THE LOCATION AND ORIENTATION OF COASTAL PARABOLIC SAND DUNES IN NEW ZEALAND

A thesis presented in partial fulfilment
of the requirements for the degree of
Master of Arts in Geography
at Massey University

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1989

ABSTRACT

No previous research into either the spatial diversity of different coastal sand dune types, or the factors influencing the location and morphology of any particular dune type has been done in New Zealand. Vertical aerial photographs were used to locate Holocene dunefields around the New Zealand coastline. The locations of dunefields in general and the spatial diversity of dune types are able to be explained by identifying the conditions most suitable for sand dune development and examining the spatial variation in these conditions.

One particular dune type, parabolic, was examined in more detail in order to discover the relative importance of different variables to the development of that dune type. The relationship between wind climate and the location and morphology of coastal parabolic sand dunes was examined in detail. Wind data from coastal sites around New Zealand were used to compute sand transport vectors using two methods - one proposed by Landsberg (1956) and the other by Fryberger (1979) - and these were compared with dune orientations obtained from aerial photographs. Although Fryberger's method has never previously been applied to coastal sand dunes, the two methods were found to produce very similar results.

Spatial variation of other aspects of dune morphology, such as the shape of parabolic dunes, were also compared to wind climate characteristics. Such comparisons were permitted by applying further calculations proposed by Fryberger which allow the directional variablity of wind to be expressed in exact terms.

The results of these studies indicate that morphological characteristics of parabolic sand dunes, such as orientation, shape and size, are largely controlled by the strength and frequency of onshore winds and the directional variability of winds. Sand transport resultants computed using the Fryberger method were found to be closely aligned to dune orientations in most cases.

This study provides some insight into the processes and variables affecting spatial variation of coastal sand dune development in New Zealand but also highlights the need for more detailed geomorphic studies of coastal dunefields in New Zealand.

ACKNOWLEDGEMENTS

I would like to express my gratitude to my supervisor Dr Mike Shepherd for all his help, advice and support during the completion of this dissertation. Thanks are also due to Val and Mooreen of the Map Shop at DOSLI in Wellington for the patience and friendliness they displayed during the weeks I spent in their company. I am also grateful for the accomodation provided for me in Wellington by Bill Ogier (and flatmates) and by Tom and Joan Ashworth.

Steve Reid of the N.Z. Meteorological Service and the farmers in the vicinity of Porangahau are thanked for their efforts to provide information used in this thesis.

Of the many people who offered words of comfort and encouragement, special thanks must be made to Richard Heerdegen, Geoff Duller, Dr Patrick Hesp, Professor Andrew Goudie, Professor John Flenley and Greer Robertson-Brown. Thanks also to Rachel, Helen and Glynnis for help with various technical matters.

This thesis is dedicated to my father, Robert Muckersie.

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CHAPTER 1

INTRODUCTION

While some coastal dune areas in New Zealand have been studied in considerable detail, little work has concentrated on the morphology of dunes or in mapping the distribution of various dune types throughout New Zealand. Dune areas that have been studied in depth have mainly been studied from a geological standpoint where the mineralogy and stratigraphy of dune sands have been the focus of research. Geological and topographical maps show areas of dune sand but do not specify dune type and rarely give an indication of the surface expression of the dune forms. Most morphological work that has been carried out has concentrated on dune areas on the west coast of the North Island, with some work having been done in a few other areas such as the east coast of Northland, the Bay of Plenty and Farewell Spit (see literature review below). Other dune areas, those along the coast of Westland and on the south coast of the South Island for example, appear to have attracted little attention, perhaps because of the less extensive nature of dune development in these places when compared to areas such as those in the Manawatu and Northland. Smaller dunefields, however, are the product of the same processes that have resulted in the development of larger dunefields and as such are also worthy of closer examination. Examination of spatial variation in dune morphology may allow the relative importance of different factors and processes affecting their development to be better understood. No previous studies have investigated the variation of either different dune types or variation in morphology of a single dune type around the New Zealand coastline.

AIMS AND SCOPE OF STUDY

This study has three main aims. The first is to determine the location of coastal parabolic dunefields in New Zealand. This is accomplished through the examination of vertical aerial photographs covering the entire coastline of the North and South Islands. The second aim is to determine whether existing methods for relating wind climate characteristics to resultant directions of sand drift can be applied in the study of coastal parabolic dune orientations in New Zealand. The third aim is to examine the spatial variation in dune location and dune type in relation to wind climate and other factors which influence dune development.

CHAPTER FORMAT

The following section of this chapter provides information about data and methods used in this study. The last section of Chapter 1 reviews literature relevant to the subjects examined in this dissertation. In Chapter 2 factors influencing coastal development in New Zealand are outlined and the distribution of coastal dunefields described. Chapter 3 looks specifically at aeolian processes and types of sand dunes formed by these processes. In Chapter 4 New Zealand's wind climate is described and methods of calculating net directions and relative values of sand transport from wind data are outlined. Wind data from a number of coastal sites around New Zealand are then analysed using these methods. In Chapter 5 the results of this analysis are discussed and in Chapter 6 the results are compared to seversl aspects of coastal sand dune morphology, particularly the orientation of parabolic dunes. Summary and conclusions follow in Chapter 7.

METHODS

USE OF AERIAL PHOTOGRAPHS

Vertical aerial photographs were used to locate and determine the orientation of parabolic dunes and blowouts of New Zealand's coastal areas. Photographs are ideally suited to provide this type of information because of the relatively small amount of time and low expense needed to examine large areas of land and because of the ease of making accurate measurements of dune size and orientation compared to undertaking the same exercise at ground level.

A collection of contact prints of all vertical aerial photographs of New Zealand, produced by New Zealand Aerial Mapping, is housed in the Map Shop of the Head Office of the Department of Survey and Land Information (DOSLI) in Wellington. A selection of photos covering most of the New Zealand coastline was chosen from this collection. These photos were usually of a scale of 1:25 000 but where coverage at this scale was unavailable, photos at 1:50 000 were used. Generally the most recent photographs were selected for study. For much of the Manawatu area photo mosaics (New Zealand Mosaic Map Series at a scale of 1:15 840), held at Massey University's Geography Department, were used in order to facilitate the mapping of such a large dune area. When areas of blowouts, parabolic dunes or linear ridges were observed, the photographs of the area were studied more closely and tracings of the dunes made. The orientations of the features were marked as lines on the tracings and later measured in degrees azimuth. Dunes were only traced if they had an obvious orientation with no attempt being made to guess the orientation of a dune with curved or irregular trailing arms.

Mean orientation values were computed for comparison with wind resultant directions. A mean value was calculated for each individual group of dunes (ie: if one cluster of dunes was seperated spatially from another group, for example in two adjacent bays, then two means were computed). If several clusters of dunes were found along a lengthy coastline of consistent/homogeneous/uniform shore alignment, one mean value was calculated for all the dunes. Separate means were also calculated for blowouts and established dunes located at the same site because of the possibility that the blowouts may have been very recent and the result of storm conditions only. In this case the orientation of the blowouts would be expected to reflect only the storm wind direction which may not coincide with the long-term wind resultant direction.

The orientations of the individual dunes were mapped as arrows (figs x - y). These arrows represent the orientation and approximate location of the dunes only and do not illustrate any other attribute of the dunes (such as size).

PROBLEMS WITH AERIAL PHOTOGRAPHS

The scale of aerial photographs can be a disadvantage when trying to discern smaller blowouts and dunes. For example, a blowout or parabolic dune of 50m to 100m in length may have an obvious orientation to a observer at ground level but the same feature would be barely detectable on a photograph with a scale of 1:50 000. This means that the number of orientations measured from the photos will not necessarily coincide with the number of dunes or blowouts with measurable orientations. Even larger dunes may be difficult to identify due to obscuring cloud (rare) or vegetation cover (a problem where exotic trees have been planted to halt movement of mobile dunes). Where parabolics are highly dissected or have non-linear trailing arms their orientation may not be discernible from a photo. Owing to the generally highly dissected nature of dunes of Pleistocene age or older, this study was restricted to examination of Holocene dunes only. The high reflectivity of dry sand means the details of blowouts can be difficult to discern so that orientations may be unclear and that blowouts may be similar in appearance to other small areas of bare sand such as those often found as paths widen near a beach. Dune lakes can also be mistaken for tongues of sand if sunlight is reflecting directly off the water. Most of these problems were solved or reduced by the use of a stereoscope but in some cases very low relief or high reflectance still caused some problems with interpretation of the photos.

SOURCES OF ERROR

There are several potential sources of error which may result in a mean orientation value differing from the real value. One which has already been mentioned is the possibility that not all dunes with measurable orientations have been represented. Finding exact grid north on photographs involved some uncertainty, particularly on long, smoothly curving coastlines which lacked reference points which could be located on maps. An error in placing north on a photo could lead to an error of up to perhaps two or three degrees in the orientation measurements. Orientations were measured to the nearest degree leading to rounding errors but these would be expected to have a negligble effect on the mean values. Observer bias is another possible source of error. A tendency to only notice dunes with orientations in the expected directions may have resulted in the exclusion of some extreme values, but hopefully this problem was minimal. Lack of experience in recognising geomorphic features from aerial photographs is more likely to have resulted in omission of some dunes. The final source of error lies in the determination of the orientation of the dunes. Deciding which way a dune is or was travelling from an image on an aerial photo requires some subjectivity so that the orientation values from two observers may not necessarily coincide. This is even true if a formula is used such as drawing a line between the mid-point between the ends of the two trailing arms and the nose of the dune because in reality these properties are not always easily defined.

WIND DATA

A request was made to S.J. Reid of the New Zealand Meteorological Service to supply wind rose data that would best describe wind conditions along large sections of the New Zealand coastline. Data from thirteen anemometer sites were subsequently supplied (see Appendicesfor details). None of these stations were located in Hawke Bay or in Canterbury so data for Napier and Christchurch were derived from Met. Service publications. Owing to the large area of sand dunes in the Rangitikei/Manawatu region, it was desirable to use wind data from a station more central to this area than those supplied by Reid. Although Ohakea is located some distance inland, it is not separated from the coast by any topographic barrier and so wind data from this location were deemed to be suitable for use in this study. A copy of these data is held by the Geography Department, Massey University.

Methods used to analyse the wind data are discussed in detail in Chapter 4 and therefore are not outlined at this point.

PROBLEMS WITH WIND DATA

The length of records for some of the stations used in this study are very short (see Appendix 1). The data for both Kaipara and Port Taharoa are from measurements taken over a period of less than two years. The brevity of this time means that it is very unlikely that this data accurately represents the average conditions at these locations. All the other stations provide measurements for five years or more but only two (Napier airport and Westport airport) are for the thirty years generally thought to be required to accurately assess climatic conditions. All anemometers are located on flat sites and most are not near to large vegetation or buildings (see Appendix 2) but the anemometer at Kaipara is located at South Head which is separated from the coastline by topography which reaches altitudes of over 500m. The presence of this higher ground must mean that the anemometer at South Head is not affected by the full force of onshore winds experienced at the coast less than 10 km away. The proximity of vegetation and buildings most affects wind characteristics at Farewell Spit, Tiwai Point, Ohakea and Westport airport (see Appendix 2).

Wind data from all stations are supplied for only eight compass directions except for the Ohakea data which is in the form of sixteen compass directions. The significance of this lack of precision is outlined in Chapter 6.

LITERATURE REVIEW

There exists a large body of literature relating to the development and morphology of sand dunes and dunefields around the world. Different aspects of dune research have included sand transport, sedimentology, morphology and relationships to wind regime, climate, climatic change and vegetation. In this section no attempt is made to summarise all of this material since adequate summaries are provided by other authors (e.g. Greeley and Iverson (1985) provide a synopsis of desert and coastal dune research, and Pye (1983c) and Goldsmith (1985) have written reviews of work on coastal sand dunes). Emphasis here is placed on the results of research relevant to processes affecting parabolic dune formation in coastal areas. These include processes which affect all sand dunes as well as those peculiar to the formation of coastal sand dunes. Literature relating specifically to studies of parabolic dune orientation and shape are of particular concern.

DUNES IN GENERAL

A considerable amount of research has concentrated on particular processes which affect dune development. Probably the most important works published on the physics of aeolian transport of sand are those by Bagnold (1941; 1979) although there are many other books and articles dealing with this subject (e.g. Johnson 1956; Warren 1979; Leeder 1982). Other work has been concerned with the interaction between sand dunes and airflow. Landsberg (1942) considered the modification of airflow over sand dunes while Olsson-Seffer (1908) was concerned specifically with wind induced movement of sand on dunes. Jungerius *et al* (1981) studied the development of active blowouts in the Netherlands and this research was used to produce a computer model based on the premise that wind gusts are of primary importance in the formation of blowouts (Jungerius 1984). An article by Malakouti *et al* (1978) examined the effects of the introduction of different types of vegetation to blowouts which tend to form on sandy rangeland in Nebraska.

COASTAL DUNES

Some work has focused on particular dune types found in coastal areas, e.g. Cooper (1958) provided detailed information on oblique and transverse ridges in Washington and Oregon, Borówka (1980) studied active barchans in Poland, and Hunter *et al* (1983) examined oblique sand dunes in Oregon, but often this type of research includes investigation of processes that are important to the development of any type of coastal dunefield.

Coastal dunes are the result of the interaction between a large number of processes which are often related in a complex manner. The attributes of coastal dunes in mid latitude swell wave environments and variables which affect their development have probably been studied to the greatest extent in Australia and New Zealand. In Australia Short and Hesp (1982) discussed the possible links between dune development and beach mode while Pye (1984) examined the connection between change in sea level and phases of transgressive dune activity. In New Zealand Gibb looked at the sources and movements of sediment (Gibb 1979a), as well as areas and rates of erosion and accretion (Gibb 1979b; Gibb 1984) around the New Zealand coastline. Studies of the development of the coastline of the Canterbury Bight (Kirk 1969), Kaitorete Spit (Armon 1973), Whatipu Beach, Auckland, (Williams 1977), between Timaru and Oamaru (Kirk 1979), the Bay of Plenty (Gibb 1977; Harray and Healy 1978; Healy 1980) and the Manawatu (Holland and Holland 1985), to name a few, have involved an examination of these factors at a smaller scale. Some studies of dune areas in New Zealand have concentrated on examining the mineralogy of the dune sands (eg: Schofield 1970; Yock 1973) while others have provided information regarding the types of vegetation found in dune areas (eg: Cockayne 1911; Esler 1979; Holland 1983a).

The morphology of coastal sand dunes in New Zealand has been examined mainly as a part of studies designed to identify phases of transgressive dune activity. Dune phases have been recognised on the Auckland west coast (Brothers 1954), in the Manawatu (Te Punga 1957; Cowie 1963), in the Northland and Auckland regions (Schofield 1975), in the Bay of Plenty (Pullar and Selby 1971), on the barrier at Kaipara Harbour (Schofield 1975; Richardson 1985), near Kawhia and Aotea Harbours (Pain 1976), on the Aupouri and Karikari Peninsulas (Hicks 1975; Hicks 1983) and on the 'Golden Coast' of Wellington (Wright 1988).

A number of papers have been published which describe efforts to stabilise mobile coastal sand dunes at various locations in New Zealand (Hocking 1964; Kear 1964; Restall 1964; Sexton 1964; Whitehead 1964; Wendelken 1974).

ORIENTATION OF PARABOLIC SAND DUNES

Parabolic sand dunes are widespread around the world but are found mainly in coastal areas. Those found at inland locations are often relict features that developed under paleoclimatic conditions. For example, dunes tended to form during the Pleistocene near the edges of ice sheets where there was a supply of sediment and limited vegetation cover. Some studies aim to interpret the characteristics of such dunes, including orientation, in order to identify climatic changes over time. Seppälä (1972), David (1981) and Filion (1987) found that the morphology and stratigraphy of parabolic dunes at inland locations in Sweden, Saskatchewan and Québec, respectively, implied a change in wind climate from the Pleistocene to the Holocene which related to the retreat of nearby ice sheets. Characteristics of coastal parabolics developed in the Pleistocene have also been used to estimate paleowind conditions (e.g. Martin and Nairn 1975).

