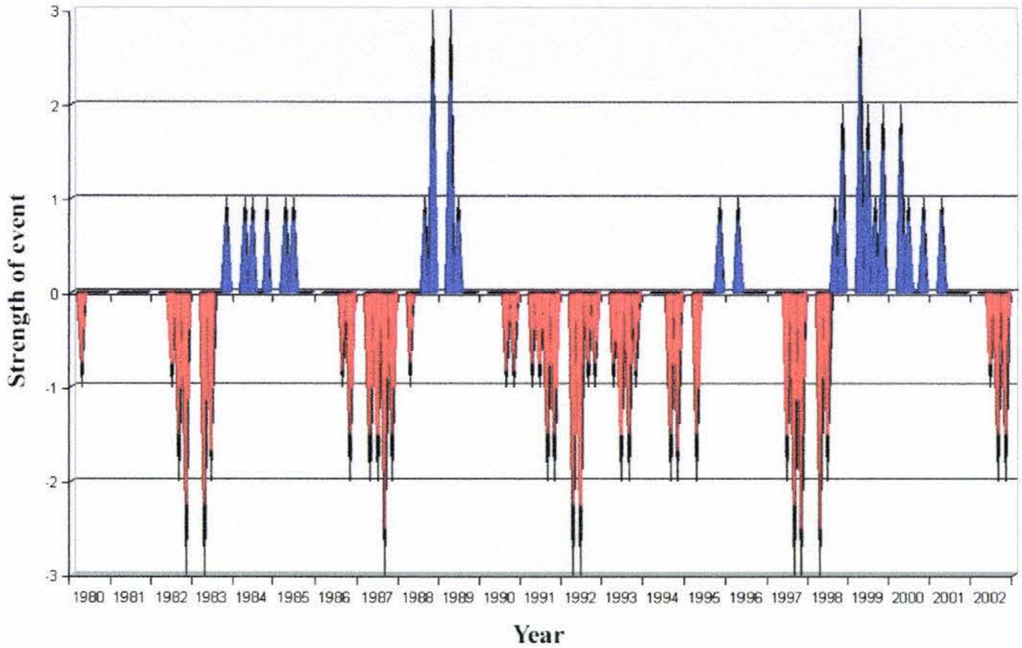


Figure 6.1 A plot of El Niño and La Niña events over the last 22 years. Red indicates El Niño events and blue indicates La Niña events. A higher value signifies a stronger event.

6.3.1 Comparison of El Niño events and RDP

The 12-year period between 1990 and 2002 is dominated by El Niño events. There are only two La Niña periods, one weak event at the end of 1995 and a second weak event in the beginning of 1996. A second stronger series of events began in the middle of 1998 and ended at the beginning of 2001. The period between 1990 and 1995 was dominated by El Niño events, and included two very strong events in 1991 and 1992. This period had a RDP of 67.84, which was the highest of all the four periods. The second period from 1995 to 2000 had a RDP of 48.68, with a period of strong El Niño events and two La Niña events during this period. The El Niño events began in 1997 and finished in the middle of 1998. The third period from 2000 to 2002 had the lowest RDP of 26.33 during which time there were no El Niño events, and only a period of weak La Niña events. The final period during 2002 had a RDP of 58.05 with a moderate El Niño event occurring during the year.

From this comparison of the data it would appear that El Niño has a significant effect on the RDP. The highest RDP was for the first period which was dominated by El Niño, including a particularly strong event. The lowest RDP was recorded for the third period during which there were no El Niño events. This is evidence that El Niño events may have a considerable effect on parabolic dune development, on the Manawatu coast.

6.3.2 Comparison of El Niño and dune development

The periods during which there was an El Niño event have a higher RDP, and this higher RDP increases the potential for parabolic dune development and migration. While dune development and migration may not always be greatest during periods of high RDP, it is significant to note that parabolic dune and surge lobe initiation occurred to occur during periods of El Niño events. While the exact dates of formation are not known for any of the parabolic dunes or their surge lobes, approximate dates of formation may be given. PD.1 and PD.2 formed sometime prior to 1990, with a probable formation date between 1987 and 1989. This corresponds with an El Niño event which occurred between 1986 and 1988. PD.3 and PD.4 developed largely between 1990 and 1995, which was a period of significant El Niño events. The surge lobes of PD.1, PD.2 and PD.4 developed between 1995 and 2000, corresponding with an El Niño event between 1997 and 1998. The only exception to this trend is the development of the surge lobe of PD.3 which occurred between 2000 and 2002, during which time there no El Niño events.

Chapter Seven: Conclusion

7.1 Rates of migration of parabolic dunes along the Manawatu coast

One purpose of this study was to provide information on the rates of migration of the parabolic dunes of the Manawatu coast, and compare these rates with the rates recorded elsewhere in the world. PD.1, PD.2 and PD.4 all had very similar rates of migration, while the rate of migration of PD.3 was less than half the rate of the other three parabolic dunes. The average rate of migration over all four of the parabolic dunes was 14.90 metres/year or 1.19 metres/ per month for the 12-year period. The average rate of migration recorded in the literature is approximately 8.0 metres per year. Therefore the rates of migration of the parabolic dunes of the Manawatu coast is significantly higher than the rates of migration, which have been recorded in the literature from elsewhere in the world.

7.2 Relationship between parabolic dune migration and development and El Niño Southern Oscillation

The second aim of this study was to establish whether there was any relationship between the behaviour of the parabolic dunes of the Manawatu coast and the El Niño Southern Oscillation events. El Niño events in New Zealand corresponded to the periods of the highest RDP along the Manawatu coast during the study period while the lowest RDP occurred during La Niña events. The highest RDP was between 1990 and 1995 during this period there was an intense El Niño event. The lowest RDP was between 2000 and 2002 and during this period there were no El Niño events and only a La Niña event. Periods of high parabolic dune development such as the development of the surge lobe occurred during these periods of El Niño events.

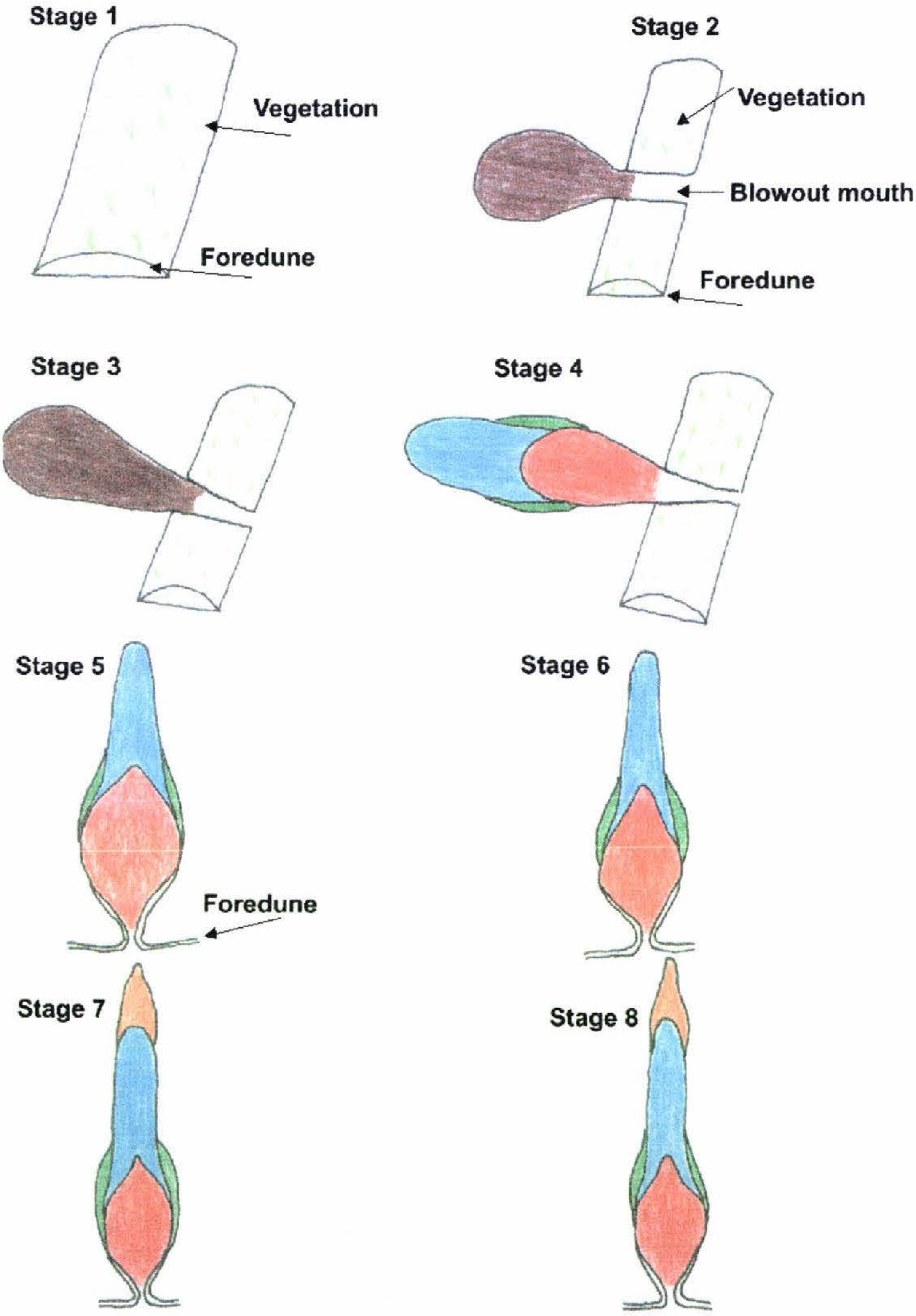
7.3 Modes of parabolic dune development and morphological change over time