The recognised importance of wind climate in the development of parabolic dunes is reflected in the many studies of parabolic dunefields around the world which have included comparison of dune orientation to some form of wind data. This has been done in articles about dunes in California (Cooper 1967), Pakistan (Verstappen 1968; Amal Kar 1987), Scotland (Ritchie 1972), Zululand (Orme 1973), Bermuda (Vacher 1973), northern Australia (Story 1982), the east coast of Australia (Pye 1982a; Pye 1983b; Thompson 1983; Pye and Rhodes 1985; Cook 1986; Ward and Grimes 1987) and in the Wanganui (Fleming) and Manawatu (Saunders 1968; Esler 1970; Holland 1983b) regions of New Zealand. In most of these articles the conclusion is that the parabolic dunes in the study area are orientated to either the 'prevailing' or 'dominant' wind direction. Few authors have distinguished between the different meanings of these two terms (see chapter 4) and this has lead to apparent inconsistancies between some articles written about the same areas (e.g. Saunders 1968 and Esler 1970).

More complex methods of analysing wind data for comparison with dune orientation were proposed by Shou (1952) and Landsberg (1956) who studied parabolic dunefields in Denmark and Britain. Jennings (1957) suggested an amendment to Landsberg's method as a result of his study of dunefields on King Island, Tasmania. These methods are outlined further in Chapter 4.

As was noted by Goldsmith (1985), in his detailed survey of global coastal dune research, Landsberg's method has not been applied in many investigations of dune areas. The few areas where the Landsberg method has been used include parabolic dunefields in Victoria (Bird 1965, as cited in Bird 1972), Virginia-North Carolina (Gutman 1977), Queensland (Pye 1982b; 1983a), and in the Kawhia Harbour (Pain 1976) and Manawatu (Shepherd 1987) areas of New Zealand. In some cases it has not been possible to use Landsberg's method owing to a lack of approporiate wind data (e.g. Verstappen 1968).

OTHER METHODS OF WIND DATA ANALYSIS

In his study of desert dune areas, Fryberger (1979) proposes a method of anaylsing wind data for comparison with desert dune type and orientation (for details of Fryberger's method see chapter 4). To the author's knowledge the method proposed by Fryberger has only been applied in one study of parabolic dunes. In this case, the research involved comparing dune bedding of cold-climate dunes in Colorado with wind data (Ahlbrandt and Andrews 1978). The author knows of no application of Fryberger's method to coastal dunes of any type.

CHAPTER 2

THE COASTAL SETTING AND LOCATION OF COASTAL DUNEFIELDS IN NEW ZEALAND

INTRODUCTION

The diagram below illustrates the main factors influencing the development of parabolic dunefields. This chapter takes a brief look at some of these factors (those in bold type) as they pertain to New Zealand (other factors in the diagram are discussed in Chapters 3 and 4).

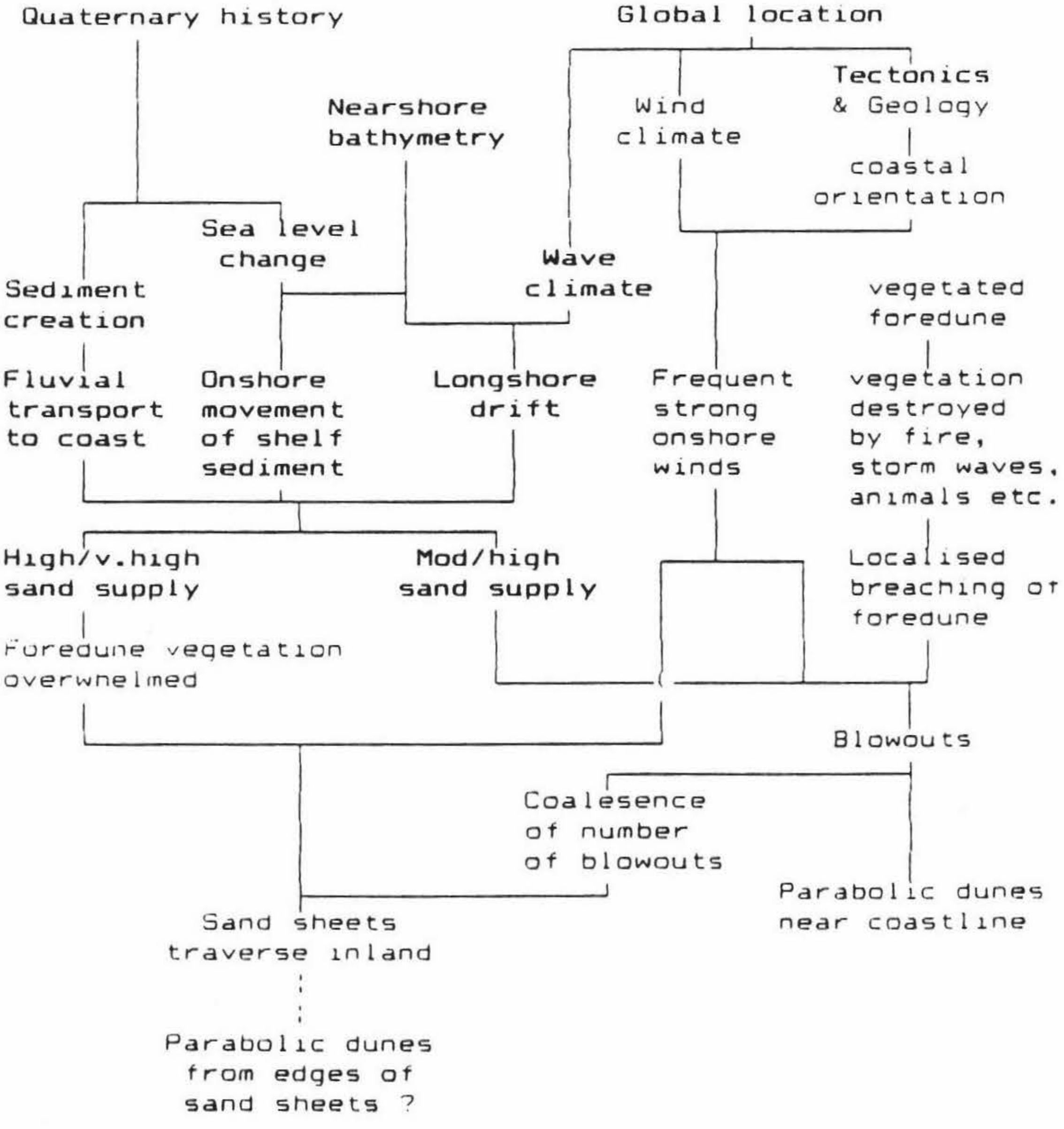


FIGURE 2.1 The main factors influencing the development of parabolic dunes. [N.B. This diagram is not intended as a complete model of the interrelationships between the factors listed. Such a diagram would necessarily be much more complex since in reality many linkages are not shown and of these factors are linked by feedback loops. The purpose of this diagram is to illustrate the main factors which can determine the location of parabolic dunes. Lines reading down the diagram indicate causal and other relationships.]

QUATERNARY HISTORY

During the Quaternary Period, climatic fluctuations and associated changes in sea level affected geomorphic processes throughout New Zealand. Glacials and stadials were characterised by colder temperatures and low sea level and interglacials and interstadials by warmer temperatures and higher sea levels. During interglacials fluvial processes dominated, soils developed and vegetation covers were widespread. Glaciations, by contrast, saw increased erosion rates in the high country as areas of protective vegetation were reduced and greater areas of the country were exposed to glacial and periglacial weathering processes. Glaciers and rivers worked to transport the increased sediment yield from the highlands to the coastline, the rivers building up fans in many places. The type of sediment varied with the type of geomorphic processes operating in the source area (glacial, periglacial, fluvial). Rivers in the South Island tended to carry glacial outwash gravels, 'rock flour' and frost shattered rock fragments from the Southern Alps. In the North Island a greater proportion of sediments were sands (Healy and Kirk 1982). Volcanic activity in the central North Island during the Quaternary supplied a great deal of sediment to the west coast and Bay of Plenty. At the open coast particles smaller than sand sized would have been either removed offshore by wave action or perhaps blown inland as loess. Estuaries formed a sink for sands and finer material.

During the Quaternary, shelf sediments would have been shifted onshore, offshore and alongshore as sea level fluctuated. Some present day coastal barriers overlie pre-Holocene coastal sediments. The barriers at Kaipara, Manukau, Raglan, Aotea and Kawhia for example, are all built on Pleistocene dune sands (Healy and Kirk 1982).

Around 15 000 years ago the present interglacial began and sea levels began to rise (Gibb 1986), transgressing over the terrigenous deposits laid down on the exposed continental shelf during the last glaciation. The rise in sea level frequently resulted in a nearshore bathymetry around much of New Zealand which was not in equilibrium with the prevailing wave climate.

Although the chronological history of most major New Zealand coastal features is not known in detail, many Australian studies have shown that for a period of time (which varied in duration depending upon the individual site) in the mid-Holocene large amounts of sediment were moved onshore. Such features as barriers (eg: Kaitorete Spit, Matakana Island), spits (eg: Kaipara Heads, Farewell Spit), tombolos (eg: Mahia Peninsula, Mount Maunganui) and areas of relict foredunes (also known as parallel dune ridges or beach ridges) (eg: Ahipara, Haldane Bay, Cannibal Bay) were probably initiated at this time. As the sediment from the continental shelf, together with additions from longshore drift (which are still contributing sediment in may areas), built the coastline outwards, the lagoons, estuaries and drowned valleys began to fill with fresh fluvial sediments deposited by rivers adjusting to a raised base level. Today some of the estuaries have been filled completely eg: the Wairau valley (Pickrill 1976), at Hotwater Beach on the Coromandel Peninsula (Healy and Kirk 1982) and the Rangitaiki Plains (Pullar and Selby 1971). In such locations sand sized sediment may be delivered to the coast in large quantities by rivers and streams.

TECTONICS

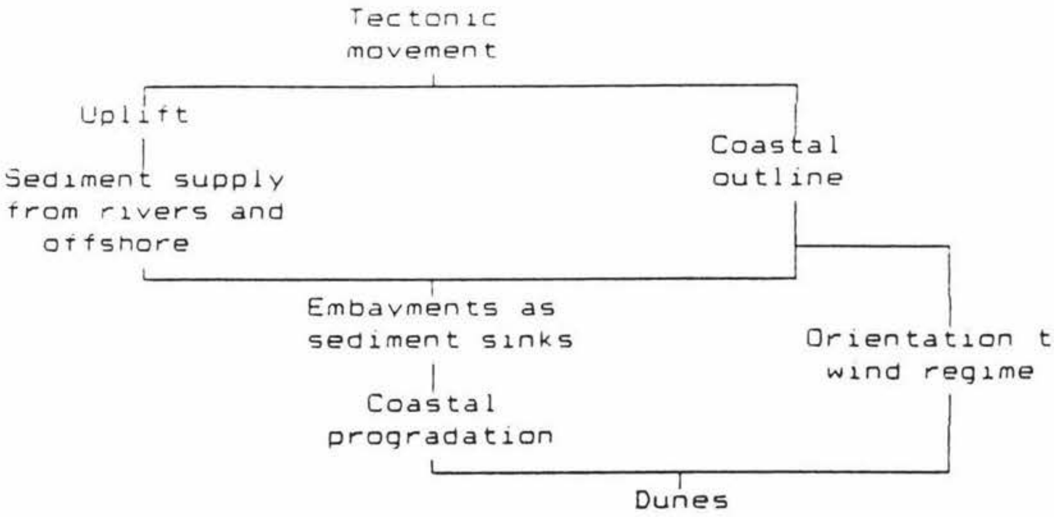


FIGURE 2.2 Principal ways in which tectonics may affect dunes. [For each line reading down the diagram read 'affects'.]

New Zealand lies along the boundary between the Indian and Pacific continental plates. In the North Island the Pacific plate is underthrusting the Indian plate while in the South Island the opposite is taking place. This plate activity means that New Zealand is very tectonically mobile with rates of vertical movement varying from imperceptible to an estimated 17 mm/yr for uplift near the Alpine Fault in the South Island (Wellman 1979) and 5 mm/yr for downwarping in the Taupo Volcanic Zone (Pillans 1986). Since areas of rapid uplift at the coast tend to form headlands (eg: Cape Palliser, Cape Kidnappers) and regions of dowmwarping form embayments (eg: Hawke Bay, Manawatu embayment), tectonic movement has been a major factor influencing the development of the coastal outline of New Zealand. The outline of the country in turn affects the transport of sediment alongshore with embayments acting as sediment sinks where progradation of the coast is possible and, under favourable conditions, sand dunes may form.

Tectonic uplift also affects the sediment supply to the coast from rivers and the continental shelf. Rapid uplift of inland ranges is accompanied by rapid erosion of these areas resulting in greater volumes of material being transported to the coast by rivers in these areas than is the case in regions of lower topography. Slow to moderate uplift at the coast may also increase sediment supplies to the coastline as the nearshore profile adjusts to the relative fall in sea level.

LOCATION AND WAVE CLIMATE

New Zealand consists of three main islands which possess a total of 11 000 km of coastline (Matthews *et al* 1983). The islands are located between latitudes 34.23°S and 47.17°S, and longitudes 167.29°E and 178.35°E and lie in a line running roughly northeast - southwest with the Pacific Ocean to the east and the Tasman sea to the west. New Zealand's location means that it's shores are exposed to swell waves generated by storm winds between latitudes 40° south and 60° south (known as the 'roaring forties', 'furious fifties' and 'screaming sixties'). These swell waves approach from a southwesterly direction and are the most frequently occuring swell (Pickrill and Mitchell 1979). Swell from tropical storms to the north also affect the country but to a lesser degree (Trenberth 1977). Locally produced wind waves (which include large storm waves) can approach from any direction. Pickrill and Mitchell (1979) classified the south and west facing coasts of New Zealand as exposed high energy coasts, the east facing coasts (which, because of their alignment northeast-southwest, are exposed to swell from the south) as high energy lee coasts, and the north facing coasts (eg: Bay of Plenty) as low energy lee coasts.

LONGSHORE DRIFT

Sediment may accumulate along a section of coastline due to the movement of material alongshore. This is a result of a process known as 'longshore drift'. Longshore drift involves movement of sediment parallel to the shore resulting in the redistribution of material along coastlines. This takes place when waves approach a coast at an angle oblique to the shoreline. 'As waves enter shallow water...they [provide] a vector of energy parallel to the shore' (Davis 1985, p413). This energy creates a longshore current which transports sediment lifted from the bed by breaking waves.

While longshore currents account for the largest percentage of sediment movement at a coastline (Davis 1985), they are augmented by the process of 'beach drift'. Unlike longshore drift, which takes place mainly in the surf zone, beach drift takes place on the foreshore as wave swash carries material up the beach at an angle oblique to the shore and backwash retreats normal to the shore, bringing some of the sediment with it (Matthews *et al* 1983). Combined, longshore and beach drift cause large amounts of sediment to move along shorelines until the flow of material is impeded by an obstruction such as a headland, breakwater or area where the wave approach is parallel to the coast. In this way the waves have a tendency to distribute sediment so that the coastline becomes smoother in outline and, if the coastal outline permits, orientated parallel to the most frequent wave direction.

This involves the supply of sediment from river mouths and the erosion of headlands, coastal cliffs and platforms, the build up of deposits in bays and the creation of/addition to spit and barrier forms across bays and natural harbours.

The dominant southerly swell waves have created a general pattern of net northward sediment drift along the east and west coasts of both main islands. This general trend is modified where the swell is channelled through straits or refracted around major headlands. Where the coast is sheltered from the southerly swell locally produced waves and swell from other directions dominate the wave climate. Refraction of southerly swell around the northwestern end of the South Island and sheltering from direct southerly swell means that the net sediment drift at Farewell Spit is to the east and along the Wanganui/Manawatu coastline to the southeast and south. Drift directions along the coast to the north of Otago, Banks and Kaikoura Peninsulas and East Cape are all roughly from north to south due to refraction of prevailing swell as well as a greater relative influence of swell from the north and east. Channelling of swell through Fouveaux Strait has resulted in a net westerly flow of material while in Cook Strait drift takes place in both directions. This also occurs in the Bay of Plenty which is sheltered from southerly swell and is influenced more by northerly swell resulting in drift at Tauraunga and at Opape from both directions. (Carter and Heath 1975; Gibb 1979; Matthews *et al* 1983).

Net sediment drift at any particular locality along the coastline may differ from the overall pattern due to the influence of local shore configuration. Flow of sediment alongshore can also be interrupted where sediment collects updrift of a headland (eg: Kaitorete Spit (Healy and Kirk 1982)) or a breakwater (eg: New Plymouth (Gibb, J.G. 1983 as cited in Arron and Mitchell 1986)), downdrift of a headland where the drift direction is reversed (eg: north of Kaikoura Peninsula (Kirk 1975)), in an embayment (eg: Hawke Bay (Gibb 1962)), where refracted swell converges (eg: around Kapiti Island (Matthews *et al* 1983)) or where the prevailing swell is normal to the orientation of the coastline.

An excellent example of the latter can be found north of Cape Egmont, on the west coast of the North Island. Here longshore currents generally flow northward carrying material from the cliffs and platforms of Cape Egmont and the rivers of the region toward Cape Reinga. As the coastline swings around to face the incoming southwesterly swell (southerly swell refracted around the South Island) the longshore drift is dramatically reduced and accretion results (Tortell (ed.) 1981; Ballance and Williams 1982; Matthews *et al* 1983). Similarly, refraction of the dominant southerly swell around northern South Island results in westerly swell into the Manawatu embayment, creating longshore movement of material southward from Cape Egmont and major river mouths. Since more sediment enters this stretch of coast than leaves it to the south, the Manawatu embayment acts as a sediment trap (Wright 1988).

NEARSHORE BATHYMETRY

Once sea level had stabilised around 6 500 years B.P. (Gibb 1984) the new offshore profile (where the seabed consisted of unconsolidated sediments) adjusted rapidly towards equilibrium with the wave climate. Whether the newly submerged sediments were moved onshore or not depended on how rapidly the level of the sea rose and on the gradient of the surface over which it had transgressed. Rapid sea level rise will result in the landward movement of the shoreline but a high rate of deposition at the shore is possible during slow rises in sea level (Curray 1964). A gently sloping, shallow inner shelf is necessary for net onshore movement of sands and gravels by waves. Where the nearshore profile is steep and the shelf narrow little wave energy is dissipated before reaching the coastline and the greater forces act to remove sediment from the shore rather than to deposit it there. In these areas drowned river valleys (eg: Marlborough Sounds), fiords (eg: Fiordland) and eroding rocky coastlines (eg: south Wellington region) eventuated. The average depth of the New Zealand contintental shelf edge is 130m but reaches depths of up to 200m off the Wairarapa coast (Lewis 1973) and 300m off Cape Egmont (Andrews and Eade 1973). The bathymetry of the continental shelf around New Zealand has affected the movement of sediment both onshore and alongshore.

In a theoretical study in New South Wales it was found that sand at a depth of 20m was disturbed by wave action around 50% of the time while at a depth of 50m was disturbed only 1% of the time (Wright 1976). The distance of the 50 m isobath from the coastline around New Zealand varies from less than one kilometre at headlands (eg: Cape Runaway to Matakoa Point, heads of the Marlborough Sounds, Cascade Point, Fiordland) to sixty kilometres from the coast in Tasman Bay. Other areas where the 50 m isobath is a substantial distance from shore is at the Firth of Thames (50 km), Kaitorete Spit (30 km), South Taranaki Bight (40 km) and Hauraki Gulf (35 km). Generally though the 50 m isobath is located between 5 and 20 km from shore around New Zealand (see FIGURES 2.3 and 2.4).

Features such as Kaitorete Spit, the barriers and spits of Tasman Bay and the west coast of Northland, the sand plains of the Manawatu embayment and the areas of beach ridges in places such as the Bay of Plenty and Cloudy Bay were created as an onshore flux of sediment occurred following the last eustatic rise in sea level (longshore drift was also important in areas like the Manawatu). The nearshore seabed of the continental shelf in this way began to be modified over time towards a situation of dynamic equilibrium with the wave climate. Today most of the nearshore profile is close to this state since there are few areas where the seabed still provides large amounts of sediment to the coastline (Gibb 1979) and some of the features built up by offshore material are in a state of dynamic equilibrium (eg: Pauanui Beach, Coromandel (Gibb and Aburn 1986)) or alteration (eg: Kaitorete Spit (Healy and Kirk 1982)) at present.

FIGURE 2.4 Nearshore bathymetry - South Island

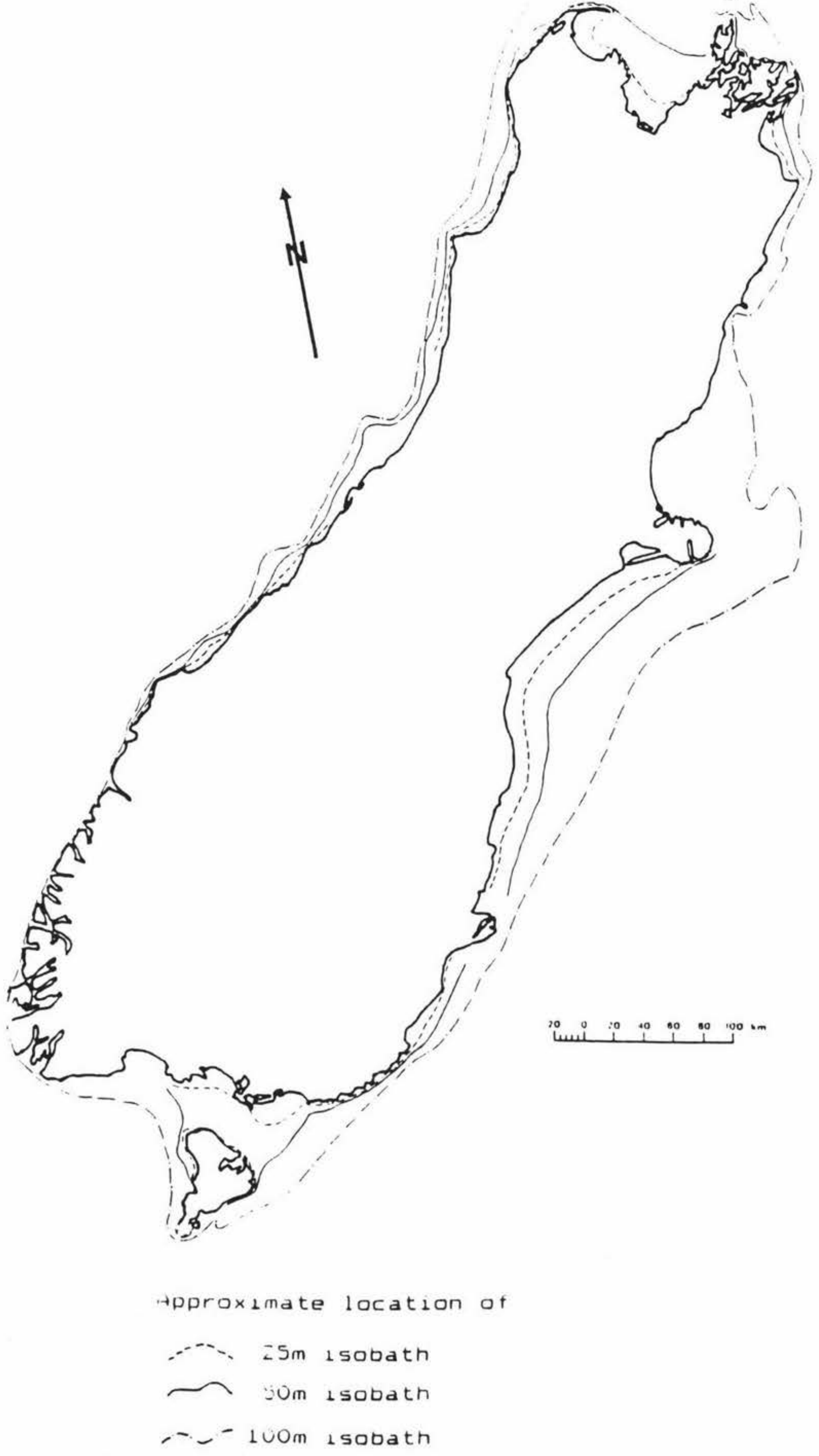
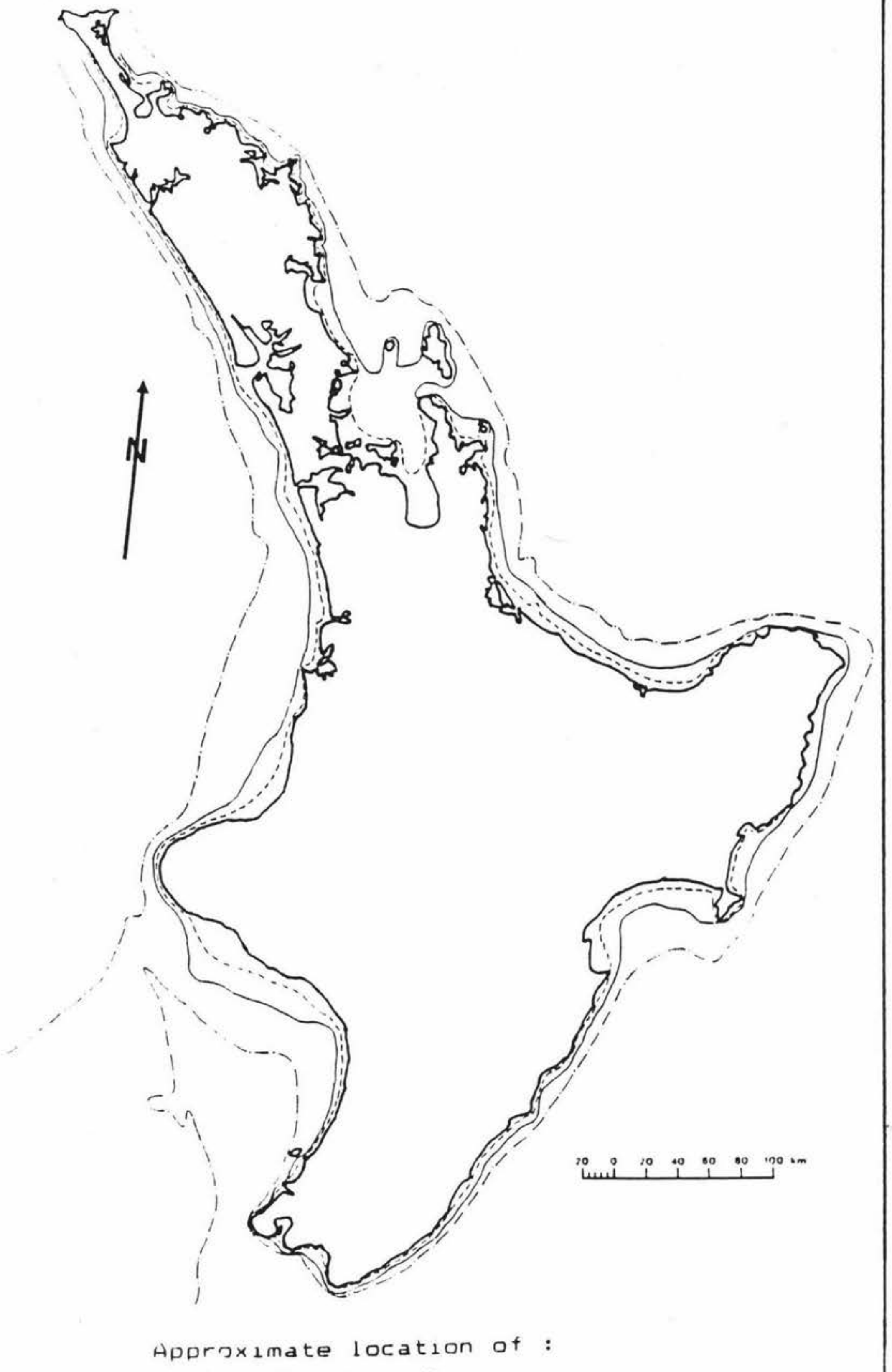


FIGURE 2.3 Nearshore bathymetry - North Island



Approximate location of :

25m isobath

50m isobath

100m isobath

As stated earlier, longshore drift is now the dominant movement of material at the New Zealand coast. This process is most effective along coastlines with smooth outlines where the nearshore seabed has a moderately gentle slope. Where the offshore profile is steep (eg: at Fiordland, Marlborough Sounds) most wave energy is reflected from the coastline and not used to transport sediment. Steep profiles are also not conducive to the development of surf zones which are necessary for the creation of longshore currents (Davies 1980). Conversely, very gentle nearshore profiles (eg: Firth of Thames, Tasman Bay) may not be characterised by high rates of longshore drift because the shallow waters allow both the obliquity of wave approach and the amount of wave energy to reach the shore to be reduced. Areas in New Zealand where longshore drift is greatest are along the smoothly curving coastlines south of Cape Egmont, north of Cape Egmont (until the coast swings around to face the prevailing swell) and Canterbury Bight, and the long nearly straight Westland and Wairarapa coastlines (Gibb 1979) : all of these are exposed to southerly swell.

DUNE AREAS OF NEW ZEALAND

(This section is concerned with the location of different coastal dune types in New Zealand. Discussion regarding the formation of these dune types can be found in Chapter 3.)

The largest accumulations of sand around the New Zealand coastline are where conditions were favourable for movement onshore of large amounts of reworked shelf material following the last post-glacial transgression and where longshore drift has worked to continue to supply more sediment to such areas than remove from them. As seen in Table 2.1, the largest areas of sand in New Zealand are by far in the Auckland/Bay of Plenty and Wellington provinces. These areas received huge amounts of sand from offshore and, as has been mentioned, both Northland's west coast and the Manawatu coast presently act as sediment traps with regard to longshore drift. Plenty of sediment is supplied to these coasts by the eroding cliffs of the Taranaki region and by the sediment load of the many rivers which flow to the west coast of the North Island (eg: Waikato, Wanganui, Rangitikei and Manawatu Rivers).

Table 2.1

Areas of Coastal Sand Dunes in New Zealand

Province	Approximate Area (hectares)
Auckland / Bay of Plenty	74 500
Wellington	37 370
Canterbury	3 530
Taranaki	2 565
Hawke Bay	2 165
Southland	1 989
Otago	1 500
Marlborough	608
Nelson	183
Westland	negligible
Total	124 410

(from Cockayne 1911)

The type of sand dune developed at different locations in New Zealand has been determined by the amount of sand supplied to the area, the wind climate of the area,the history of disturbance to vegetation covering the sand and the topography of the coastal site. As seen from Table 2.1, the areas of the New Zealand coastline to have experienced the largest accumulations of sand since the last post-glacial marine transgression have been the Auckland/Bay of Plenty and Wellington areas. In areas where the supply of sand and the sand moving ability of onshore winds have been high, transgressive dune formation may have been a natural process with vegetation unable to become fully established in such conditions. Other areas where vegetation had been able to stabilise the sand blown from the beach would have been likely to be characterised by a series of foredunes. A number of factors could lead to the development of blowouts within the relict foredunes or the contemporary foredune.

Probably the most common factor leading to the generation of transgressive dunes in New Zealand's recent history has been disruption of vegetation through human activity. Coastal sites were popular for Maori occupation from their arrival in New Zealand around 1000 years ago as evidenced by the remains of middens at many locations, especially in the North Island (Wellman 1962). Stratigraphic evidence suggests Maori people cleared some coastal sites of vegetation by burning (Wellman 1962; Hocking 1964; Whitehead 1964). The affects of Maori activity were minor, however, compared with the wholesale destruction of native vegetation that followed the arrival of Europeans in the early 1800's. Early settlers grazed and mustered cattle on sand country as areas inland were being cleared of bush, and scrub was burnt off to clear coastal land for farming (Hocking 1964; Whitehead 1964; Wendelken 1974). Such anthropogenic activity lead to mobilisation or remobilisation of previously fixed sands in areas such as the Manawatu (Wilson 1959; Cowie 1963; Saunders 1968) and near Aotea and Kawhia Harbours (Pain 1976).

Although stratigraphic studies show that periods of transgressive dune activity occured prior to arrival of humans in New Zealand (eg: Cowie 1963; Pain 1976; Hicks 1983) there can be no doubt that interference with coastal vegetation increased the extent of drifting sands. Since the 1950's concerted (although not always consistent) efforts have been made to stabilise transgressive dunes by planting marram to encourage foredune development (thereby cutting off sand supply to dune sheets) and pine plantations, such as those at Woodhill and Santoft. In some places localised destruction of foredune vegetation still takes place as a result of farming practises, recreational activities or construction of buildings (eg: Holland and Holland 1985).