The third aim of this study was to examine modes of parabolic dune development and how the parabolic dunes develop over time, and to try to identify a pattern of development. Parabolic dune development in the Manawatu coastal setting begins with a vegetated, stable foredune which due to the removal of vegetation becomes unstable. Following destabilisation wind erosion forms a blowout in the foredune which then moves back into the foredune complex behind the actual foredune. The blowout then continues to increase in size and a parabolic dune then begins to form. The deflation basin and depositional lobe are the first parts of the parabolic dune to form and are relatively small features. As the parabolic dune grows and begins migrating inland trailing arms form either side of the depositional lobe. As development and migration continues the deflation basin and depositional lobe grow in size, in particular the depositional lobe. The trailing arms continue to grow at the downwind end and erode at the upwind end. Once the parabolic dune has reached maturity, and if climatic conditions are suitable, a surge lobe develops beyond the downwind end of the depositional lobe. Surge lobe development then continues usually at a higher rate than the rest of the parabolic dune.

7.4 Model of development for the parabolic dunes of the Manawatu coast

The fourth aim of this study was to develop a model development of the parabolic dunes of the Manawatu coast. The basis for this model was examination of parabolic dune behaviour based on aerial photographs over the 12-year period, and the study of other models of parabolic dune behaviour based on examples found elsewhere in the world. The model may be able to be used in other locations, however it is developed to be used for the Manawatu coastal setting.

Model of Parabolic Dune Development



Key

- Blowout
- Deflation Basin
- Depositional Lobe
- Trailing Arms
- Surge Lobe

Figure 7.1 Model of parabolic dune behaviour and development for parabolic dunes found on the Manawatu coast.

Stage One

- Vegetated intact foredune prior to blowout formation

Stage Two

- Removal of vegetation by wave action, or other factor
- Destabilisation of foredune as a result of vegetation removal leading to blowout formation

Stage Three

- Continued blowout development and enlargement
- Deflation basin may begin developing

Stage Four

- Continued blowout development then becomes a former blowout
- Trailing arm and depositional lobe development begins

Stage Five

- Small parabolic dune has developed with unvegetated depositional lobe and vegetated trailing arms
- Deflation basin, depositional, lobe and trailing arm development continues

Stage Six

- Depositional lobe widens and lengthens downwind and begins migrating inland

- Deflation basin lowers in height if not already at base level. May expand laterally and migrate downwind
- Trailing arms develop at downwind end and erode at upwind end, possibly leaving remnant knobs

Stage Seven
- Continued development and growth of parabolic dune complex
- Once parabolic dune reaches a certain level of maturity and climatic conditions are suitable a surge lobe is likely to develop

Stage Eight
- Surge lobe development continues and at a rate higher than seen on the rest of the parabolic dune
- The parabolic dune complex continues to develop and migrate inland
- After time the foredune may reform across the blowout. This was not observed on the study dunes so may not occur until well after the dune reaches maturity.

This eight stage model allows prediction of parabolic dune development for along the Manawatu coast.

7.5 Implications for parabolic dune management

By better understanding the processes involved in the development and migration of parabolic dunes, management techniques of these dunes can be improved. Parabolic dune development and migration over farmland is becoming an increasingly common issue along the Manawatu coast. Management practices will become easier and more efficient to implement if parabolic dune behaviour can be predicted. The eight stage model of parabolic dune development will allow for better prediction of future behaviour and thereby make future management practices more effective.

References

Anton, D.; Vincent, P. (1986): Parabolic dunes of the Jafurah Desert, Eastern Province, Saudi Arabia. *Journal of Arid Environments,* vol 11, pp 187-198.

Battiau-Queney, Y.; Fauchois, J.; Deboudt, P.; Lanoy-Ratel, P. (2000): Beach-dune Systems in a Macrotidal Environment along the Northern French Coast (English Channel and Southern North Sea). *Journal of Coastal Research,* (ICS 2000 Proceedings) New Zealand, pp 580-592.

Brough,G.R. (1998): *Aspects of blowout dynamics and implications for coastal management along the Manawatu Coastal Zone.* Unpublished Honours Thesis, Massey University, Palmerston North.

Burgess, S.M. (1983): *The climate and Weather of Manawatu and Horowhenua.* New Zealand Meteorological Service. Wellington.

Bussel, M.R. (1988): Mid and late Holocene pollen diagrams and Polynesian deforestation, Wanganui district, New Zealand. *New Zealand Journal of Botany,* vol 26, pp 431-451.

Carter, R.W.G.; Hesp, P.A.; Nordstrom, K .F. (1990): *Erosional landforms in coastal dunes.* In Nordstrom, K. ; Psuty, N. ; Carter, B. (Ed): Coastal Dunes Form and Process, pp 217-250. John Wiley & Sons. Brisbane.

Compton, R.R. (1962): *Manual of Field Geology.* John Wiley & Sons, INC. London.

Cooke, R.U.; Warren, A.; Goudie, A.S. (1993): *Desert Geomorphology.* UCL Press Limited. London.

Cooper, W.S. (1958): Coastal sand dunes of Oregon and Washington. *Geological Society of America Memorandum,* vol 101.

Cooper, W.S. (1967): *Coastal Dunes of California.* The Geological Society of America, Inc. Boulder.

Cowie, J.D. (1963): Dune-building phases in the Manawatu District, New Zealand. *New Zealand Journal of Geology and Geophysics,* vol 6, pp 268-280.

El Nino and Climate Forecasting Page NIWA. http://www.niwa.co.nz/rc/atmos/clivar/elnino

Esler, A.E. (1978): Botany of the Manawatu District New Zealand. *DSIR Information Series* No. 127, Department of Scientific and Industrial Research. Wellington.

Filion, L.; Morisset, P. (1983): Eolian Landforms along the Eastern Coast of Hudson Bay, Northern Quebec. *Nordicana,* vol 47, pp 73-94.

Fryberger, S.G. (1978): Techniques for the evaluation of surface wind data in terms of eolian sand drift. US Geological Survey, Open File Report, pp 78-405, 24p

Fryberger, S.G. (1979): Dune forms and Wind regime. In Mckee, E.D (ed). A Study of Global Sand Settings. U.S Geological Survey, Professional Paper, 1052 pp 157-169

Heerdegen, R.G. (1972): *The Geography of the Manawatu: Landforms of the Manawatu.* Department of Geography. Palmerston North.

Hesp, P.A. (2000): *Blowouts and parabolic dunes: evolution and dynamics.* In Saunders, B.G.R. (Ed): The South of the North: Manawatu and its Neighbours, pp 40-41. Geography Programme: School of People Environment and Planning, Massey University, Palmerston North.

Hesp, P.A. (2001): The Manawatu dunefield: environmental change and human impacts. *New Zealand Geographer,* vol 57, pp 33-40.

Hesp, P.A.; Shepherd, M.J. (1978): Some aspects of the late Quaternary geomorphology of the lower Manawatu Valley, New Zealand. *Journal of Geology and Geophysics,* vol 21, pp 403-412.

Hesp, P.A.; Thom, B.G. (1990): *Geomorphology and evolution of active transgressive dunefields.* In Nordstrom, K. ; Psuty, N. ; Carter, B. (Ed): Coastal Dunes Form and Process, pp 253-288. John Wiley & Sons. Brisbane.

Hesp, P.A.; Hyde, R. (1996): Flow Dynamics and geomorphology of a trough blowout. *Sedimentology,* vol 43, pp 505-525.

Hicks, D.L. (1975): *Geomorphic Development of the southern Aupouri and Karikari Peninsulas with special reference to sandunes.* Unpublished Masters Thesis, University of Auckland, Auckland.

Holland, L. (1983): The Shifting Sands of The Manawatu. *Soil and Water,* vol 4, pp 3-5.

Landsberg, S.Y. (1956): The Orientation of dunes in Britain and Denmark in relation to wind. *Geography Journal,* vol 122, pp 176-189.

McArthur, J.L. (1998): *45.121 Introductory Physical Geography.* Geography Programme, School of Global Studies. Massey University.

McFadgen, B.G. (1985): Late Holocene stratigraphy of coastal deposits between Auckland and Dunedin, New Zealand. *Journal of the Royal Society of New Zealand of New Zealand,* vol 15, pp 27-65.

McGlone, M.S.; Wilshurst, J.M. (1999): Dating initial Maori environment impact in New Zealand. *Quaternary International,* vol 59, pp 5-16.

McKee, E.D. (1979): Introduction to a study of global sand seas. In McKee E.D. (Ed): *A Global Study of Sand Seas,* pp 1-19. US Geological Survey.

McKelvey, P. (1999): Sand Forests: A historical perspective of the stabilisation and afforestation of coastal sand in New Zealand. Canterbury University Press. Christchurch.