A prograding coastline is more likely to develop a series of low foredune ridges whereas a stable or slightly receding coastline will tend to develop one higher contemporary foredune (Shepherd 1981). Higher foredunes, because they are exposed to higher wind velocities, are more susceptible to blowouts. As supplies of shelf sediments have dwindled many of the areas around New Zealand that may have previously been prograding are now stable or even eroding. It has been estimated that for the last hundred years around 56% of the coastline has been static, 25% suffered erosion and 19% accreted (Gibb 1979b). As the nearshore zone reached equilibrium in response to stable sea levels following the last postglacial marine transgression, the potential for higher foredune development and blowout activity has increased. Erosion of foredunes may have been exacerbated by a mean rate of sea level rise of 'about 1.2 mm per year during the past century' (Royal Society of New Zealand 1988, p23).

Sequences of undisturbed relict foredunes are found in many areas in New Zealand. In the North Island, for example, they are found at Ahipara and Te Horo on the west coast, in the Bay of Plenty and at Rangaunu Bay on the east coast. In the South Island many small areas of foredunes exist including those near Charleston and Birchfield on the west coast, Riverton on the south coast and at Cannibal Bay and Cloudy Bay on the east coast. Such undisturbed sequences tend to be more common on the west coast of the South Island, the Bay of Plenty and the east coasts of both islands because of the lower levels of wind energy affecting those locations (see Chapters 4 and 5). The contemporary foredunes at many of the sites on the east coast of the North Island and in the Bay of Plenty are characterised by small blowouts (eg: East Beach, Opoutere Beach, Mount Maunganui).

Where vegetation has been unable to, or has been prevented from, stabilising large quantities of sand being blown inland, and where the coastal land is reasonably flat transgressive sand sheets have formed. Today active sheets are almost entirely exclusive to the north of the North Island. Unvegetated sand covers large areas at Ninety Mile Beach and at the entrances to Kaipara, Manakau, Raglan, Aotea and Kawhia Harbours, and smaller areas at Great Exhibition Bay and Houhora Bay. It is interesting to note that the sand sheets of Ninety Mile Beach have a very high silica content and may never have supported a significant level of vegetation (Wendelken 1974). Examples of sand sheets which are now stable can be found in the Wanganui and Manawatu regions.

Where the coastline is backed by a cliff three types of dune are possible. Examples of echo or under-cliff dunes are found in some areas such as Taranaki (Cockayne 1911) where cliffs are steep and sand supply not very great. Climbing dunes, where the sand body is in contact with the cliff, are quite common. Examples are those at Reef Point (Tauroa Point) (Cockayne 1911), Castlepoint and at Penguin Place near Taiaroa Head. Holocene cliff-top dunes such as those in the Kawhia Harbour area (Pain 1976) are not as widespread but can be found at places along the Taranaki coastline.

The most extensive parabolic dunefields are located on the west coast of the North Island. Most of the remaining coastal parabolic dunes of New Zealand are present along the southern coast of the South Island. While blowouts occur at many locations on the west coast of the South Island, east coast of both islands and the Bay of Plenty, very few sites are exposed to sufficient onshore wind energy to allow blowouts to develop into parabolic dunes. For the same reason, few of these areas feature sand sheets which can generate parabolics.

CHAPTER 3

SAND TRANSPORT AND DEPOSITION - THE ROLE OF WIND AND VEGETATION

A large number of variables influence the transportation and deposition of sand by wind. The most important of these variables are examined in the first section of this chapter, leading to a discussion in the second section of the types of dunes formed by aeolian processes

AEOLIAN TRANSPORT OF SAND

MECHANICS OF AEOLIAN TRANSPORT

Air may be seen as a perfectly viscous fluid (ie: moves at any level of applied stress) which, when moving in the form of wind, allows layers of air to slip past one another. Thus shear is distributed throughout the depth of flowing air (Statham 1977). Most of the energy lost from the air body through it's interaction with the surface is lost as heat but some is used for the transportation of sediment (Warren 1979).

Transportation of sand particles by the wind requires that forces operating to shift a particle must overcome the resistance of the particle to movement. Resistance forces involve gravity acting on individual grains and frictional and cohesive forces between particles. Forces acting to move particles include shear, lift and ballistic impact (Warren 1979; Leeder 1982). Shear stress involves differential pressure on the windward and lee sides of particles (created by airflow over the particle) which encourages movement of the grain in the direction of the airflow. Lift forces may result from turbulent eddies within the flow (Statham 1977) or from the Bernoulli effect. The latter occurs where a vertical pressure gradient exists. This may come about as a result of acceleration of flow over obstacles (eg: pebbles, sand grains) or from the usual vertical velocity profile where velocity increases with distance from the bed. Both of these situations result in higher velocities and lower pressures above the surface compared to the pressures around the grains, encouraging movement of the grains upward (Warren 1979). Unlike shear and lift forces, ballistic impact does not directly involve airflow characteristics. When a sand grain which has been transported returns to the surface, its impact causes a transfer of momentum to the surface grains, causing some of these grains to be entrained themselves (Leeder 1982).

Sand grains which are temporarily lifted from the surface, transported for a distance, and then return to the surface are said to have 'saltated'. Saltation accounts for about 75% - 80% of total aeolian transport of sand. The other 20% -25% is transported in the form of surface creep (Statham 1977; Chorley, Schumm and Sudgen 1984). This occurs when wind velocities are not great enough to lift grains from the bed. Instead, such grains roll along the surface as shear stress of airflow and impact of other grains overcome frictional and cohesive resistance.

Where grains are entrained through lift and shear forces alone the necessary wind velocity is greater than if ballistic impact is involved as well. This means that initiation of movement requires a higher wind velocity than is needed for the maintenance of saltation. Bagnold (1941) recognised this and used the term 'fluid threshold' to refer to the critcal wind velocity needed for initial transportation to occur. The term 'impact threshold' was used for the velocity necessary to maintain saltation. For sand sized grains (0.0625 mm to 2.0 mm diameter) the fluid threshold velocity is always greater than the impact threshold velocity and both increase with increasing particle size.

EFFECTS OF WATER

The effects of the presence of water on aeolian transport of sand are complex but generally it is believed that as moisture content increases, the rate of transport decreases (Statham 1977). According to some authors, the presence of water on the surface is a major factor influencing the ability of wind to transport sand. Water held between sand grains raises the critical threshold velocity required for entrainment, especially for the first 2% of moisture content (Davies 1980). Wind tunnel experiments have indicated that for a water content of 0.1%, the threshold velocity for movement of sand is around 34 cm/s (0.66 knots). Water content of 3.0%, by comparison, requires a wind velocity of 58 cm/s (1.1 knots) to shift the sand (Belly 1964 as cited in King 1972). This effect is caused by an increase in the cohesion of a body of sand through surface tension forces in layers of water at points where the grains touch. Surface tension increases initially with increasing water content but decreases again with high values of moisture (Statham 1977). In conditions of very high moisture content however, sand bodies become smoother and have fewer surfaces exposed to airflow reducing the likelihood of entrainment (Statham 1977; Davies 1980). Where sand is moist but the air is relatively dry, winds can quickly dry the surface layer of sand (provided the water table hasn't been reached) and allow entrainment of sand to occur (Holm 1968). Rain, fog and dew can therefore affect the transport of sand (Holm 1968). These effects have been considered to be potentially important where the prevailing wind is regularly accompanied by rain so that sand transport directions in that area may not reflect that direction but may reflect dry wind directions instead (Holm 1968; Crofts 1971 as cited in Statham 1977).

By contrast, in their study of blowout development, Jungerius *et al* (1981) found that the effect of rainfall on sand movement was 'limited'. They suggested that 'rain is not very effective in stabilizing the sand apart from the short periods during which rainfall actually occurs' (p386) and that this is probably due to the rapid drying of the sand which occurs during the strong wind conditions often associated with rainfall. Sarre (1989) recorded observing sand movement during a number of 'squalls featuring strong gusty winds accompanied by heavy rainfall' at his field site in Southwest England and suggested that the impact of raindrops themselves may provide the energy to initiate movement. Precipitation appeared to have little effect on overall sand transport in this area (Sarre 1989). Borówka (1980) also concluded that 'ground moisture does not hinder eolian transportation, especially not at high wind velocities' (p75). Evidence was also found that some surface moisture may even have the effect of increasing sediment transport because the bedforms present with dry sand are absent with moist sand, lowering the surface roughness and therefore allowing higher velocity winds to flow unimepeded across the surface (Borówka 1980).

EFFECTS OF SALT CRUST FORMATION

Salt crust or beach salcrete forms when swash or spray from breaking waves evaporates, leaving a cement of marine salts which may bind sand grains together forming a crust up to several centimetres thick (Pye 1980). Heavy mineral sands and fine sands are most susceptible to the formation of crusts due to the smaller spaces between grains (Pye 1980). The presence of such crusts effectively raise the threshold wind velocity and have therefore long been acknowledged as a possible factor limiting sand movement and subsequent dune formation, especially in tropical areas (eg: Broughey (1957) and Morton (1957) as cited in Pye (1980)). Pye (1980) concludes however that the effect of salt crusts on the development of dunes in tropical areas is only minor compared with major factors such as wind strength, sand supply and beach orientation. In temperate areas crusts are generally thinner and more easily destroyed by saltating grains from adjacent uncemented surfaces (Svasek and Terwindt (1974) as cited in Pye (1980); Sarre (1989)).

THRESHOLD WIND VELOCITY

According to Zenkovich (1967), winds of velocities less than 5 m/s (9.7 knots) cannot shift sand whereas velocities of 20 m/s (38.8 knots) are capable of moving fine shingle. Such values are impossible to compute theoretically because of the complexity of variables involved and must be determined by experiments and field measurements (Leeder 1982). When attempting to predict the critical threshold wind velocity for a body of sand, simplifications (eg: mean grain size) and assumptions (eg: many variables ignored) are made and equations may be used. Fryberger (1979) calculated that the threshold wind velocity at 10 m above the ground for dry quartz sand grains with an average diameter of 0.25 - 0.30 mm to be around 12 knots. This was determined using equations from Belly (1964 as cited in King 1972) and Bagnold (1941).

RATE OF SAND TRANSPORT

The rate of transport of sand is usually taken to be proportional to the cube of the wind speed above the threshold value (Chorley, Schumm and Sudgen 1984). This means that winds of

16 m/s (31 knots) perform the equivalent work in 24 hours as an 8 m/s (15.5 knot) wind does in 3 weeks (Bagnold 1941). Strong winds (around 14 m/s or 27 knots) are the most effective sand transporters in terms of quantities moved.

EFFECTS OF TOPOGRAPHY

Topography has effects on sand movement because any obstacle to wind flow will alter that flow in terms of both velocity and direction. The topography of the land adjacent to the coastline will have an effect on sand movement inland from the beach. Given onshore winds of sufficient strength to shift sand, a cliffed coast will be likely to stop or hinder inland movement of sediment. Reverse flows from the cliff can lead to a gap between the deposits and the cliff resulting in an 'echo dune'. Where the cliff is low enough and the sand supply great enough, sand may be able to climb the cliff. Where a plain is adjacent to a coast however, sand transport inland has the minimum of topographic interference.

The characteristics of the beach itself, as a source of sand, affect the transportation of sand. Dissapative type beaches have low angle slopes which offer less resistance to wind than a steep reflective beach (Short and Hesp 1982) and they also tend to be wide, exposing a greater amount of sand to winds at low tide (Davies 1980; Short and Hesp 1982). Since beach mode varies with the amount of wave energy received at a beach, it also varies over time, becoming more reflective in calmer conditions and more dissipative as a result of storms. Mode also varies spatially even at the scale of a single beach where part of the beach is sheltered from incoming swell by headlands and the rest exposed to the waves. Since the direction of incoming swell often coincides with the direction of the prevailing onshore wind, this increases the probability of transgressive dune development at the exposed ends of beaches.

Coasts with larger tidal ranges will also have a greater width of sand exposed to winds (at low tide) (Davies 1980).

EFFECTS OF VEGETATION

The shape of sand dunes depends on a number of factors including wind characteristics (eg: one, more or no dominant wind directions) and sand supply. Vegetation also affects wind flow, and therefore sand transport. The particular flow effects depend on the characteristics of the vegetation. Large trees can individually act as any other solid object. Where a group of trees and/or bushes exist, the movement of the sand will be constrained. If the sand supply is great enough however, sand can be blown up the windward face of a dune and over the crest into the body of trees. In this way, sand dunes can pass over a densely forested area (Pye 1983).

On most temperate coastal areas, the major influencing vegetation consists of sand-binding grasses rather than shrubs or trees (Warren 1979). Grasses act as semi-permeable obstacles which create a roughness element on a sand surface, effectively altering the height of the aerodynamic surface, above which flow is unimpeded (Statham 1977). If the grasses are very dense and virtually impermeable to a wind flow, the wind velocity at the aerodynamic surface may be zero. In other words, vegetation has the ability to absorb shear stress imposed by the airflow so that entrainment of sand particles is less likely to occur (Statham 1977). This effect of vegetation on sand movement allows topographic features to be built in the form of fixed or impeded dunes whereby sand is deposited where the vegetation causes a reduction in wind velocity. As the sand is deposited, certain species of grasses will continue to grow, allowing a stationary dune to build up.

At the scale of an individual plant, shadow dunes may be formed. A shadow dune is a pyramidal shaped bedform which is constructed to the lee of a semi-circular, semi-permeable to non-permeable roughness element (Hesp 1981). These forms have a triangular shape in plan with a short side adjacent ot the plant. The axis of the triangle runs parallel to the wind direction and is characterised by a ridge of sand running from a maximum height immediately behind the grass to nil height at the apex of the triangle (Hesp 1981). Flow around the plant creates wind eddies flowing from the plant edges to the axis of the triangle. Opposing vortices meet at the axis which forms the zone of maximum depostion. The greatest sheltering and strongest reverse flows exist immediatily behind the plant and decrease leeward of it, resulting in less deposition with distance. Since the dunes areal extent is controlled by the width of the plant involved, the height of the dune is also controlled by this variable. With the length of the dune controlled and the slopes constrained to the angle of repose, the height of the ridge can clearly only reach a certain maximum value (Hesp 1981).

The pattern of deflation and deposition, and the bedform created, varies with different species of grass. The three main grasses in New Zealand coastal areas are Ammophila arenaria (marram), Spinifex hirsutus and Desmoschoenus spiralis (pingao) - the first an introduced plant and the latter two natives to New Zealand. Marram grass plants are rhizomatous and tend to grow in an erect, clumped manner to a height of between 0.5 and 1.0 m (Davies 1980; Hesp 1981). The high plant density (leaves per area) of marram in it's lower half mean that the near surface airflow is strongly affected by the plant. Airflow is almost completely blocked from passing through the lower section of the plant, forcing velocities to fall dramatically withim and just behind the plant, but to accelerate around the edges. This acceleration means that eddies behind the plant are stronger, leading to a pronounced bedform to be shaped within the zone where sand transport is minimal. The faster wind speeds around the plant may also lead to deflation around the plant, accentuating the clumped nature of the associated bedform (Holland 1983a).

Pingao, by comparison, grows more openly than marram and has more flexible leaves. These characteristics allow winds to penetrate the plant to a greater extent, with airflow at higher velocities within and behind the plant and actual deceleration around the plant (Holland 1983a). This airflow pattern means that deflation around the plant does not occur. Since higher velocities exist to the immediate lee of the plant and no acceleration takes place around the plant, eddies are not as strong as they are around the marram plant. Since it is the eddies which serve to bring material to the axis of the dune form, the shadow dunes associated with pingao are lower and less distinct than those occurring to the lee of marram plants (Holland 1983a).

Spinifex is a stoloniferous plant (Wilcock 1983) and appears to have characteristics which are intermediate between marram and pingao, resulting in a bedform intermediate between the two types of shadow dune.

SAND DUNES

UNVEGETATED SAND DUNES

A 'topographic feature of aeolian origin composed of sand grains deposited down-wind from a natural source of sand', such as a beach, is termed a sand dune (Holm 1968). Dunes act as storages for sand which may be mobile or fixed (by vegetation or cement). As topographic features, sand dunes affect wind flows and therefore sand movement. They, as well as any other small topographic form (eg : ridge, hill, large rock outcrop), act as impermeable obstacles to wind with uncemented and unvegetated dunes being the most free to modify shape in response to changing wind conditions. This freedom to alter shape contrasts with an object like a large rock which, because it cannot change it's shape, acts as a block to wind, resulting in sand deposition and/or deflation around it.