Molloy, L. (1988): *Soils in the New Zealand Landscape the living mantle.* Mallinson Rendel Publishers Ltd. Wellington.

Muckersie, C.; Shepherd, M.J. (1995): Dune phases as time-transgressive phenomena, Manawatu, New Zealand. *Quaternary International,* vol 26, pp 61-67.

Price, W.A. (1950): Saharan sand dunes and the origin of the longitudinal dune: a review. *Geography Review,* vol 40, pp 462 - 465.

Pye, K. (1982): Morphological Development of Coastal Dunes in a Humid Tropical Environment, Cape Bedford and Cape Flattery, North Queensland. *Geografiska Annaler,* vol 64A, pp 213-227.

Pye, K. (1983): *Coastal dunes.* Progress in Physical Geography, vol 7, pp 531-557.

Pye, K. (1993): *Late Quaternary development of coastal parabolic megadune complexes in Northeastern Australia.* In Pye, K. & Lancaster, N. (Ed): *Aeolian Sediments Ancient and Modern,* pp 23-44. University of Reading, Reading.

Pye, K.; Tsoar, H. (1990): *Aeolian sand and sand dunes.* Unwin Hyman Ltd. London.

Robertson-Rintoul, M.J. (1990): *A quantitative analysis of near-surfacewind flow pattern over coastal parabolic dunes.* In Nordstrom, K.F. ; Psuty, N.P. ; Carter, R.W.G. (Ed.): Coastal Dunes: Form and Process, pp 57-78. John Wiley & Sons Ltd, Brisbane.

Salinger, M.J.; McGlone, M.S. (1990): New Zealand climate-the past two million years. In New Zealand Climate Report 1990, pp 13-17. *Royal Society of New Zealand,* Wellington.

Shepherd, M.J. (1985): The origin of the Koputaroa dunes, Horowhenua , New Zealand. *New Zealand Journal of Geology and Geophysics,* vol 28, pp 323-327.

Shepherd, M.J.; Lees, C.M. (1987): Holocene alluviation and transgressive dune activity in the lower Manawatu, New Zealand. *New Zealand Journal of Geology and Geophysics,* vol 30, pp 175-187.

Shepherd, M.J.; Price, D.M. (1990): Thermoluminescence dating of late Quaternary dune sand, Manawatu/Horowhenua area, New Zealand: a comparison with ^{14}C age determinations. *New Zealand Journal of Geology and Geophysics,* vol 33, pp 535-539.

Story, R. (1982): Notes on Parabolic Dunes, Winds and Vegetation in Northern Australia. *Division of Water and Land Resources Technical Paper* No. 43.

Strahler, A.; Strahler, A. (1996): *Introducing Physical Geography.* John Wiley & Sons, INC., Brisbane.

Sturman, A.P.; Tapper, N.J. (1996): *The Weather and Climate of Australia and New Zealand.* Oxford University Press. Auckland.

Thompson, C.H. (1983): Development and weathering of large parabolic dune systems along the subtropical coast of Eastern Australia. *Zeitschrift fur Geomorphologie,* vol 45, pp 205-225.

Wilson, C.J.N. (1993): Stratigraphy, chronology, styles and dynamics of Late Quaternary eruptions from Taupo volcano, New Zealand. *Philosophical Transactions of the Royal Society London,* 343, 205-306.

Wolfe, S.A.; David, P.P. (1997): Parabolic Dunes: Examples from the Great Sand Hills, Southwestern Saskatchewan. *The Canadian Geographer,* vol 41, pp 207-213.

Appendix A: Documentation of Wind Data Analysis

Opening data from attachment

1) Open the attachment up in a word document. To do this, open a new word document, click on file then open. Click on all files and then click on the attachment. (E05231PH.LST)
2) Highlight the sections you want i.e. 1960-65
3) Edit, Copy
4) Open a new word document.
5) Paste the highlighted data into the new word document.
6) Save this new document as .txt (text only)
7) Close this document.
8) In Excel, open this document.
9) Select fixed width, click on next and insert any columns by clicking on the data in the appropriate place where you want your columns.
10) Click finish, and you will have the data you want on an excel spreadsheet.

Conversion of Raw Data to a Pivot Table

a) Creation of Speed Classes

Once the data is in an Excel Spreadsheet, there should be 6 columns.
Column A - Year
Column B - Month
Column C - Day
Column D - Hour
Column E - Direction
Column F - Speed

A column needs to be inserted between columns E and F. Selecting the top cell in column E, then "insert" and then select column can do this. Now the new column, column F, should be labelled Direction (rounded). This is needed because some of the raw data direction values are not factors of 10.

The formula to go in this column is =ROUND(E2,-1) where E2 is the cell that needs to be rounded.

Now Speed is in Column G.

Column H should be converted into a speed class column, where the speeds in Column G are grouped into different classes. These classes are 0-02m/s, 02-04m/s, 04-06m/s, 06-08m/s, 08-1 Om/s, 10-12m/s, 12-14m/s and so on.

To convert the speeds in to the appropriate classes an IF function must be used.

=IF(G2<2,"0-02",IF(G2<4,"02-04",IF(G2<6,"04-06",IF(G2<8,"06-08",IF(G2<10,"08-10",IF(G2<12,"10-12",IF(G2<14,"12-14",IF(G2<16,"14-16",))))))))

What this formula is saying is that If the cell G2 (those cells in column G) is less than or equal to 2, then we will call it 0-02, and if G2 is less than or equal to 4, then we will call it 02- 04 and so on. It is important that those new values that we want to enter into the spreadsheet have "" around them, i.e. the "0-02" and "02-04" have speech marks around them. It is also important that the correct number of brackets is inserted at the end of the formula.

A downfall with the IF Function is that only seven commands may be used. Therefore the example above cannot be extended to include values less than 18 and higher. To overcome this problem a nested IF Function must be used. A nested IF Function is a formula, which asks that values already given by the previous IF Function remain the same and then expands the previous IF Function to account for higher values. Therefore 5 or 6 higher categories may be included, until all of the seven commands have been used up.

The nested IF Function should be set up in column I, and it should be labelled 2nd Spd Class. The specific IF Function that was used in this analysis looked like this:

=IF(G2<16,H2,IF(G2<18,"16-18",IF(G2<20,"18-20",IF(G2<22,"20-22",IF(G2<24,"22-24",IF(G2<30,"24-26"))))))

This says that if the value in cell G2 (speed) is less than or equal to 16, let it remain what it was previously, i.e. keep it the same as what it is in cell H2. The formula then goes on to say that if G2 is less than 18, then put it in the speed class 16-18 and so on. Note that H2 does not have speech marks around it. This is important, if you wrote "H2", H2 would literally appear in the cell and not the value contained in H2.

Once the formulas have been set up in the first row of the column they may be applied to the rest of the data by dragging the little black square (located at the bottom right hand corner of the cell) down to the bottom of the spreadsheet. A quick way to do this is drag over a few rows and then scroll down to the bottom of the spreadsheet, hold down the shift key and then left click with the mouse on the very last cell where the formula is to be applied. Then push control D or go to edit on the tool bar, then fill and down.

b) Sorting the Data

i)

Within this data from NIWA there are speed values for directions of 0 degrees as well as 360 degrees, therefore for this analysis the 0 degrees values need to be deleted, as they are known as calms, as all of the values seem to be accompanied by 0 m/s. The calms have been accounted for in the WR plot wind rose.

The 0 degrees values are deleted by the following steps:

1) Highlight all data
2) Go to data on the tool bar
3) Click on sort
4) Sort first by Direction (DIR), and secondly by speed.
5) Highlight all of the data that has 0 degrees values in the direction column and delete them.
6) Then go to Edit on the tool bar, select delete and then select move cells up. This will delete the area where the 0 degrees data was and now the data of 10 degrees values should be at the top of the spreadsheet.

ii)

Included in the data are also 990-degree directions. These represent where the winds are light and variable and speeds are under 1m/s. In very light wind conditions, the anemometer vane may move through a full 360 degrees making it impossible to mean the direction so 990 degrees is used.

In this analysis all speeds at a direction of 990 degrees were deleted. At this stage the data has already been sorted by direction and then speed, so all that needs to be done to remove the

990-degree directions is to highlight all data with such a direction, (they will be found at the bottom of the spreadsheet) and then delete them.

A further step is to be carried out, this is not for the purpose of the Pivot Table, but it is to be used in the calculation of the Drift Potential. We need to find the average wind velocity in each speed class. This is done for classes 06 and above, i.e. all those that are above the critical velocity. To do this the following steps must be taken;

1) Highlight all of the data
2) Go to Data, Sort, then sort by Speed and then by Direction (DIR)
3) At the bottom of the pivot table, enter speed class labels in column F, (the Direction rounded column). These speed class labels are:

06-08
08-10
10-12
12-14
14-16
16-18
18-20
20-22
22-24
24-26

4) Now in column G, next to the speed class 06-08, highlight the cell. Then press the sum button on the tool bar, it looks like £ it is the SUM function. Then in column G find all the speed values that fall into the category 06-08, highlight them with the mouse. The border that surrounds them if you have selected them correctly should be black and white and it should be moving around the selected cells.
5) Before entering, take note of the little yellow box this tells you the number of rows and the number of columns you have selected. When you have all the data that you want within the black and white moving border, write down the number of rows that you have highlighted (from the yellow box). Note though, as soon as you take you finger off the mouse it will disappear. To get the box to reappear all you need to do is hold down the shift key and click with the left mouse button on the selected cells.

6) Now once you have the sum of all the wind velocities in the cell next to the speed class 06-08, all that you need to do is to divide by the number of velocities that there were in that class, (i.e. the number of rows stated in the yellow box) The formula should then look similar to this: =SUM(G312:G401)/90, this formula is saying that it added up all the cells from G312 to G401 and divided by 90 (the number of values that there were).

7) Make sure that you self check to make sure all of the values look alright, that is that they are within the limits of the category and that are approximately somewhere in the middle. An example:

06-08	6.81784
08-10	8.865487
10-12	10.73834
12-14	12.94969
14-16	14.97515
16-18	16.6442
18-20	0

8) Now these averaged values will be used in the calculation of the Drift Potential, described later on in this description.

c) Creating a Pivot Table Now that the raw data has been edited, we can create a Pivot table.

1) Select all *(excluding the average wind velocities located at the bottom of the sheet)*
2) Go to Data on the tool bar
3) Click on Pivot Table/Report
4) Work through the wizard.

Step 1 - click next
Step 2 - click next, the range has already been selected
Step 3 - click on layout, which will bring up another window where the following can be done;

In this step the format of the pivot table has to be created. Pull DIR(round) from the right and place in on the left vertical column on the table. Similarly pull 2^{nd} Spd Class from the right and place in on the top horizontal row on the table. Lastly pull 2^{nd} spd class once again and place it in the centre of the table, it should automatically show up as count of spd class. We need to change this, as we want the data in the form of % of total. This is done by double clicking in the 2^{nd} spd class in the centre, a "pivot table field" window should show up. Select options and then select"% of total" found under the heading "show data as;". Step 4 - Select where you want the pivot table, and click finish.

Note that once a pivot table is created the only way to alter it is to alter the actual data that was used to create it in the first place. Once the actual data has been altered the refresh icon must be clicked on the pivot table so it itself is altered.

Creating Rose Diagrams on Excel

Once a pivot table has been created a rose diagram may be produced.

1) Highlight all data in the pivot table, excluding the totals and grand total.
2) Click on chart wizard in the tool bar
3) Select Radar, then select filled radar
4) Work through the 4 steps, to get the specifications correct.

Creating Rose Diagrams on WRPlot

The data from Niwa came in six columns labelled A-F, (as described above). This data must now be manipulated so it can be used in the WRPlot programme.

Several things must be done

1) Convert years to only the last two figures. That is 1982 should be 82 and so on. Insert a column between columns A and B.
Use IF function in the new column B. e.g.

=IF(A2=1968,"68",IF(A2=1969,"69",IF(A2=1970,"70",IF(A2=1971,"71",IF(A2=1972,"72",I F(A 2=1973,"73",IF(A2=1974,"74")))))))

2) Convert directions so they also only appear as two figures. That is 350 degrees should read 35. This can be done by using another Rounding function =ROUND(A2/10,0) This is done in column G.

3) Convert Wind speed from meters per second to knots. This is done by a Rounding function namely =ROUND(H2*1.9425,0). Done in column I.

So in summary the spreadsheet should have the following columns:

Column A: Year
Column B: years reduced to last 2 digits
Column C: Month
Column D: Day
Column E: Hour
Column F: DIR
Column G: direction reduced to last 2 digits
Column H: Speed
Column I: Speed (kts)

4) Once all this has been done, the CONCATENATE Function must be used in Excel, this puts all of the data into one cell so that it can be easily saved as a txt file. This formula should be set up in column K. An example of the concatenate function is as follows; =CONCATENATE(12345,TEXT(B2,"00"),TEXT(C2,"00"),TEXT(D2,"00"),TEXT(E2,"00"), 999, TEXT(G2,"00"),TEXT(I2,"000"),999,99,99)

The concatenate function reads the Columns as follows;

Element	Columns
NWS Surface Station Number	1-5
Year	6-7
Month	8-9
Day	10-11
Hour	12-13
Ceiling Height (Hundreds of Feet)	14-16 <
Wind Direction (Tens of Degrees)	17-18
Wind Speed (Knots)	19-21 <
Dry Bulb Temperature (Degrees Fahrenheit)	22-24 <
Total Cloud Cover (Tens of Percent)	25-26 <
Opaque Cloud Cover (Tens of Percent)	27-28 <

5) Now the entire spreadsheet can be filled by dragging the top cell (the one with the formula) downwards by the little black square in the bottom right hand corner. Or alternatively highlight several of the top cells in the column, then scroll down to the bottom of the spreadsheet hold down the shift key and click the left mouse button simultaneously in the very last cell at the bottom of the column. Then go to Edit on the tool bar then "fill" and "Down", the shortcut for this is to just press control and D.

6) The next step is to sort the data. Highlight the whole spreadsheet, go to Data on the toolbar then select sort. Sort by Direction and then by speed.

7) Delete all data with 990 degrees directions, again these will be located at the bottom of the spreadsheet.

8) Highlight the whole of column K. This is the data that we use in the WR Plot programme. Copy it (ctrl.C) then open a new document, go to Edit, "paste special" and then select values. This will paste the data into the new document. Save this document as its date then type after it inci calms, e.g. 1.2.82-3.5.85 incl.calms.xls. This is done because this data is used to find the % calms in that period.

9) Next save it the same document as a text file. Go to save as, then in the list under "save as type:" select text (tab delimited), e.g. 1.2.82-3.5.85 incl.calms.txt. Two windows will appear after this has been done, click ok or yes to both of them.

10) Finally save again as a .dat file. This is easily done by again going to save as;, then simply typing .dat at the end of the file name.
So it should look like this; 1.2.82-3.5.82 incl.calms.txt.dat

11) Now repeat the above steps, but only highlight part of column K. Here we leave out all the data that has a direction of 0 degrees. Copy and paste this data into a new document. Then save it the same way as before. First as an excel document .xls, then text .txt and lastly .dat

The file name I used for this section of data was i.e. 1.2.82-3.5.85 concate.xis etc.

12) Now close these documents, and select no when asked if you want to save changes.

13) Open WR Plot. It should come up in the Met Data Information area. Here select File, then go and find the concatenated files that were saved. Firstly open the incl.calms file. Open the txt file, not the .dat or .xls file. You may need to change the files of type to "all files".

14) Once this has opened, write down the values that appear in the Data File Info Box. Namely the Average Wind Speed and Calm Winds Frequency.

15) Open up the Pivot table that correlates to the same period. With the pivot table, go to the top left hand corner where the 3 grey sections are. Click the right mouse button here, then go to the wizard, layout, double click on 2nd spd class in the middle section, go to options and then under summarise by, select count, then show data as normal.

16) Back on the WR Plot programme, select the frequency count tab, the total values should be the same as the total values found at the bottom of the pivot table. Make sure that the wind classes are correct, for this they should be the same as the pivot table i.e. 0-2, 2-4, 4-6 etc. The classes can be modified by going to utilities on the tool bar and modify wind classes. A new window should appear, in here change the values to 0.1,2,4,6,8,10 respectively. Then click ok.

This is purely a checking procedure. Now go back to the Met Data Information area, highlight the Data file and click remove.

17) Next open up the concate.txt file of the same time period. The Ave wind speed value should be the same as before but the Calm Winds Frequency should read 0%. Compare the values under the frequency count tab with the pivot table. Now change the pivot table by going to the wizard again, then layout, double click on the centre as before, go to options then % of total. Now compare values in the Frequency Distribution Tab with the new % values in the pivot table. Note the values in the WR Plot need to be multiplied by 100 for them to be the same.

18) Now that we have checked that all the data is correct, change the wind classes to 0.1, 3,6,9,12,15. Then go to the wind rose tab, and zoom in and out until it suits. For all of my wind roses I set the outer ring to 30% (Done by zooming in or out). Now go to print. Add a title and then click the disk icon. Save as .emf file.

19) Close WR Plot and open Adobe Illustrator 9.0. And perform the following steps;

1) File open, then open the .emffile.
2) Once opened, select all by "ctrl A"
3) Go to Object on the tools bar, then transform and then scale
4) Scale the object to 9%
5) Click outside the page so the object is unselected
6) Choose the white filled arrow from the bar on the left.
7) With this arrow draw a rectangle around the wind rose only,(to do this click the mouse outside the page to deselect everything first) leave out the key and title and try not to get any boarder or normal lines.
8) Copy, "Ctrl C" open a new document, press ok to the window that comes up. Then paste, "ctrl V".
9) Go to View on the tool bar and "Show grid"
10) Move the wind rose with the black arrow, so that there are 4 small squares on either side of it, and it is 3.6 big squares up from the bottom of the page.
11) Use the white arrow to highlight things you don't want and press delete.
12) Go back to the original document (by going to window on the tool bar and then selecting the appropriate document), select the Key with the white arrow and copy and paste as before. Locate the Key, 4 small squares from the left hand side of the page and 1.1 big squares up from the bottom of the page. Again use the white arrow to remove items that are not wanted.
13) Type a in a Title by using the T icon on the left tool bar.
14) Save the document
15) NB: you can zoom in and out by pressing ctrl and either + or -.