Mobile dunes occur where there is an abundance of sand available and the dune is active enough and/or the climate is harsh enough to prevent vegetation from becoming established. The windward slopes of such dunes are usually gently sloping (3 to 15 degrees) compared to the leeward slope (33 to 35 degrees). Because the wind created the slope, the windward face must be gentle enough to allow the transportation of sand up the slope. The lee slope, by comparison, derives its gradient from the angle of repose for dry sand. Wind velocities are reduced in the rear of large topographic obstacles such as dunes and the wind does not have the ability to transport much material there. Instead, sand which is transported to the crest of the dune is dropped to the other side and the grains merely roll or slump en masse to an angle which can be maintained through friction.

These unvegetated mobile dunes tend to occur mainly in desert areas where abundant sand is present and the environment is hostile to vegetation, although they can occur in coastal areas if the sand supply is great enough. Where winds tend to come from one predominant direction, barchans may form as discrete bodies of sand within areas of little sand (Mabbutt

1977; Greeley and Iversen 1985). Transverse ridge dunes also tend to form where there is one main wind direction but where there is a larger supply of sand (Mabbutt 1977; Warren 1979; Freyberger 1979). Longitudinal, or linear, dunes exist in areas with high sand supply and more variable wind regimes (Derbyshire, Gregory and Hails 1979; Freyberger 1979). Where wind directions are complex, star dunes may form (Freyberger 1979). The latter dunes tend not to migrate due to the multiple wind directions they form in (Greeley and Iversen 1985).

VEGETATION AND DUNE DEVELOPMENT

The effect$ on sand transport by grasses becomes more complex when considering a community of plants rather than individual clumps of grass. Foredune terraces may be initiated by the growth of shadow dunes behind pioneer dune species which have grown from seeds left along the drift-line by the spring tide (Chapman 1976; Hesp 1981, 1984b). If the terrace is colonised by one of the grasses discussed earlier, a foredune may develop. Marram and Spinifex both have the ability to rapidly disperse over sand compared to pingao. As the grasses spread and trap sand moving inland from the beach the plants grow to avoid being buried. Marram's tendency to cause higher forms to be built also leads to the development of higher foredunes compared to the other grasses (Esler 1970; Holland 1983a). This reflects the ability of the high density marram to continue to effectively lower surface wind velocities even as the dune reaches a greater height (winds increasing with altitude). Spinifex and pingao have respectively lower densities and therefore lower abilities to stop sand transport when exposed to higher wind velocities.

On a prograding shoreline, if the vegetation on the foredunes is not disturbed, a series of foredunes may develop as new dunes are initiated by the deposit of seeds by spring tides. Such series of foredunes are known as parallel dunes (Bird 1972), dune ridges, beach ridges (Davies 1980) or relict foredunes (Hesp 1984b).

The heights that marram grass can allow foredunes to grow up to makes the foredune susceptible to erosion in the form of blowouts (Esler 1970; Holland 1983a). This is especially so due to the clumped nature of marram growth, allowing winds to accelerate around the dense individual plants into the less dense areas in between, causing sand transport to become more likely. Strong winds may cause a sizeable amount of material to move in this way, initiating a blowout.

Compared to marram, blowouts are less common where Spinifex is growing (Esler 1970). Spinifex stolons tend to find hollows in the foredune and spread more evenly than marram, resulting in a more regular roughness surface for wind to pass over (Wilcock 1983). Pingao dunes reach heights which are much lower and therefore are not exposed to higher wind velocities, removing much threat of blowouts developing (Holland 1983a). Where Spinifex and pingao occur together however, blowouts are more common (Esler 1970), possibly because of the height of the dune (due to the Spinifex) and the uneveness of the surface (due to the lower density and slower growth rate of pingao compared to Spinifex).

Blowouts may be initiated on any foredune ,however, if the covering vegetation is sufficiently disturbed. This can occur if storm waves reach the foredune and erode sections of it, leaving areas of bare sand between the vegetated parts. Traffic (either pedestrian or vehicular) when frequent and channelled over a narrow area can destroy the vegetation cover over the area and expose sand to the wind. This can become a major problem where people build either permanent or seasonal accommodation near a beach and constantly seek access to the beach via a particular path. Grazing of animals and burning are also common ways in which coastal vegetation may be removed (Bird 1972).

PARABOLIC DUNES

Once any deflation has begun from within the vegetated area, the grass will die off due to a lack of additions of sand. As the grass dies there is nothing left to modify wind flow and stop further sand transportation, creating a positive feedback situation. In this way, blowouts may lead to the development of parabolic dunes which, while mobile, consist of a nose of advancing unvegetated sand with trailing 'arms' which are partly vegetated (see FIGURE 3.1). This type of dune funnels wind down it's axis to the nose, creating an environment hostile to vegetation along the axis, and allowing sand to be transported to the nose of the dune to feed its advance. Sand blown up the windward slope of the nose reaches the crest and is deposited on the steeper lee face, allowing the nose to advance in a conveyor belt fashion. Once sand supply has been cut off and the dune has stopped moving vegetation can become established on the nose, preventing further transport of the sand. However, if the vegetation cover is sufficiently disrupted (eg: by repeated trampling by stock or people) and sand is exposed to the wind the dune may become remobilised.

If sand supply is cut off from the dune but strong winds keep the head of the dune mobile, the sand at the nose of the dune may eventually be exhausted, leaving only the trailing arms as topographic expression (see FIGURE 3.2). These arms are often referred to as longitudinal or linear ridges (Bloom 1978; Landsberg 1956; Kear 1978). A diagram provided by Hicks (1975, between pages 51 and 52), which is reproduced here in FIGURE 3.3, suggests that ridges of this type may be developed directly from foredune blowouts. However, Hicks does not give any references to support this hypothesis and the present author has no knowledge of any other research that would suggest this manner of dune development. Hicks appears to base his model on observations of 'longitudinal ridges up to four metres high and a hundred metres long' (p52) within his study area in Northland, New Zealand. It seems more likely that these features are, in fact, remnants of parabolic dunes which are common in that area.

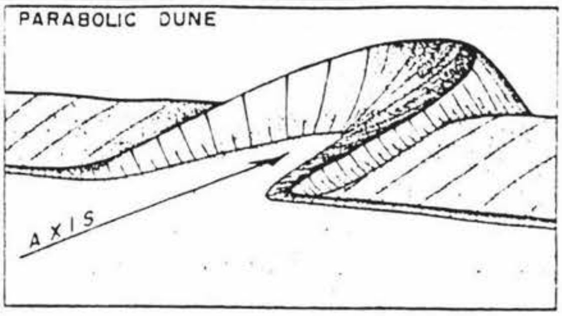


FIGURE 3.1 Stylised diagram of a parabolic dune (Bird 1972)

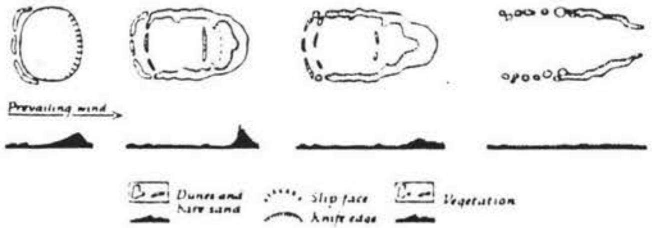


FIGURE 3.2 Development of linear ridges from a blowout (Landsberg 1956)

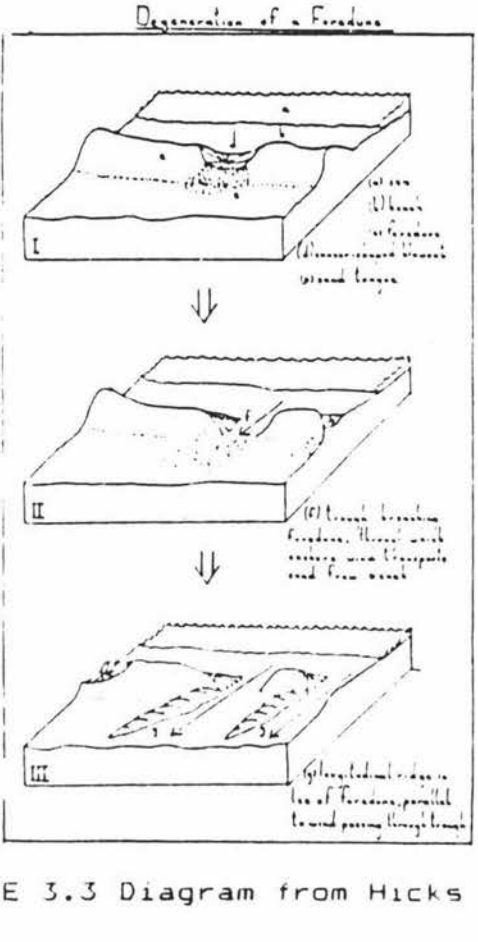


FIGURE 3.3 Diagram from Hicks (1975)

Parabolic dunes may also form from transverse sand sheets which have moved inland from a coastline and begun to be stabilised by vegetation. As vegetation begins to become established on the leading edge of the sheet, 'blowouts' can form as sections of unfixed sand move further inland, leaving the vegetated parts behind. This results in a series of parabolic dunes, some of which have broken away totally and form discrete dunes, and others which remain connected by the trailing 'arms' of the dunes. Examples of this type of dune development can be seen in the Manawatu embayment of New Zealand. Studies of dune succession at Currituck Spit, Virginia/North Carolina (Hennigar 1977) have revealed that sand sheets can also 'metamorphose' to form large parabolic dunes. A sequence which has been documented at many sites on the spit involves the break up of sand sheets into sand hills as sand fencing at the coast cut off sand supply. As vegetation began to become established on the sand hills their morphology changed, resulting in the formation of large parabolic dunes (Hennigar 1977).

Given the way in which parabolic dunes develop, it would be expected that the orientation of the axis of a parabolic dune would reflect the directional characteristics of the sand transporting winds which produced the dune. The following chapter examines New Zealand's coastal wind climate and methods of analysing wind data for comparison with parabolic dune orientation.

CHAPTER 4

THE NEW ZEALAND WIND CLIMATE AND ANALYSIS OF WIND DATA

NEW ZEALAND WIND CLIMATE

Unequal levels of solar radiation received by the equatorial and polar regions of the globe results in an exchange of energy across the globe via atmospheric and oceanic currents. The atmospheric currents take the form of vertical and horizontal movements of air; the latter being referred to as winds. The patterns which air movements form lead to belts of fairly consistent wind characteristics forming between certain latitudes.

New Zealand lies between latitudes 34°S and 48°S, partly within the Horse Latitudes which are centred around 30°S (and may extend from 25°S to 40°S with seasonal shifts). This is a high pressure belt characterised by dry sinking air and light winds. The country as a whole however, lies within the belt of prevailing westerlies between latitudes 35°S and 60°S. Here the winds blow from all directions but those from the westerly quarter predominate. Warm air from the tropics converges with colder air masses from the southern ocean causing a series of alternating anticyclones and troughs of low pressure to form. These systems, with fronts and often depressions, cross over New Zealand with roughly one anticyclone passing over the area each week (Robertson 1967). Particular types of weather are associated with different segments of this ongoing sequence. Cool southwesterly winds (associated with the approach of an anticyclone) alternate with warmer northwesterly winds (associated with the passing of an anticyclone). Between anticyclones troughs of low pressure with related fronts and depressions exist. The passage of a trough involves a change from strong winds from the northwest to winds from a southerly quarter. Following a trough of low pressure, winds can approach from any direction from northwest to southeast, depending on the particular situation.

New Zealand's length relative to the size of the systems passing over it mean that winds of different directions affect different areas of the country to different degrees. Table 4.1 illustrates the higher frequency of light winds in the north of the country, the increasing relative importance of cold fronts and associated southerly flow towards the south of the country and the dominance of winds from the westerly quarter over the country as a whole.

Table 4.1

Percentage Frequency of Controlling factors in New Zealand
(adapted from Watts 1947 as cited in Maunder 1970)

Controlling factor	Northern[1]	Central[2]	Southern[3]
Anticyclone (light winds)	28	19	20
Cold front	5	6	10
Warm/Stationary front	3	3	3
Depression	6	6	6
Flow from :			
north	5	4	3
northeast - east	6	4	5
east - southeast	5	10	8
south	3	7	8
southwest	11	9	11
southwest - west	11	7	6
west	4	4	4
northwest	4	12	8
north - northwest	9	9	8

1. north of Napier and New Plymouth
2. central region
3. south of Farewell Spit and Cape Campbell

These systems, as a part of the global pattern of atmospheric circulation dictate the overall wind directions and strengths over the New Zealand area. The dominance of westerly winds means that the west and south facing coasts are generally windier than the east and north facing coasts. However, these surface winds may undergo considerable modification upon reaching a landmass after travelling across the open ocean. Topography may have the effect of channelling wind, causing greater wind speed and often changing direction. Friction between air and the land surface causes wind to lose energy and velocity causing the level of wind energy at the coast to often be greater at the coast than even a short distance inland. Deflection over and around obstacles to the general wind flow can cause considerable spatial variation in wind characterisitics. In addition, topographic barriers such as New Zealand's main axial ranges can cause sudden changes in weather conditions at places to either side of the barrier if the general wind direction changes slightly in relation to the barrier.

Locally created winds, in the form of katabatic winds and land-sea breezes, may also exist in an area and may reinforce or oppose general wind flows. Katabatic winds blow down valleys at night as a result of air cooling at higher altitudes. The cold air has a higher density than the air at lower altitudes and thus moves downhill by gravity flow. Owing to New Zealand's mountainous terrain, this type of of air flow is reasonably common. Land-sea breezes are created by pressure differences over land masses and oceans caused by uneven heating and cooling of the different bodies. Sea breezes have been measured at velocities of up to 10 - 12 m/s in New Zealand (Maunder 1970) but land breezes tend to be less strong because the ocean surface does not heat to the same extent as land, making pressure differences less at night than in the afternoon.

The combination of general and local wind patterns create the wind climate at any particular location. The wind data used in this study are from anemometers chosen for their location near the coast on flat exposed sites, where the effects on wind patterns by the presence of trees, buildings (see append.) and local topography are minimal. This maximises the probability that the data from any station will describe the wind climate along the coastline adjacent to the station with some accuracy.

Table 4.2

Anemometer Station	Stretch of Coast
WEST COAST NORTH ISLAND	
South Head, Kaipara	Northland west coast
Port Taharoa	Auckland/Waikato/King Country
Cape Egmont	Taranaki
Wanganui Airport	Wanganui region
Ohakea	Rangitikei/Manawatu/Horowhenua
Te Horo	Wellington region
EAST COAST NORTH ISLAND	
Marsden Point	Northland/Auckland/Coromandel
Tauranga Airport	Bay of Plenty
Napier Airport	Hawke Bay
Castlepoint	Wairarapa
WEST COAST SOUTH ISLAND	
Farewell Spit	Farewell Spit
Westport Airport	west coast Nelson/Westland
Haast	Otago
SOUTH COAST SOUTH ISLAND	
Tiwai Point, Bluff	Southland
EAST COAST SOUTH ISLAND	
Oamaru Airport	Otago/Canterbury
Christchurch airport	Canterbury

Table 4.2 lists the anemometer stations from which the data used in this study were obtained, together with the area which each was taken to represent. The greater number of stations selected from the North Island reflects the fact that over 90% of the total area of coastal dunes in New Zealand is located in the North Island (see Table 2.1). Although most of New Zealand is covered by the data some areas were omitted (such as East Cape, southern Wellington, Marlborough, Fiordland) because in those areas dunes are absent or rare. In the following section the (geomorphically effective) wind regimes and drift potentials for different areas will be discussed.

These values will represent the drift potential situation along the coastline adjacent to the actual site of the anemometer stations to various degrees in different areas. Where the coast is reasonably regular in outline and is exposed to the prevailing large scale southwesterly flows, such as the west coast of the North Island north of Kawhia Harbour, the station data should represent the wind climate along that section of coast fairly well. Where locally produced or topographically influenced winds tend to dominate the wind climate, winds are more spatially variable and therefore the data from the selected meteorological station is less likely to be representative. This is the situation along the eastern coasts of both islands and the west coast of the South Island. The shape of the coastline is also an important factor since winds that are onshore in, for example, one of the embayments on the south coast Southland may be totally dissimilar in direction from the winds that are onshore in an embayment not far away in southeastern Southland. These problems could potentially be partially solved by the use of data from a greater number of anemometer stations but interpolation will always be necessary due to the spatial variation of factors such as those mentioned above.