Calculation of Drift Potential (Dp)

The calculation of the Drift Potential is the preliminary step to determining the Resultant Drift Potential (RDP) and the Resultant Drift Direction (RDD).

This calculation comes from Fryberger Method it is used to derive weighting factors, these weighting factors represent the relative rates at which winds of differing average velocities can move sand (Fryberger), it is set out in the table below.
For each direction in factors of 10 degrees, the total Dp is calculated after performing several steps. The first of which is finding the average wind velocity in m/s for each

speed class. Sometimes just the middle value is used, i.e. in the speed class 6-8 the average value used would be 7m/s. I found the value using a different method, which was described previously under the title "Conversion of Raw Data to Pivot Table", part b, (ii).

The values calculated in that section are the values that are now entered into the V(m/s) column (column C). It is easy enough to just copy and paste them into the spreadsheet. Note however that you must you paste special. Which is found under the edit column on the tool bar, select paste special then select values. Otherwise

#REF! will appear in the cell.

The entire spreadsheet is made so that as soon as these values are pasted in, they will automatically be pasted down the spreadsheet for each direction.

There are also formulas entered into columns D, E and F. So that the spreadsheet will automatically square the mean values V^2 in column D, take the critical velocity (Y() which is 6m/s, away from the average velocity (V) in column E and lastly in column F, the V^2 is factor. The reason that the value of $V^2(V-V_t)$ is divided by 100 is to reduce weighting factors for the convenience in plotting sand roses etc.

Below is an example of the calculation of the weighting factors;

A	B	C	D	E	F	G	H
	spdclass	V(m/s)	V^2	V-Vt	V^2*(v-vt)/100	t	DP
10							
	6-8	6.7856	46.04437	0.7856	0.36172455	0.33	0.119369
	8-10	8.895589	79.04437	2.895589	2.291323734	0	0
	10-12	10.8100636	116.8596	4.810164	5.621139805	0	0
	12-14	12.95506667	167.8338	6.955067	11.67294936	0	0
	14-16	14.4136	207.7519	8.4136	17.47941091	0	0
	16-18	0	0	-6	0	0	0
	18-20	0	0	-6	0	0	0
	20-22	0	0	-6	0	0	0
	22-24	0	0	-6	0	0	0
	24-26	0	0	-6	0	0	0
				Total DP=		0.119369	

And an example of the specific formulas used to derive these values.

A	B	C	D	E	F	G	H
	spdclass	V(m/s)	V^2	V-Vt	V^2*(v-vt)/100	t	DP
10							
	6-8	6.7856	=+C3^2	=+C3-6	=+D3*E3/100	0.33	=F3*G3
	8-10	8.895589	=+C4^2	=+C4-6	=+D4*E4/100	0	=F4*G4
	10-12	10.8100636	=+C5^2	=+C5-6	=+D5*E5/100	0	=F5*G5
	12-14	12.95506667	=+C6^2	=+C6-6	=+D6*E6/100	0	=F6*G6
	14-16	14.4136	=+C7^2	=+C7-6	=+D7*E7/100	0	=F7*G7
	16-18	0	=+C8^2	=+C8-6	=+D8*E8/100	0	=F8*G8
	18-20	0	=+C9^2	=+C9-6	=+D9*E9/100	0	=F9*G9
	20-22	0	=+C10^2	=+C10-6	=+D10*E10/100	0	=F10*G10
	22-24	0	=+C11^2	=+C11-6	=+D11*E11/100	0	=F11*G11
	24-26	0	=+C12^2	=+C12-6	=+D12*E12/100	0	F12*G12
				Total DP=		=SUM(H3:H12)	

The next step is to multiply the weighting factor for each speed class (column F) by the percentage occurrence of wind in that category. This is done on the spreadsheet by entering the percentage occurrence of wind in the 't' column. These values come from the pivot table (percentage frequency). Below is a copy of part of the specific pivot table used in the above Dp calculation. You can see that the 0.33% in the 10 degree / 06-08 class was used and placed in the Dp calculation in the 10 degree section within the 06-08 category.

Count of 2nd spd class	2nd spd class		
DIR(round)	0-02 02-04 04-06	06-08 08-10 10-12 12-14 14-16	Grand
10	1.48% 3.29% 0.66%	0.33% 0.00% 0.00% 0.00% 0.00%	5.76%
20	0.33% 3.95% 0.82%	0.00% 0.00% 0.00% 0.00% 0.00%	5.10%
30	0.16% 1.81% 0.49%	0.00% 0.00% 0.00% 0.00% 0.00%	2.47%
40	0.00% 0.82% 0.66%	0.16% 0.00% 0.00% 0.00% 0.00%	1.64%

You can also see that nothing would be entered in the 't' column for 20 or 30 degrees, but 0.16 would be added in the 't' column for 40 degrees.

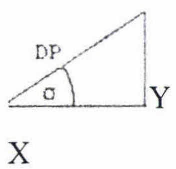
After entering these values the Drift Potential for each of the directions are found. The Drift Potential is the sum of the values in column H.

In the spreadsheet the DP values will then automatically be entered in the RDD/RDP calculation table.

Resultant Drift Potential (RDP), and Resultant Drift Direction (RDD).

The fundamentals behind these calculations are as follows;

The cos and sin rule is used, where the DP is the hypotenuse and you solve for X and Y respectively. Once the values of X and Y are found, the value of the angle sigma can be determined, this angle is in fact the RDD, the Resultant Drift Direction.



That is, cos σ= X/DP (adjacent over hypotenuse) and therefore once rearranged

X = DP * cos σ

Sin σ = Y/DP (opposite over hypotenuse) and then rearranging gives Y = DP * sin σ.

Then once the values of sin σ, cos σ and Drift Potential (DP) are found, they can be plugged into the formula and hence by taking the inverse of cos you can find **X,** and by taking the inverse of sin you can find Y.

The spreadsheet for the calculation is set out in 7 columns

Column C - Direction

Column D - Drift Potential (values being transferred from the workings at the top of the spreadsheet)

Column E - Cos

Column F - Dp*Cos

Column G - Sin

Column H - Dp*Sin

Column I - Dp*10

C	D	E	F	G	H	I
		RDP AND RDD CALCULATION				
		X		Y		
Direction	DP	COS	DP*COS	SIN	DP*SIN	DP*10
10	0.119369	0.984808	0.117556	0.173648	0.020728	1.1937
20	0	0.939693	0	0.34202	0	0.0000
30	0	0.866025	0	0.5	0	0.0000
40	0.057876	0.766044	0.044336	0.642788	0.037202	0.5788

The Cos values in column E have been calculated by converting the degrees in column C to radians by multiplying the number of degrees by Pi/180 and then taking Cos of this function. Similarly the Sin values in Column G are calculated in the same way, firstly by converting the degrees in column C to radians (multiply by Pi/180) and then taking the Sin of this value. The actual formulas which are used in the spreadsheet are: column E =COS(C501*PI()/180) and column G =SIN(C501 *PI()/180).

In columns F and H, the DP is multiplied by the values found in columns E and G respectively. The formula looks like this; =+D501*E501 in column F and like this =+D501*G501 in column H. This then gives us the X and Y values.

An example of the formulas of the above portion would appear like this;

C	**D**	**E**	**F**	**G**	**H**	**I**
		RDP AND RDD CALCULATION				
		X		**Y**		
Direction	DP	COS	DP*COS	SIN	DP*SIN	DP*10
10	=+G15	=COS(C501*PI()/180)	=+D501*E501	=SIN(C501*P1()/180)	=+D501*G501	=D

501*10

20=+G28=COS(C502*PI()/180)=+D502*E502=SIN(C502*P1()/180)=+D502*G502=D

502*10

30=+G41=COS(C503*PI()/180)=+D503*E503=SIN(C503*P1()/180)=+D503*G503=D

503*10

40=+G54=COS(C504*PI()/180)=+D504*E504=SIN(C504*PI()/180)=+D504*G504=D5

04*10

At the bottom of the RDD and RDP Calculation sheet there are formulas which calculate Total Dp', Total X' and "Total Y', 'Ave X' and 'Ave Y', RDP, RDP/DP and RDD.

	C	D	E	F	G	H	I
538	SUM	75.26490354		0.11562283		-23.2129246	752.6490
539	AVERAGE			0.00321175		-0.64480346	
540							
541	RDP=	23.21321252					
542							
543	RDP/DP=	0.308420146					
544							
545	RDD=	271.5658154					
546		-1.5658154	-89.714614				

Total Dp, is just the sum of all Dp's in column D. Formula: =SUM(D501 :D536) Total X is found at the bottom of column F (F538). Formula: =SUM(F501:F536)
Total Y is found at the bottom of column H (H538). Formula: =SUM(H501:H536)
Ave X is in cell below Total X (F539). Formula:
=+AVERAGE(F501:F536)
Ave Y is in cell below Total Y (H539). Formula: =+AVERAGE(H501
:H536) Note that in column I, is just Dp multiplied by 10.