PREVIOUS METHODS OF COMPARING WIND DATA TO DUNE ORIENTATION

Many in-depth studies of parabolic dunefields around the world have included comparison of the orientation of the dunes to some form of wind data. Cooper (1967) concluded, after examining conditions along the Californian coast, that 'essentially unidirectional effective wind' (p111) conditions were necessary for parabolic dune development. Wind roses were compared to the orientations of longitudinal and parabolic dunes in Pakistan in a paper by Verstappen (1968). In this paper Verstappen suggests that the longitudinal dunes in the region formed from parabolics but Amal Kar (1987) refutes this, claiming that variations in wind climate within the dune region have lead to the development of different dune forms in different areas. From his study of the coastal sand dunes of Scotland, Ritchie (1972) noted that while the total development of a dune area depends on average wind conditions, strong winds of short duration from any direction may generate features with orientations which are 'random to the average or resultant wind direction'(p21). Orme (1973) vectorially added wind data of all speeds and directions and compared the resultant to the orientation of dunes along the coast of Zululand. In this case the dunes appeared to be orientated to the prevailing wind rather than the resultant direction (Orme 1973). The orientation of coastal dunes in Bermuda seemed to better explained by a wind rose of gale force winds than a wind rose of all winds (Vacher 1973). 'Sand Moving Ability' roses were calculated and favourably compared to the orientation of parabolic dunes at coastal sites in northern Australia by Story (1982). Parabolic dunes on the east coast of Australia have been found to be aligned with the prevaling southeast trade winds (Pye 1982a; Pye 1983b; Thompson 1983; Pye and Rhodes 1985; Cook 1986; Ward and Grimes 1987). In addition to this, Pye (1983a) suggested that

> 'the main factor limiting dune development [in northern and central Queensland] appears to be the localized occurence of well-sorted coastal sand bodies in areas exposed to onshore wind energy' from the southeast

and that, by comparison,

> 'the distribution and and scale of dune formations shows little relationship with rainfall, length of dry season, tidal range, or the outlets of major rivers' (Pye 1983a, p180).

In New Zealand, Fleming (1953, p34) noted that 'active dunes [in the Wanganui region] are advancing parallel to the resultant direction bisecting the angle between the two dominant strong wind directions'. At the same time, Fleming states that 'prevailing onshore winds' (p24) have transported dune sand inland. Both Saunders (1968) and Holland (1983) found that dunes in the Manawatu are orientated to the 'predominant' wind direction while Esler (1970) claimed that the direction of sand movement in the Manawatu reflects the 'prevailing' wind. Whittow (1984) defines 'prevailing wind' as 'the wind which blows most frequently at any location' (p421) and 'dominant wind' as 'the wind that plays the most significant part in a local situation' (p152). Wilcock (1983) equates the dominant wind with the most effective sand moving wind and notes that while the dominant wind may often coincide with the prevailing wind on windward coasts, this is not often the case on leeward coasts. The dominant and prevailing wind directions are very similar or the same along most of the west coast of the North Island and this has lead to the apparent inconsistency in the literature mentioned above.

While attempting to explain the orientation of parabolic dunes along a section of the Danish coast, Shou (1952) saw the need for 'an exact expression of the direction determining influence of the wind' (p370). He proposed a method of calculating the '*direction-resultant of wind work*'(Shou's italics) where the Beaufort values of the wind speed (for winds > Beaufort 4) were multiplied by the percentage of occurrence for all wind directions. These values were then used to construct a vector diagram from which a resultant could be derived. Although this method had good results when applied to Shou's study area, Landsberg (1956) found it lacking in her study of dunes in Denmark and Britain. She proposed a slightly more complicated method of computing wind vectors (details of this method are discussed below) and these compared favourably with the majority of dune orientations in her study. Jennings (1957) suggested that only onshore winds should be used for calculation of Landsberg's wind resultant because the prevailing winds affecting a coastline characterised by transgressive dune development are not always onshore winds, and the beach supplies most or all sand for dune development. The advantages of this modified version were illustrated in Jennings' (1957) application of Landsberg's calculations to dunes on King Island, Tasmania. Bird (1965, as cited in Bird 1972) applied the same method when studying dunes at Ninety Mile Beach, Victoria, with similar results. Pye (1982b; 1983a) found that dunes at various locations along the Queensland coast were aligned with the Landsberg vector for *all* wind directions but this is not surprising considering the almost unidirectional nature of the wind climate along this coast. Gutman (1977) compared Landsberg's wind resultant to parabolic dunes in his study area, Currituck Spit in Virginia-North Carolina, but found that a better correlation was achieved when only onshore winds were used in his calculations. In New Zealand Pain (1976) and Shepherd (1987) used Landsberg's method to compute wind resultants for their study areas, near Kawhia Harbour and in the Manawatu respectively, and in both cases good correlations with dune orientation were achieved.

Fryberger (1979) provided a method of calculating rates of sand drift in desert dune areas which, like Shou's and Landsberg's wind vectors, can be vectorially added to produce a resultant. Fryberger's method also allows computations of directional variability of winds and levels of wind energy to be made. Details of Fryberger's method are discussed below. To the author's knowledge this method has not been applied to coastal dunes anywhere in the world.

Apart from the few cases outlined above, little work has been done to compare dune orientations with wind data in New Zealand. In his study of dunefields in Northland, Hicks (1975) measured the orientation of dunes in his study area but only measured the alignment of the *crests* rather than the axes of the dunes and no analysis of wind data was performed. Hicks' measurement of the orientation of dune crests appears to be related to his unusual hypothesis of dune formation (a description of this can be found in Chapter 3).

ANALYSIS OF NEW ZEALAND WIND DATA

The form of the data obtained for this study, as shown below, permits analysis using both Method B of Landsberg (Landsberg 1956) and drift potential calculations of Fryberger (Fryberger 1979).

Table 4.3 Form of data used in this study.

OHAKEA		ALL OTHER STATIONS	
Compass directions	Wind speed groups (knots)	Compass directions	Wind speed groups (knots)
360°	1 - 3	360°	1 - 3
30°	6 - 10	45°	4 - 10
60°	11 - 20	90°	11 - 16
90°	21 - 30	135°	17 - 21
120°	31 - 40	180°	22 - 27
150°	40 +	225°	28 +
180°		270°	
210°		315°	
240°			
270°			
300°			
330°			

Both of these methods provide ways of quantifying geomorphically effective winds at a site in the form of wind vectors which, when added, produces a resultant vector which represents the net average direction and relative magnitude of potential sand movement by wind at that site.

LANDSBERG METHOD

Method B of Landsberg's 1956 paper is shown below :

$$b = s \sum_{j=3}^{7+} n_j (v_j - V_t)^3$$

where b is the length of the wind vector for a particular wind direction
s is a scaling factor of 10^{-3}
n_j is the frequency of occurence of winds of velocity j
j is a Beaufort number
v_j is mean wind speed for Beaufort interval in mph
V_t is wind speed 'at which average drift sand begins to move' (Landsberg 1956) = 10 mph = 8.7 knots

Since V_t = 8.7 knots, and given the way in which the wind data are grouped, only winds of greater than 10 knots are used in calculating wind vectors (Landsberg 1956).

Values of v_j are as shown :

Met. Service wind speed groups* (knots)	Beaufort number	Mean speed (mph) = v_j
11 - 16	4	15.5
17 - 21	5	21.1
22 - 27	6	28.0
28 +	7+	?

* for all stations except Ohakea

A problem arose when a mean speed was required for an open interval (28 knots +) (this problem did not arise for the Ohakea data since no observations were recorded for the 40 knots + group). On the basis of frequency of winds >28 knots and overall mean wind speeds for the anemometer sites, the sites appeared to fall into two natural groups. The groups were labelled A and B and each was assigned a different mean wind speed for the 28 knots + wind speed interval (see Apendix 2).

Group A included sites where frequency of winds > Beaufort 7 are less than 18 per thousand and mean wind speeds are less than 11 knots. Group B included sites where frequency of winds > Beaufort 7 are greater than 17 per thousand and mean wind speeds are greater than 11 knots.

The values for the mean wind speed (v_j) for the Beaufort 7+ intervals were chosen to be 35 mph and 39 mph for group A and B respectively. Since no information was available regarding the distribution of the frequency of winds > 28 knots, the values for v_i for the two groups were chosen arbitrarily as the mean of the Beaufort 7 interval and the mean of the Beaufort 7 plus Beaufort 8 intervals combined. This allowed the greater proportion of higher velocity winds at the locations in group B to be taken into account.

Using these values wind vector diagrams for the different stations were able to be constructed and the resultant vectors obtained. The resultants can be described in terms of length (magnitude) and direction (degrees azimuth).

Where Landsberg (1956) (studying coastal dunes) and Fryberger (1979) (studying inland desert dunes) computed resultants using winds from all directions, Jennings (1957) suggested that ' onshore winds must play a more vital role in coastal dune evolution than offshore ones' (Jennings 1957, 474) and constructed wind resultants using onshore winds only. Since coastal parabolics generally form by winds blowing sand inland from a coastal source, a higher correlation with dune orientation would be expected from these resultants than ones constructed using winds from all directions. This would be especially so where offshore winds are prevalent. Since this is the case in some areas of New Zealand (most notably along the east coasts), resultant vectors were also computed for all sites using onshore winds only .

This required different vectors to be calculated for different sections of coast due to variation of orientation of the shoreline. To calculate vectors for any particular section of coastline, data were taken from the anemometer station closest to area. The data were then manipulated so that only the onshore winds at the dune location were represented.

For some stations (e.g. Tiwai Point) the onshore resultant differed only slightly from the all-winds resultant, while for others (e.g. Oamaru, Castlepoint) the differences were quite large. Because of the predominance of westerly winds over N.Z. as a whole, the east coast of the country tends to experience a greater proportion of offshore winds making the differences in the directions of the onshore-only and all-winds resultants greater for the east coast stations.

The lengths of the vectors, representing the magnitude of the resultant, vary from station to station allowing comparison of the relative 'windiness' of the different locations. For example, Tiwai Point experiences more geomorphically effective winds than Westport Airport, as reflected in the magnitudes of the resultant vectors for these locations (see Table 4.11).

FRYBERGER DRIFT POTENTIAL CALCULATIONS

Fryberger (1979) used the Lettau equation for the rate of sand drift (based on shear velocities) as a basis for a weighting equation for sand movement. The equation describing relative sand drift potential at a site is :

$$Q \propto V^2(V - V_t)t$$

where Q = annual rate of sand drift
V = average wind velocity at 10m height
V_t = impact threshold wind velocity at 10m
(= 12 knots using Bagnold 1941)
t = duration of wind (frequency of occurence)

$V^2(V - V_t)$ is the weighting factor derived from the Lettau equation. Calculation of the weighting factors is shown in Table 4.4 (note that the stations were divided into two groups in order to arrive at mean wind speeds for the highest wind velocity category, as was done for the Landsberg calculations).

Table 4.4

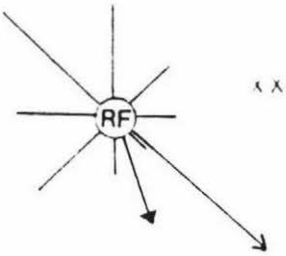
Velocity Category (knots)	**Mean velocity in category (V)**	V^2	$V - V_t$	**Weighting factor** $V^2(V - V_t)/100$
11 - 16	13.5	182.3	1.5	2.7
17 - 21	19.0	361.0	7.0	25.3
22 - 27	24.5	600.3	12.5	75.0
28 - 33 *	30.5	930.3	18.5	172.1
28 - 40 **	34.0	1156.0	22.0	254.3

* for group A
** for group B

The weighting factor for any velocity group was multiplied by the percentage of time that winds from that velocity group were blowing from any one of the eight compass directions listed in the Met. Service data. The numbers calculated for a direction are added, giving the sand drift potential for winds from that direction. These provide a 'measure of the relative amount of potential sand drift at a station for a stated period of time.'(Fryberger 1979). Once drift potentials have been calculated for all eight wind directions, these may be expressed as vectors and a sand rose constructed (see FIGURES 4.2 to 4.17).

To keep the roses similar sizes, all vectors for any location were divided by a number sufficient to reduce the longest vector to less than 50 units (each unit expressed on the sand rose as one millimetre). This number is referred to as the reduction factor. The vectors for the different directions were added to form a resultant representing the net direction of sand drift and the 'net sand transport potential when winds from various directions interact' (Fryberger 1979) for the different anemometer sites. Visual comparison of the magnitudes of the vectors and resultants between stations may be more difficult than with the Landsberg vectors

Key to Sand Roses



XX Abbreviation for anemometer station

RF Reduction Factor

╲ sand drift potential for winds >10 knots

↘ sand drift potential resultant for winds >10 knots

↓ sand drift potential resultant for winds >21 knots

Abbreviations used for anemometer stations

MP	Marsden Point
KS	Kaipara, South Head
TA	Tauranga airport
PT	Port Taharoa
CE	Cape Egmont
NA	Napier airport
WA	Wanganui airport
OH	Ohakea
TH	Te Horo
CA	Castlepoint
FS	Farewell Spit
WE	Westport airport
CA	Christchurch airport
HA	Haast
OA	Oamaru
TP	Tiwai Point