	C	D	E
538	SUM	=SUM(D501:D536)	
539	AVERAGE		

540			
541	RDP=	=+SQRT((F538^2)+(H538^2))	
542			
543	RDP/DP=	=D541/D538	
544			
545	RDD=	=270-(+ATAN(H539/F539))	
546		=(+ATAN(H539/F539))	=D546*180/PI()

RDP, RDP/DP and RDD are calculated nearer to the bottom to the left. A sample of these formulas are shown above.
The RDP formula is Pythagoras. The total value of X is squared and added to the total squared value of Y. The square root is then taken to give the magnitude of the hypotenuse, and thus the value of the RDP

The RDP/DP is simple, just the RDP already calculated divided by the total Dp.

And lastly the RDD is the sigma angle. The formula shown in the table above is rather complex. It came from Hiams example. It is again using trigonometry. Tan a =Y/X (opposite over adjacent). Here the average value of Y is divided by the average value of X, and the inverse tan is taken. This is the same as arctan. In this calculation the resultant value is taken from 270 degrees, we never did find out why Hiam did this, it had something to do with the relativity of the compass.

In cell D546 gives the arctan value without it being taken from 270 degrees, the value, which excel gives in this cell, is in radians and hence in E546 the value is converted to degrees. Thus we finally have the value of the RDD.

Note that Excel works these calculations out the same as if you calculator was in RAD mode. Therefore if you were to check you calculations on your calculator, if it was in RAD mode the answer you should get when dividing Ave. Y by Ave. X and taking inverse tan, should give the same answer as you get in cell D546.

If your calculator is in DEG mode, the answer you get from the same calculation should match the final answer in cell E546.

Note also that it is indifferent when calculating the RDD, whether you use the Average X and Y values or the Total X and Y values.

The last issue to deal with here is to interpret the RDD.
If the RDD is positive, you measure the value clockwise from North (0°),
If the RDD is negative, you measure the value anticlockwise from South (180°)

There are four possible examples, this is because the RDD may reside in any of the four quadrants of the compass.

Note in each case the angle **pb** is equal to the RDD

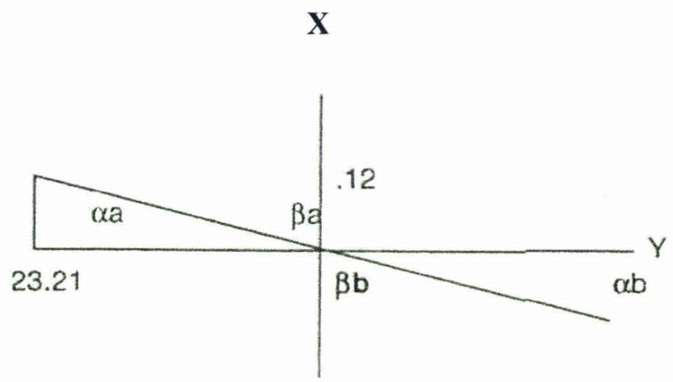
Examples:

1)

Total X=.1156

Total Y=-23.2129

RDD =-89.7146



tan σ = X/Y

tan σ =.1165/-23.2129

σ = -0.2875

P = -90 - σ

-90 - -0.2875 = -89.7124

Here RDD is measured anti clockwise from South (180°), **βb**

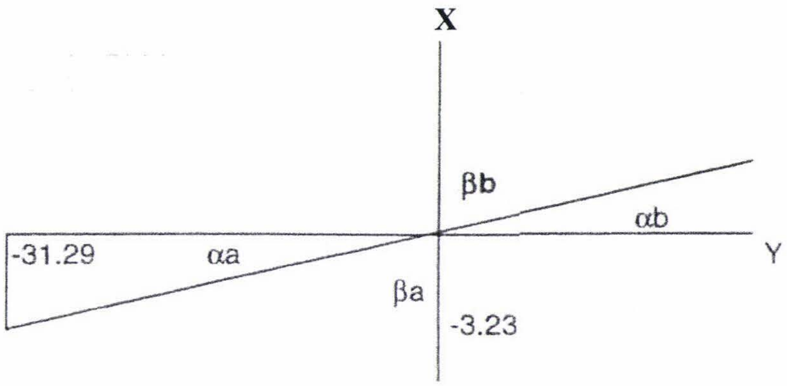
Alternatively;

2)

Total X = -3.2331

Total Y = -31.2906

RDD = 84.10



tan σ = X/Y

tan σ =-3.2331/-31.2906

σ = 5.8992

β = 90 - σ

90-5.8992=84.10

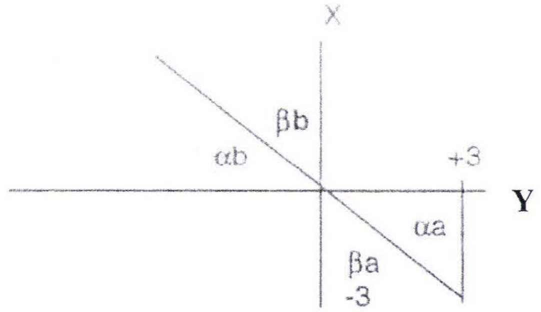
Here RDD is measured clockwise from North (0°), **βb**

NB: For the following two examples the values are made up, as we never had an RDD in these last two quadrants.

3)

Total X = -3

Total Y = +3



$\tan \sigma = X/Y$

$\tan \sigma = -3/3$

$\sigma = -45$

$\beta = -90 - \sigma$

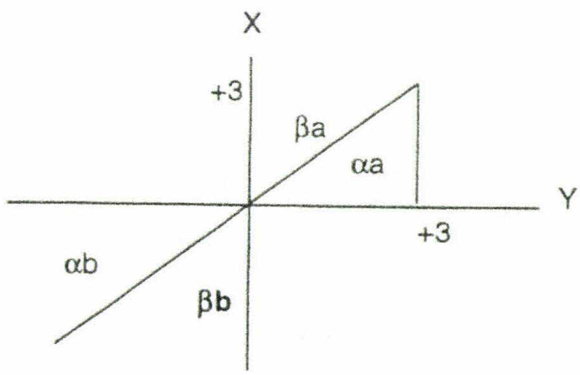
$-90 - -45 = -45$

Here RDD is measured anti clockwise from North (0°), β**b**

4)

Total X = +3

Total Y = +3



$\tan \sigma = X/Y$

$\tan \sigma = +3/+3$

$\sigma = 45$

$\beta = 90 - \sigma$

$90 - 45 = 45$

Here RDD is measured clockwise from South (180°), β**b**

Note: If RDD is negative p = -90 - σ, and it is measured anti clockwise

If RDD is positive p = 90 - σ, and it is measured clockwise

Creating Sand Roses

To create sand roses for this data, we use Corel Draw.

The data used to create the roses comes directly from the RDD and RDP calculation table, as the rose is just a pictorial view of the Dp's at each direction. The RDP is also featured extending to the correct length and correct direction (RDD).

1) Open new graphic in Corel Draw.

2) Draw a line to any length, keeping it straight by holding down the control key whist moving the mouse. (Note the Line tool is 4th down on the tool bar to the right of the screen.)

3) To the right of the screen select the "transformation tab", select position and then enter some number. I used 50 for horizontal (H) as well as 50 for vertical (V). Whatever values you use make sure that you use the same ones though out the entire process.

4) Hit Apply

5) Find your line again. This is done easiest by using the Zoom Function. It is located on the left hand tool bar, 3rd down. Use the Zoom out to find your line. NB. When using the Zoom In, click the icon, and then point you mouse at the area you want to zoom in on and click.

6) Once the line is found, zoom in on it

7) Now we will set it to its appropriate length. Make sure that it is selected, next go to the Size Icon on the right hand side. Horizontal should always be zero, if it is not it means that you didn't hold down the control key when originally drawing the line. Enter a value into the Vertical box. This value should be the DP for 10 degrees, if there is no DP value for the10 degrees category, enter the next DP value.

8) Press Apply.

9) Next make a Duplicate of the line. To do this make sure the line has been selected with the arrow, and the press Ctrl D.

10) Now move the Duplicated line so it fits over the original line. This is down by holding down Ctrl and moving it with the arrow keys.

11) Next we need to rotate the duplicated line to the correct position. Make sure that the line is selected, click again on the centre x so that arrows appear around the line. You need to move the little circle (which indicates the point of rotation (POI)) to where the point of rotation is to be. In this case we want the POI to be at the bottom of the Line. This can be dragged down with the mouse whist holding down the Ctrl key.

12) Next go to the Rotation Arrow under the Transformation tab and enter in the amount you want it to be rotated. Here you have to be careful, if you just type in 10 it will rotate it to 350 (compass position). Therefore you need to type in 350 if you want it to rotate to the 10 degree position. Therefore for a 20 degree position you need to type in 340 etc. Once the value is typed in press apply to duplicate.

13) Now you will be left with two lines, one at North and one at ten degrees. Now we need to add more lines. This is done by:

i) Selecting the north line (with black arrow)

ii) Duplicating it (ctrl D)

iii) Bringing the duplicate back so it is directly on top of the original (ctrl and arrows)

iv) Setting the duplicate to the correct length (Make sure when you set the length that in size box the bottom middle portion of the square is selected this make sure that the line is stretched only upwards.

v) Rotating the line

14) Once you have worked your way around back to north, you should be left with your original line. This line is turned into the RDP. Therefore don't duplicate it, just set it to the correct length, in the case of the example above it would be 23.21.

15) Now the hard part is to get the rotation correct. The RDD here is -89.71. This means it should be measured anti clockwise from 180 degrees (South).

16) Thus this is 180- 89.71 = 90.29 i.e. the angle is 90.29 degrees from North (clockwise) Now to get Corel Draw to put it on the correct angle you must take 90.29 away from 360. 360-90.29= 269.71. Thus type in 269.71 in the rotation box and hit apply.

17) Now the sand rose is complete. You may need to scale them if you want to print several out.

18) This is done by selecting the entire sand rose, (Ctrl A), Then go to 'Scale and Mirror' under the Transformations Tab, and alter the horizontal and vertical scales. I scaled them to 60%.

Creating Bar Graphs in Grapher

Highlight columns C and D in the "RDD and RDP Calculation Table" Make sure that the data you have copied encompasses all Directions from 10-360 and all their corresponding Dp's.

Copy and Paste them into a new worksheet in grapher.

Go to Graph on the tool bar, select new graph then bar graph.

This will automatically make a bar graph, however some alterations need to be made so that all the graphs are similar with the same axes etc.

TO CHANGE

1) X axis: Double click on the x-axis
2) A window entitled Graph 1- X axis 1 will appear
3) Make sure the tab is set to Axis. On the right hand side of the window there is Axis limits, unclick the tick in the Axis max box and replace the 400 with 360.
4) To the left hand side is a title box. Type the label for the X axis in here. You can change the font and size by clicking on editor. (In my graphs, I wrote "DIRECTION" in Aerial, size 14pt and bold.)
5) Double click on X axis again. Click the "tick marks" tab at the top of the window. In the "Major" box change spacings from 100 to 10.
6) Next go to the "Tick labels" tab. Change the angle to 45 deg. in the Major Tick Labels box.
7) Double click on Y axis, and enter another title. Here I put "DRIFT POTENTIAL", again in 14pt Aerial and Bold.
8) Change Axis Max to 120.
9) Select the entire Graph, go to Graph on the toolbar, and Graph Title. Here I just put the dates surrounding the periods of data in Bold Aerial, 20 pts.
10) Next I made the Graph fit the page, by dragging the graph.

Make sure that you save the worksheet, otherwise you will lose the graph!

<u>DB8 Stoss 12.11.01-20.3.02</u>

• Firstly the data had to be arranged into the correct format namely;

Year	Month	Day	Hour	Direction	Speed
2001	11	12	12.30	286	9.2

• Next the Hour and Direction data was altered.

The time can only have two digits from 00 to 23, thus the minutes must be rounded. In this case I rounded everything upwards. Thus 2.30 would become 3.00. The hour 24 was relabelled to hour zero.

For the analysis, the direction must be in multiples of 10. Therefore the function =ROUND(G3,-1) was used, this can do conversions of 286 to 290.

• The wind speed then was allocated into speed classes. See the other booklet for a more complete explanation (Pg.l).

The easiest way to do this is copy the formula from my excel spreadsheet straight into yours, and then drag and fill.

• All of the data was then highlighted and then sorted. This is done by going to Data on the tool bar. Sort, then sort by DIR then Wind Speed.

• Within the data there are directions of both 0 and 360. In all other data I have seen, the dates with a bearing of 0° were accompanied with Om/s. This is not the case here. Therefore dates with 0° bearings and a wind speed over Om/s must be combined with the 360° data. All the other data with 0° bearing and wind speeds of Om/s are to be deleted. These are known as calms and are accounted for in the WR Plot wind rose.

• Thus the 0° direction was replaced with 360° when the accompanied wind speeds were greater than Om/s. These directions were altered in the DIR(round) column. The entire spreadsheet was sorted again by DIR(round) then Speed and the calms were deleted.

• The spreadsheet now looks like;

Year	Month	Day	Hour	DIR	DIR(round)	Wind Speed	Spd Class	2nd spd class
2001	12	9	5	14	10	0.0	0-02	0-02

2001	12	9	3	11	10	0.1	0-02	0-02
2002	3	15	24	7	10	0.2	0-02	0-02
2001	11	25	6	12	10	0.4	0-02	0-02
2001	11	14	6	6	10	0.4	0-02	0-02
2001	11	17	20	15	10	0.4	0-02	0-02

• This takes us up to page 3 in the booklet. On the bottom of the spreadsheet there is the average wind velocity in each speed class. I have described the procedure to do this in the booklet.

• Note that there are some cases where there is overlap, as shown below where 2.0 is in both speed classes. However note that this is not incorrect it is just the rounding that has caused this. The first 2.0 actually is equal to 1.997 and the second 2.0 is equal to 2.002. (See Table below).

2002	2	10	23	185	180	2.0	0-02	0-02
2001	12	2	23	75	70	2.0	02-04	02-04
2002	1	9	8	189	190	2.0	02-04	02-04

• The next step is to create the pivot table, this is outlined in the booklet, I have copied that section and pasted it below.

c) Creating a Pivot Table

Now that the raw data has been edited, we can create a Pivot table.

1) Select all *(excluding the average wind velocities located at the bottom of the sheet)*
2) Go to Data on the tool bar
3) Click on Pivot Table/Report
4) Work through the wizard.
Step 1 - click next
Step 2 - click next, the range has already been selected
Step 3 - click on layout, which -will bring up another -window -where the following can be done;
Step 3 - In this step the format of the pivot table has to be created. Pull DIR(round) from the right and place in on the left vertical column on the table. Similarly pull 2nd Spd Class from the right and place in on the top horizontal row on the table. Lastly pull 2nd spd class once again and place it in the centre

of the table, it should automatically show up as count of spd class. We need to change this, as we want the data in the form of% of total. This is done by double clicking in the 2nd spd class in the centre, a "pivot table field" window should show up. Select options and then select"% of total" found under the heading "show data as;". Step 4 - Select where you want the pivot table, and click finish.

- Now the Pivot table can be used to calculate the Drift Potential. This is done by using the Drift Potential template (included).
- The outline to do this is on pg 7 of the booklet.
- The average velocity values, which were calculated before the pivot table was done (below) are pasted into the template, into column C.

06-08

08-10

10-12

12-14

14-16

16-18

18-20

20-22

22-24

24-26

26-28

28-34

7.00

9.02

10.95

12.95

14.97

16.96

18.96

20.80

22.89

24.92

26.93

29.19

Remember to use paste special, values to do this otherwise, #REF! Will appear in the cell.

So now you should have;

CALCULATION OF DP. RDP AND RDD

DBS Stoss 12.11.01-20.3.02

Direction spdclass	V(m/s)	V^2	V-Vt	V^2*(v-vt)/VlOO t	DP
10	7.0560279	49.78753	1.056028	0.52577	0
6-8	9.0205927	81.37109	3.020593	2.457889	0
8-10	10.9535190	119.9796	4.953519	5.943211	0
10-12	12.9547776	167.8263	6.954778	11.67194	0
12-14	14.9701288	224.1048	8.970129	20.10249	0
14-16	16.9649879	287.8108	10.96499	31.55842	0
16-18	18.9558065	359.3226	12.95581	46.55314	0
18-20	20.7971329	432.5207	14.79713	64.00067	0
20-22	22.8911111	524.003	16.89111	88.50992	0
22-24	24.9196226	620.9876	18.91962	117.4885	0
24-26	26.9275000	725.0903	20.9275	151.7433	0
26-28	29.1850000	851.7642	23.185	197.4815	0
28-34	TOTAL DP =				0

20

6-8	7.0560279	49.78753	1.056028	0.52577	0
8-10	9.0205927	81.37109	3.020593	2.457889	0
10-12	10.9535190	119.9796	4.953519	5.943211	0
12-14	12.9547776	167.8263	6.954778	11.67194	0

• Now open the pivot table, the values within it should be %frequency, as below. If not refer to page 4 (creating a pivot table)

DBS Stoss 12.11.01-20.3.02 Pivot Table. % Frequency

Count of 2nd spd class	2nd spd class								
DIR(round)	0-02	02-04	04-06	06-08	08-10	10-12	12-14	14-16	16-18
10	0.13%	0.10%	0.03%	0.12%	0.13%	0.22%	0.10%	0.13%	0.1
20	0.08%	0.08%	0.15%	0.08%	0.17%	0.15%	0.15%	0.15%	0.02
30	0.12%	0.05%	0.15%	0.15%	0.15%	0.15%	0.12%	0.15%	0.12
40	0.13%	0.15%	0.05%	0.12%	0.27%	0.30%	0.24%	0.27%	0.17

• These values must be transferred into the Drift Potential template. This does take some time, as each value must be typed in. Note that only values greater than 6m/s are used and that the figures in bold are the ones that were transferred for the first direction (10).