FIGURE 4.1 Anemometer sites

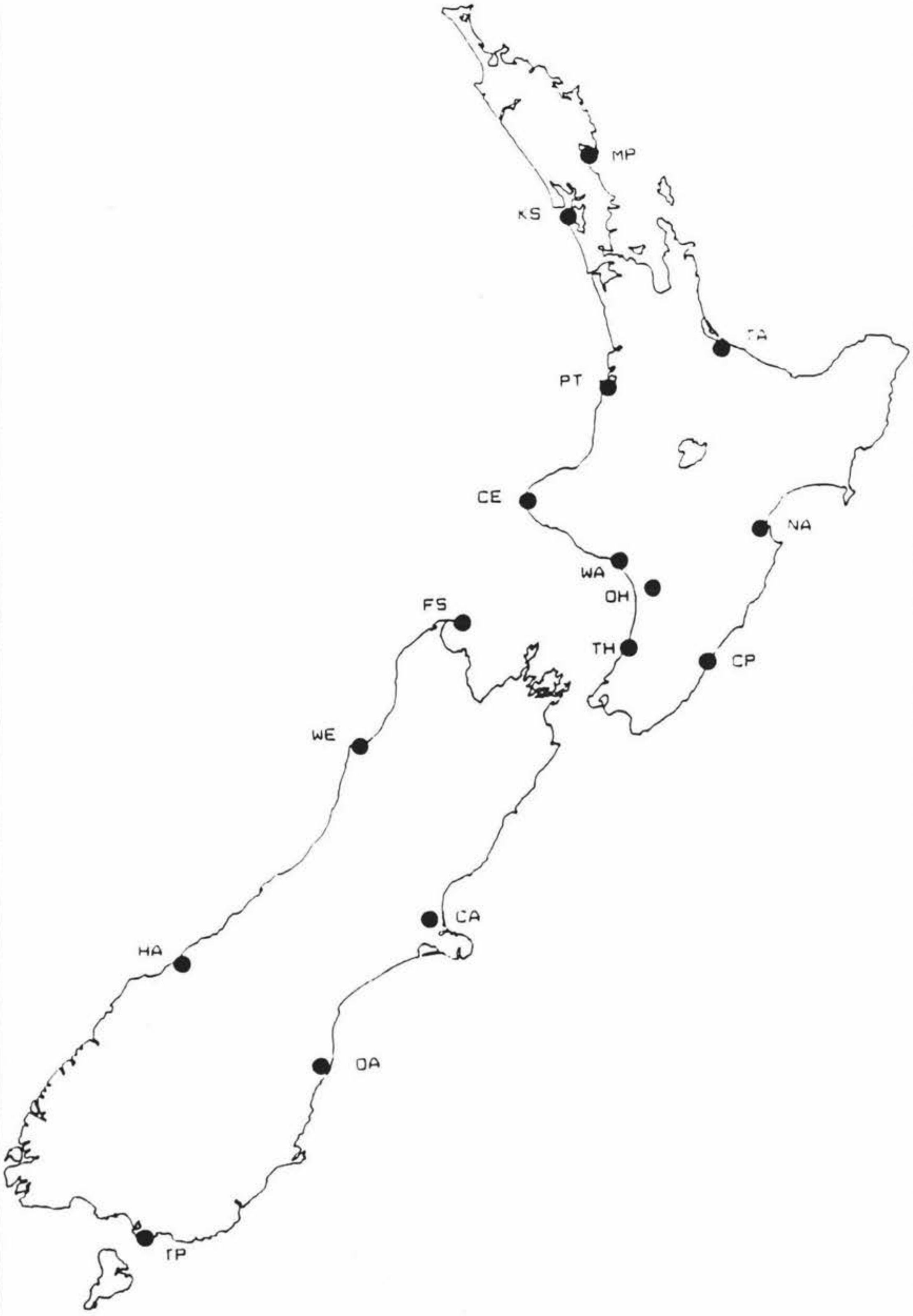


FIGURE 4.2 Sand rose - Marsden Point

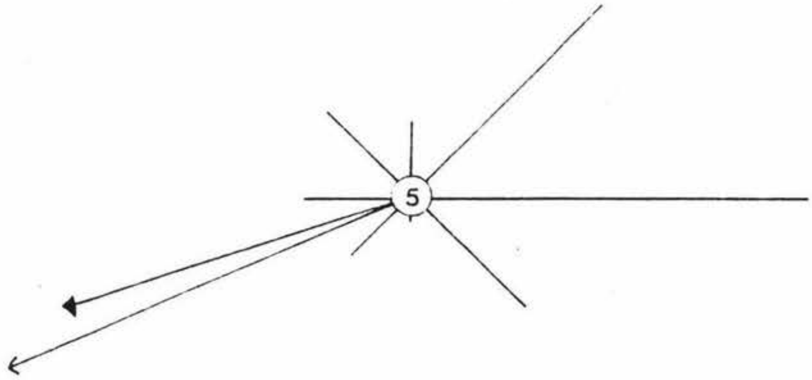


FIGURE 4.3 Sand rose - Kaipara, South Head

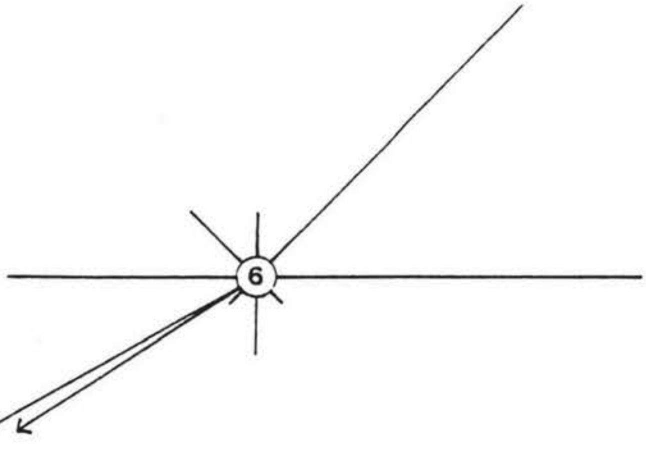


FIGURE 4.4 Sand rose - Tauranga airport

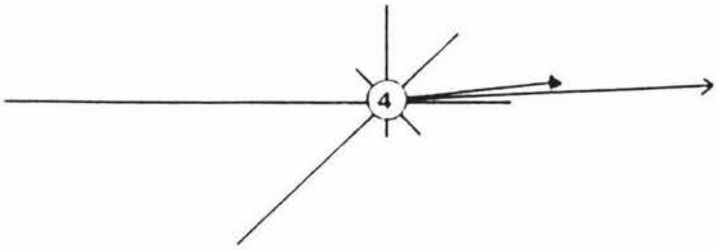


FIGURE 4.5 Sand rose - Port Taharoa

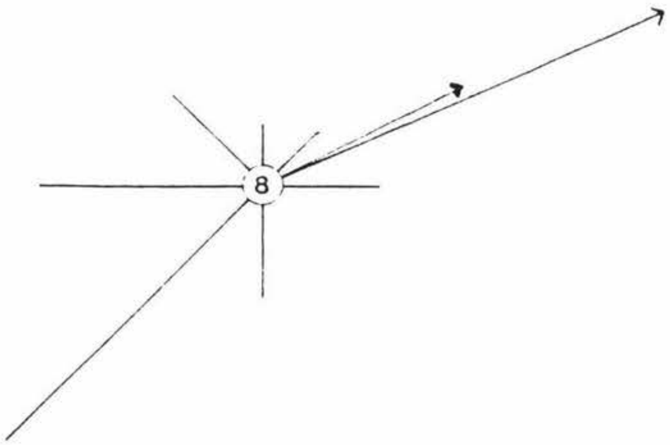


FIGURE 4.6 Sand rose - Cape Egmont

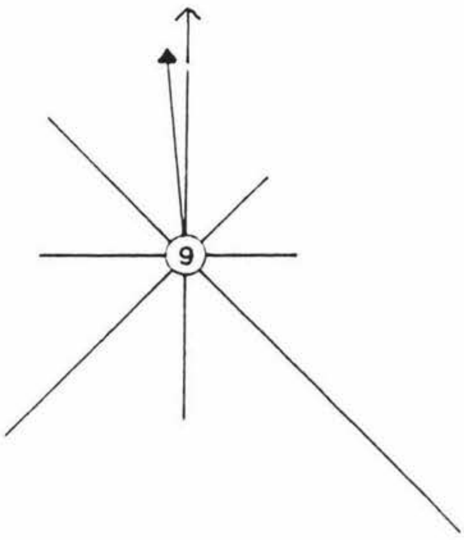


FIGURE 4.7 Sand rose - Napier airport

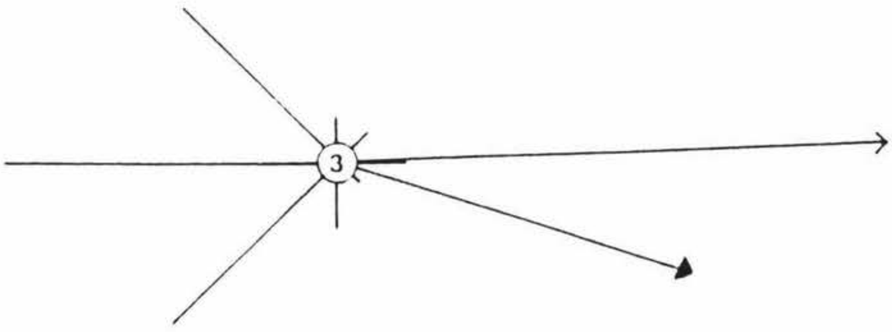


FIGURE 4.8 Sand rose - Wanganui airport

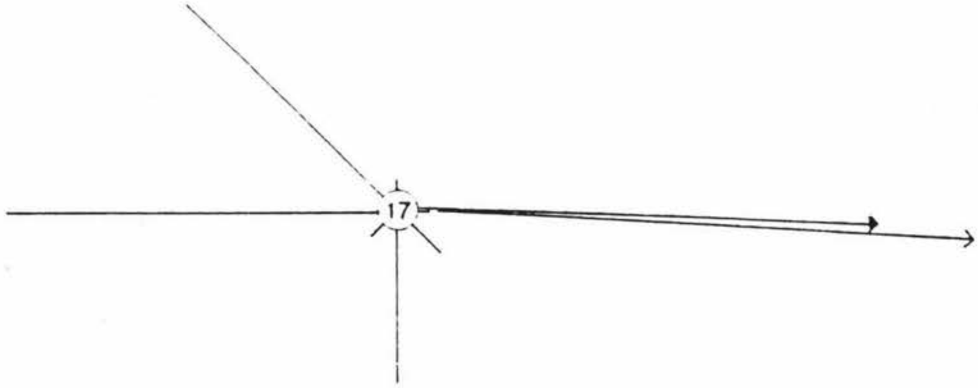


FIGURE 4.9 Sand rose - Ohakea

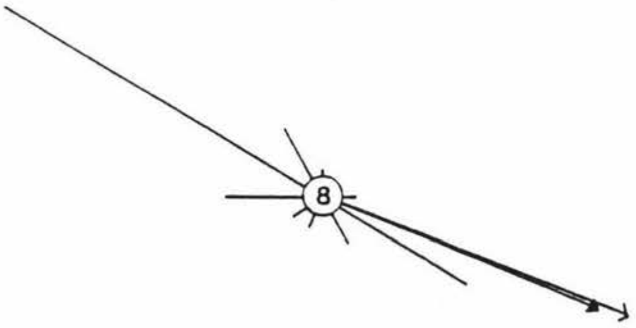


FIGURE 4.10 Sand rose - Te Horo

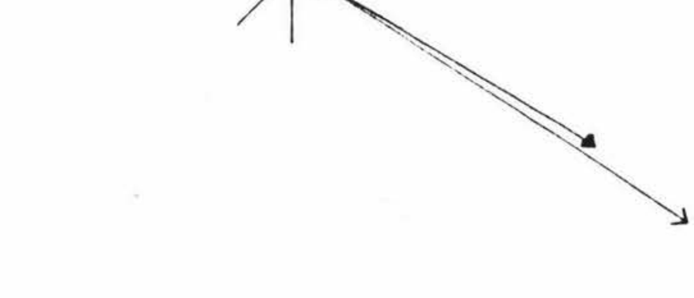


FIGURE 4.11 Sand rose - Castlepoint

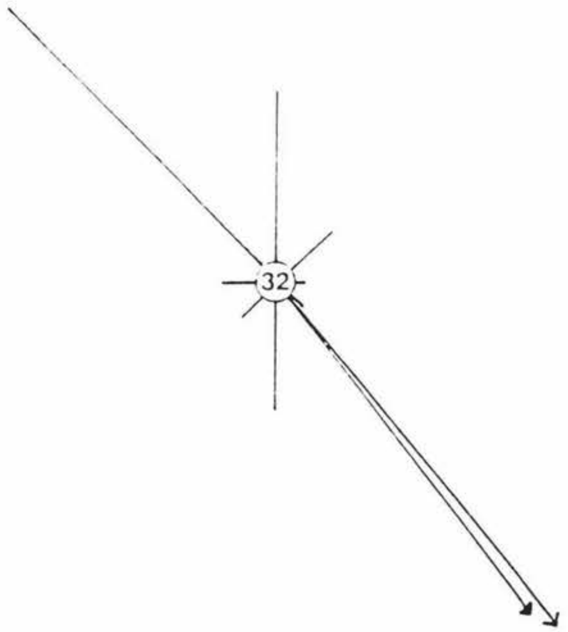


FIGURE 4.12 Sand rose - Farewell Spit

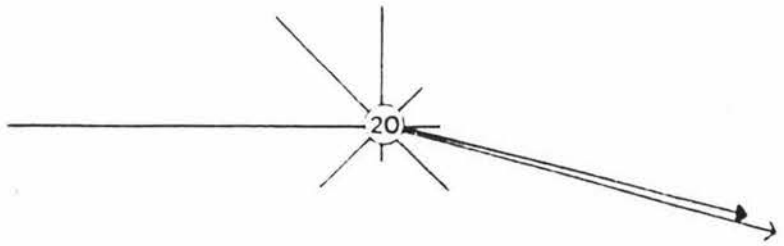


FIGURE 4.13 Sand rose - Westport airport

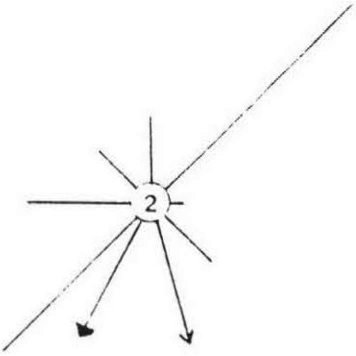


FIGURE 4.14 Sand rose - Christchurch airport

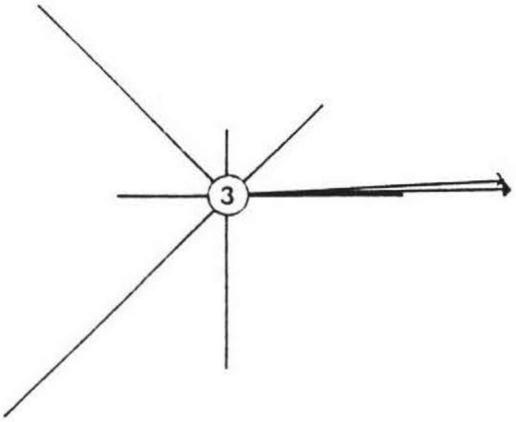


FIGURE 4.15 Sand rose - Haast

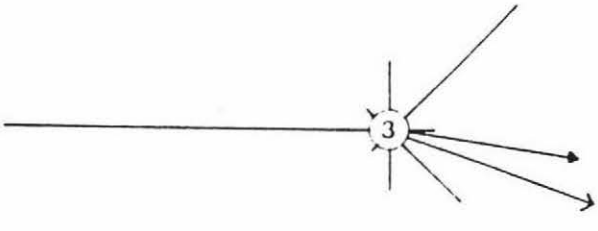


FIGURE 4.16 Sand rose - Oamaru airport

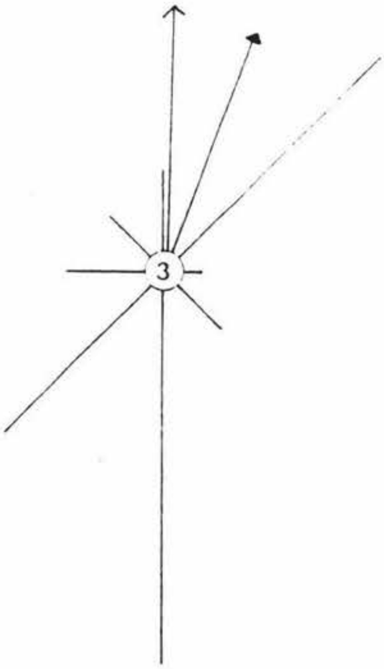
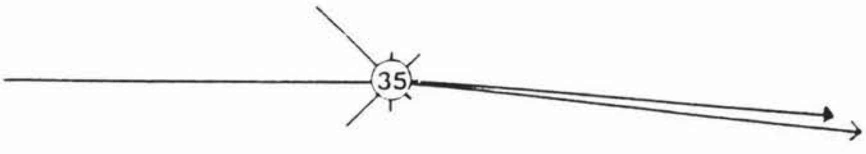


FIGURE 4.17 Sand rose - Tiwai Point, Bluff



because different reduction factors are used for each diagram. The reduction factor is shown in the centre of each sand rose to assist comparisons.

As with the Landsberg calculations, resultants were calculated for onshore winds as well as for all winds.

Strong storm winds can be very effective in intiating blowouts as well as moving sand inland so the drift potential of strong winds (Beaufort 6 +) alone are of interest. To see if strong winds cause drift in the same direction as all winds > 10 knots or not, resultants for all winds of velocities of > 21 knots were also computed. In Table 4.5, below, these directions are listed and the differences shown.

Table 4.5

Location	X Resultant direction for all winds > 10 knots	Y Resultant direction for all winds > 21 knots	|X - Y|
Marsden Point	67°	72°	5°
South Head, Kaipara	57°	61°	4°
Tauranga airport	267°	264°	3°
Port Taharoa	247°	243°	4°
Cape Egmont	180°	175°	5°
Napier airport	268°	267°	1°
Wanganui airport	273°	272°	1°
Ohakea	291°	292°	1°
Te Horo	303°	302°	1°
Castlepoint	321°	322°	1°
Farewell Spit	285°	284°	1°
Westport airport	345°	28°	43°
Haast	289°	280°	9°
Christchurch airport	267°	269°	2°
Oamaru	182°	200°	18°
Tiwai Point, Bluff	276°	274°	2°

For most locations the directions of the two resultants are very similar. At Westport however they differ by 43° indicating that the strongest winds and more moderate winds tend to blow from quite different directions at this location. This is also the case at Oamaru and Haast although to a lesser degree.

Fryberger also provides methods for assessing both the level of wind energy and directional variability of the wind at a location.