Direction	spdclass	V(m/s)	V^2	V-Vt	V^2*(v-vt)/100	t	DP
10							
	6-8	7.0560279	49.78753	1.056028	0.52577	0.12	0.06309
	8-10	9.0205927	81.37109	3.020593	2.457889	0.13	0.31952
	10-12	10.953519	119.9796	4.953519	5.943211	0.22	1.3075
	12-14	12.9547776	167.8263	6.954778	11.67194	0.1	1.16719
	14-16	14.9701288	224.1048	8.970129	20.10249	0.13	2.61332
	16-18	16.9649879	287.8108	10.96499	31.55842	0.1	3.15584
	18-20	18.9558065	359.3226	12.95581	46.55314	0	0
	20-22	20.7971329	432.5207	14.79713	64.00067	0	0
	22-24	22.8911111	524.003	16.89111	88.50992	0	0
	24-26	24.9196226	620.9876	18.91962	117.4885	0	0

	26-28	26.9275	725.0903	20.9275	151.7433	0	0
	28-34	29.185	851.7642	23.185	197.4815	0	0
				Total DP = 8.626484			
20							
	6-8	7.0560279	49.78753	1.056028	0.52577	0.08	0.04206
	8-10	9.0205927	81.37109	3.020593	2.457889	0.17	0.41784
	10-12	10.953519	119.9796	4.953519	5.943211	0.15	0.89148
	12-14	12.9547776	167.8263	6.954778	11.67194	0.15	1.75079

• When the entire pivot table has been transferred, the DP, RDP, RDP/DP and RDD can be found. These will be shown on the last page of the Dp template.

	C	D	E	F	G	H	I
604	SUM	1337.804		-169.434		-735.802	13378.0401
605	AVERAGE			-4.70649		-20.439	
606							
607	RDP=	755.0582					
608							
609	RDP/DP=	0.564401					
610							
611	RDD=	268.6555					
612		1.344471		77.0325			

• The most confusing bit here is the RDD.

> Cell D611 has the formula =270-(+ATAN(H605/F605)). It is trigonometry. Tan o =Y/X (opposite over adjacent). Here the average value ofY is divided by the average value ofX, and the inverse tan is taken. This is the same as arctan. In this calculation the resultant value is taken from 270 degrees, we never did find out why Hiam did this, it had something to do with the relativity of the compass. This value therefore should be ignored.

> Cell D612 gives the arctan value before it was taken away from 270 degrees. This value is in radians.

> **Cell E612** gives the value that we require, this is in degrees, and it is this value that is plotted on the sandrose.

> Pages 12 and 13 show how the RDD should be plotted depending on whether it is negative or positive and also on the nature of the Total X (Cell F604) and Total Y (Cell H604) values.

> Because in this case the RDD is 77.0325 (positive) and both Total X and Total Y are negative, the RDD should be measured clockwise from North.

- The sandroses can be created easily, by plotting the Dp's for each degree. To do this I used Corel Draw. There is a description of the procedure on page 14.

Windroses

The procedure on page 4 should be followed. The easiest way to do this is to get a copy of the raw data, ensuring that it is in the form of six columns;

A Year

B Month

C Day

D Hour

E Direction

F Speed

And then insert columns between columns A and B (Year and Month) and columns E and F (Direction and Speed). Then take my sample WRPlot spreadsheet and directly copy and paste the formulas and then drag and fill to complete the spreadsheet.

The formula to convert the year into two figures may need to be altered depending on the years your data is for, however this is easy see page 4.

Year		Month	Day	Hour	DIR		Wind Speed	speed (kts)
200101	11	17	20	0	0	0.0	0	1234501111720999000009999999
200101	11	18	23	0	0	0.0	0	1234501111823999000009999999
200101	11	18	23	0	0	0.0	0	1234501111823999000009999999
200101	11	19	21	0	0	0.0	0	1234501111921999000009999999

Finally you should end up with a format that is the same as above.

Note again that you must change any 0° directions, which have wind speeds greater than Om/s to 360° as we did for the pivot table. Once this is done the entire spreadsheet needs to be sorted by direction and then speed.

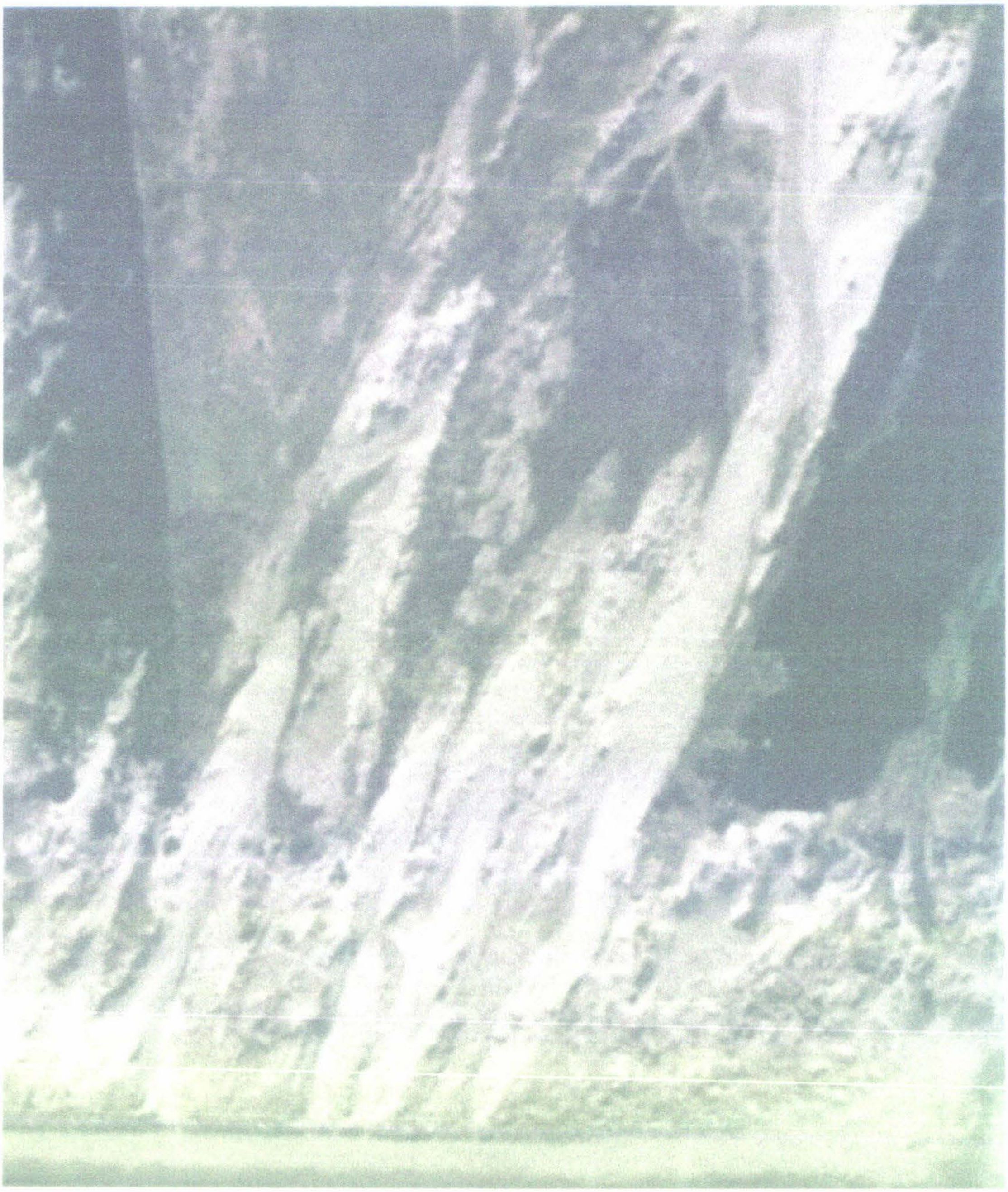
Get WRPlot Programme from the Website www.lakes-environmental.com

- On page 6 of the booklet, (part 16 and 17 of creating a windrose) I described a checking mechanism whereby the data from the pivot table is checked against the data in the WRPlot programme. Unfortunately with your data I was unable to get the numbers the same.
- The problem seems to lie in the first speed class. 0-02, it is these numbers that differ the most. What I think could be the problem is that your data has very low m/s readings, whereas all the other data I have analysed started at values of0.5m/s.
- In both the Pivot Table and the data for WRPlot I used only values corresponding to 1 knot or greater. Namely wind speeds 0.258 m/s and greater.
- Note also that the WRPlot programme counts data above 0.1 m/s.
- Another problem I have found, is the WRPlot program separates the data into only 16 direction classes, N, NNE, NE, ENE, etc. In excel I have used 10's of degrees ie. 10,20,30 - 360. Therefore when comparing the tables, the categories cannot be compared. However Note that the Grand total for both the Pivot table and the WRPlot count tables was 5700. Therefore there is some other kind of sorting been going on in the WRPlot programme, and I'm not sure what.
- The fortunate thing however is that the Drift Potential and hence the sandrose relies on speeds greater than 6m/s. The data with wind speeds greater than 6 m/s is consistent between the pivot tables and the WRPlot programme, thus the sandrose will be correct.
- With regard to the windrose, perhaps you could contact lakes environmental software www.lakes-environmental.com to enquire why the two count tables vary. info@weblakes.com However you could still compare the windrose that it produces with any other type of windrose that you already have.

Appendix B: Aerial Photographs of the Parabolic Dunes

Aerial photograph of the study site taken on 2nd July 1990

Aerial photograph of the study site taken on 21st July 1995



Aerial photograph of the study site taken in February/March 2000

Aerial photograph of the study site taken on 21st February 2002

Aerial photograph of the study site taken on 20th December 2002