WIND ENERGY

The energy level is based on the value of total drift potential (DP). This value is the sum of drift potentials for all 8 directions, expressed as vector units (before reduction). Fryberger's classification of wind energy is shown below :

Table 4.6

DP value (vector units)	Level of Wind Energy
< 200	low
200 - 399	intermediate
400 +	high

(Fryberger 1979)

This classification is based on a set of drift potential values ranging from approximately 80 to 489 vector units taken from desert regions only. The DP values for the sixteen anemometer sites around the New Zealand coastline ranged from 205 vector units (for Westport airport) to 3389 vector units (for Castlepoint), indicating that the exposed coastal sites are subject to much higher levels of wind energy than the inland desert sites studied by Fryberger (1979). If the New Zealand data is grouped using the Fryberger classification, there are no low energy sites, only three intermediate energy sites and all the others fall into the high energy group. Given the factors mentioned above the author proposes a different classification for relative wind energy levels around the New Zealand coastline based on the values for drift potential at the sixteen sites used in this study. These values are listed below.

Table 4.7

Location	DP values (vector units)
Westport airport	205
Haast	292
Napier airport	351
Christchurch airport	412
Tauranga airport	441
Oamaru airport	464
Marsden Point	678
Te Horo	748
Ohakea	770
Port Taharoa	996
South Head, Kaipara	1061
Cape Egmont	1679
Wanganui airport	2016
Farewell Spit	2242
Tiwai Point, Bluff	2652
Castlepoint	3389

Given the natural groups that the data appear to form, the following classification is proposed :

Table 4.8

DP value (vector units)	Level of Wind Energy
< 550	low
550 - 1399	intermediate
1400 - 2399	high
2400 +	very high

As with Fryberger's classification, this is only intended for use with the data in this study and not for universal application. Use could perhaps be extended to the rest of the New Zealand coastline but could not apply to inland areas. Further discussion of the wind energy levels at the different sites in this study can be found in Chapter 5.

DIRECTIONAL VARIABILITY OF WIND

Fryberger calculated values to measure the relative directional variability of winds received at different locations. This involved dividing the resultant drift potential (RDP) by the drift potential (DP) for each site, where the RDP is the magnitude (in vector units) of the resultant drift direction (before reduction). Fryberger provided an arbitrary classification of directional variability where low values of RDP/DP indicate high directional variability and high values indicate low variability.

Table 4.9

RDP/DP	**Directional Variability**
0.0 to < 0.3	high
0.3 to < 0.8	intermediate
0.8 +	low

Values for RDP/DP for the sixteen New Zealand sites were computed and are listed below.

Table 4.10

Location	**RDP/DP**	**Directional Variability**
Westport Airport	0.14	high
Cape Egmont	0.15	
South Head, Kaipara	0.19	
Oamaru Airport	0.21	
Haast	0.23	
Christchurch airport	0.24	
Marsden Point	0.31	intermediate
Tauranga Airport	0.36	
Ohakea	0.42	
Port Taharoa	0.44	
Farewell Spit	0.44	
Castlepoint	0.52	
Napier Airport	0.60	
Wanganui Airport	0.62	
Te Horo	0.63	
Tiwai Point	0.78	

COMPARISON OF LANDSBERG AND FRYBERGER METHODS

As seen from Table 4.11, the resultants obtained by both methods were generally very similar in direction.

Table 4.11

Directions of all-winds
(>10 knots) resultants

Location	Landsberg	Fryberger	Differences
Marsden Point	69°	67°	2°
South Head, Kaipara	57°	57°	0°
Tauranga Airport	268°	267°	1°
Port Taharoa	249°	247°	2°
Cape Egmont	176°	180°	4°
Napier Airport	270°	268°	2°
Wanganui Airport	280°	273°	7°
Ohakea	292°	291°	1°
Te Horo	302°	303°	1°
Castlepoint	322°	321°	1°
Farewell Spit	284°	285°	1°
Westport Airport	360°	345°	15°
Haast	287°	289°	2°
Christchurch airport	267°	267°	0°
Oamaru Airport	184°	182°	2°
Tiwai Point, Bluff	274°	276°	2°

Allowing for probable errors in vector addition (due to rounding of values, use of reduction factors and resolution to only one millimetre for vector length) and measurement of resultants (due to resolution to only one degree in direction) the agreement between the two methods is good for most locations. However Cape Egmont, Wanganui Airport and Westport Airport resultants show differences between the two methods of 4, 7 and 15 degrees respectively.

This is due to the comparatively greater emphasis that Landsberg's equation puts on the higher wind speed groups. For example, if frequency of occurance is kept constant but the mean wind speed for a direction is increased from 15 knots to 30 knots, then the magnitude of the Landsberg vector increases by a factor of 39 whereas the Fryberger vector increases it's magnitude by a factor of only 24. This is due in part to the different ways in which values for mean velocity are manipulated in the different equations and also to the different threshold velocities used each equation. The threshold velocity in the Landsberg equation is 10 mph (8.7 knots) 'at which average drift sand begins to move' (Landsberg 1956). The value used by Fryberger is the higher one of 12 knots which was computed using an equation from Bagnold 1941 giving the impact threshold velocity at a height of 10 metres. Landsberg does not state whether her value of 10 mph is the threshold velocity at the surface or at some height above the surface.

Accordingly, the two methods will produce resultants of differing directions where the directions of the greatest frequencies of higher wind speeds do not correspond to the directions of the greatest frequencies of lower wind speeds. Of the New Zealand locations, the most extreme example is Westport Airport where the difference in directions produced by the two methods is 15°. Earlier in this chapter it was noted that at Westport the drift resultant directions for winds >22 knots and for winds >10 knots differed markedly. At this site most of the lower velocity winds (11 - 21 knots) come from the western quadrant; they comprise a total of 11.3% of all winds. The percentage of stronger winds (22 knots +) from this quadrant is 0.3. The percentage of lower and higher velocity winds from the *northern* quadrant however, are 6.4 and 0.6 respectively. This is reflected in the higher direction value of the 360° azimuth for the Landsberg resultant compared to 345° for the Fryberger resultant. The Landsberg resultant, putting a greater emphasis on the higher wind speed groups, represents resultant drift from due north compared to Fryberger's north-northwest.

Given that the two methods agree for the majority of the anemometer sites, that Fryberger's method permits a number of additional calculations apart from drift resultants and that Fryberger's sand roses are more easily interpreted than Landsberg's wind resultant vector diagrams, only the results of applying Fryberger's method will be discussed in subsequent chapters except where data from Wanganui or Westport are concerned.

CHAPTER 5

AEOLIAN SAND DRIFT POTENTIAL AROUND THE NEW ZEALAND COASTLINE

INTRODUCTION

Levels of wind energy and directional variability used here are those from the classifications and calculations in Chapter 4. All rainfall data are from New Zealand Met. Service (1979).

POTENTIAL SAND DRIFT AROUND THE NEW ZEALAND COASTLINE

WEST COAST NORTH ISLAND

The level of total wind energy along the North Island's west coast is generally intermediate except at Wanganui and the exposed location of Cape Egmont where the energy levels are high. The frequency of calm conditions range from <0.5% at Te Horo in the south to around 8% at Kaipara in the north and at Ohakea which is a greater distance inland than the other stations. Directional variability of effective winds is intermediate at all locations apart from Kaipara and at Cape Egmont which have high variability.

The proportion of total drift potential that is directed in a generally onshore direction at a location is related to the directional variability.

Table 5.1

Location	Total Drift Potential (VUs)	Directional Variability (RDP/DP)	DP value Onshore	Onshore Drift Potential (VUs)	Onshore Wind Energy
South Head, Kaipara	1061	0.19	41%	435	low
Port Taharoa	996	0.44	70%	697	int
Cape Egmont	1679	0.15	60%	1007	int
Wanganui airport	2016	0.62	92%	1855	high
Ohakea	770	0.42	72%	555	int
Te Horo	748	0.63	86%	643	int

From Table 5.1 it would appear that the area with the wind conditions least suited to development of coastal dunes is the far north near Kaipara where the level of wind energy directed in an onshore direction is low. This result seems odd since the prevailing winds along this stretch of coast would be expected to be from a westerly direction as they are at Port Taharoa to the southwest and Marsden Point to the northeast. Given this anomaly together with the short period of time over which measurements were taken (see

Appendices) and probable orographic influence at this location (see above), it is suggested that the Kaipara drift potential rose be applied to this area with caution.

The Manawatu embayment (around Wanganui in particular) appears to experience the most favourable conditions for transgressive dune development. This can also be seen from Table 5.1 and also the drift potential roses for Wanganui, Ohakea and Te Horo which show resultants directed in onshore directions.

Most of the west coast of the North Island is exposed to the prevailing southwest winds. At Port Taharoa winds from the west and southwest predominate and the area is largely protected by topography from flow from the northeasterly quarter.

At Cape Egmont the resultant drift potential direction is from the south which is onshore for the southern part of the cape but not the north. The northern part of the cape would be expected to be sheltered from southwesterly flow. Cape Egmont itself is exposed to winds from all directions but southwesterlies and southeasterlies involve the greatest drift potential. The southeasterly winds probably involve southerly winds channelled through Cook Strait and deflected around Mount Egmont (Taranaki).

South of Cape Egmont, the South Island begins to have a sheltering effect so that at Wanganui, Ohakea and Te Horo the proportion of southwesterly winds is very small. At Wanganui a degree of chanelling of westerly winds combined with some deflection of southwest winds around the northern tip of the South Island result in dominance of drift potential from the northwest and west. Southerlies channelled through Cook Strait also influence the area. Shelter from flow from the north and east is provided by topography although the presence of the topographic low in the vicinity of the Manawatu Gorge to the southeast leads to a slight increase in effective winds from this quarter.

At Ohakea the deflection of winds around the South Island and their funnelling through the topogrphic low between the Ruahine and Tararua ranges results in northwesterly winds dominating with opposing southeasterlies reducing the resultant drift potential. Te Horo also experiences a predominance of northwesterly winds producing a resultant more than ten degrees more northerly than that of Ohakea. South and southwesterly winds result from channelling of flow between Kapiti Island and the mainland as well as parallel to the Tararua Ranges. Northerly winds are also more common at Te Horo than at Wanganui or Ohakea because of the increased angle of deflection around the South Island and because the coastline at Te Horo and the ranges to the east both run northeast-southwest.

At all sites the resultant direction for winds >10 knots differs less than 6° from the resultant for winds >21 knots (see Table 4.5). This indicates that all the effective winds at these locations blow from different directions in similar proportions.

Over the west coast as a whole, annual rainfall is moderate (from 900mm - 1400mm). With the exception of Kaipara, the proportion of effective onshore winds tend to be highest in spring at all locations. By contrast rainfall tends to be highest in winter when depressions and associated frontal systems pass more frequently over New Zealand (Burgess 1988). At Wanganui airport the 'most persistant heavy rains' are associated with winds from the east-southeast close to the centres of active depressions (N.Z. Met. Ser. 1982). Although onshore winds often coincide with showers (N.Z. Met. Ser. 1982; Thompson 1981; Maunder 1974; Burgess 1988), these tend to be heaviest inland from the coast due to the effect of orography.

WEST COAST SOUTH ISLAND

The wind climate varies considerably along the length of the west coast of the South Island. While wind energy at Farewell Spit is high, further south at both Westport and Haast the energy levels are low. Calm conditions exist for 7.3% of the time at Farewell Spit and for 8.6% and 17.7% of the time at Westport and Haast respectively. Direction of the winds at the southern stations varies more also, resulting in even lower amounts of energy directed onshore at Westport and Haast. Because of the Farewell Spit station's unique location near the tip of a very long sand spit all wind directions can be taken to be onshore.

Table 5.2

Location	Total Drift Potential (VUs)	Directional Variability (RDP/DP)	%DP value Onshore	Onshore Drift Potential (VUs)	Onshore Wind Energy
Farewell Spit	2242	0.44	100%	2242	high
Westport airport	205	0.14	55%	113	low
Haast	292	0.23	58%	169	low

At the exposed location of Farewell Spit the drift resultant is from the west-northwest reflecting the dominance of effective winds primarily from the west and secondarily from the north and northwest. The drift resultant for winds >21 knots differs by only one degree from the >10 knots resultant. This location is provided with some shelter from southerlies and southwesterlies by the South Island land mass. Southeast winds tend to be deflected by the Marlborough Sounds resulting in a lower proportion of these winds than might otherwise be the case. Although the drift potential of these winds may be small in comparison with those from the west, it must be remembered that the reduction factor of the Farewell Spit rose is 20 indicating that the absolute DP from those directions is quite high.

South of Farewell Spit, the presence of high mountain ranges close to the coast affects the wind climate dramatically. The Paparoa Ranges, Southern Alps and other ranges modify synopic scale winds in two principal ways. Strong west and northwest winds are largely prevented from affecting the coastal areas due to a 'cushion' of air adjacent to the ranges which is created as a result of these conditions. This 'upwind blocking effect' creates lower wind speeds at the coast and intensified wind speeds at the summits of the ranges (Cherry 1976). The other effect is the channelling of winds from a southwesterly or northeasterly direction parallel to the coastline, resulting in increased wind speeds. The result of both of these effects can be seen on the rose for Westport where northeast and southwest winds almost cancel each other. The northeast winds tend to be the stronger of the two at this location leading to a 43° difference between the drift resultants for winds >10 knots and >21 knots (see Table 4.5).

Because of the low overall level of wind energy at this location, locally generated winds play a proportionally greater part here than in the west coast locations of the North Island. Katabatic winds can reach quite high speeds in this region due to the very cold temperatures often experienced in the higher altitudes inland (Hessell 1982). At Westport the percentage of southeast winds increases in the autumn and winter indicating that at least some of these winds would be katabatic winds flowing down the Buller Gorge to the coast. These offshore winds are less effective than the onshore winds overall, resulting in an onshore drift resultant at Westport.

Katabatic winds from valleys to the south and southeast of Haast create a similar effect to that experienced in Westport. Limited north and northwest winds and a channelling effect of winds from the northeast are also indicated by the drift potential rose. Haast's wind climate differs from that of Westport in the lack of southwesterly winds and the greater proportion of westerly winds in this location. Both of these effects may be attributed to the presence of Jackson Head and Cascade Point not far to the south of Haast. These features would shelter Haast from southwest winds and possibly increase the velocity of westerly winds affecting the area. During the winter strong winds approach Haast from all directions but for the rest of the year westerly winds dominate the higher velocity groups. On average a greater proportion of winds from 10 to 21 knots come from the easterly quarter than the westerly quarter but because westerly winds clearly dominate the winds >21 knots, the drift resultants for winds >10 knots and >21 knots differ with the latter being 9° more westerly (see Table 4.5).

The wind climate of Fiordland would be expected to vary spatially due to the high relief and uneven topography.

Almost all rainfall that occurs in the Westland area is accompanied by winds from the west or winds with a northerly component whereas dry weather tends to be associated with calm conditions or easterlies (Hessell 1982). Rainfall is very high over most of Westland with mean annual values of over 2000 mm at Westport and over 3000 mm at Haast. The combination of reduced onshore wind speeds and a high total of rainfall associated with onshore winds mean that potential for sand movement inland along much of the west coast is very low. A lack of orographically induced precipitation at Farewell Spit means that annual rainfall (1200 mm) and the distribution of rainfall through the year bears more resemblance to west coast locations in the North Island than those in the south. This, combined with a much higher drift potential, makes Farewell Spit a location much more potentially favourable for aeolian processes than the rest of the west coast of the South Island. (All rainfall data from New Zealand Met. Service (1979)).

SOUTH COAST SOUTH ISLAND

Although the level of wind energy received at Tiwai Point, Bluff,is very high calm conditions exist for nearly 10% of the time. When the wind does blow it tends to be at higher velocities and from the west. The directional variability of the winds here is the lowest af all the stations examined with a value of 0.78. This falls very close to the 0.8 boundary between intermediate and low values of directional variability in the classification discussed in Chapter 4.

Table 5.3

Location	Total Drift Potential (VUs)	Directional Variability (RDP/DP)	%DP value Onshore	Onshore Drift Potential (VUs)	Onshore Wind Energy
Tiwai Point	2652	0.78	78%	2069	high

The reduction factor used to draw the drift potential rose for Tiwai Point is 35 - the highest one for all the stations. This is due to the overwhelming dominance of westerly winds at this location. The drift resultant directions for winds >10 knots and >21 knots are 6° and 4° north of west respectively. Northwest and southwest winds together with the westerlies account for most of the drift potential. As winds from the westerly quarter are funnelled through Foveaux Strait they tend to form westerlies. Locally generated winds have very low influence on the overall wind climate relative to these winds. Katabatic winds would be expected to flow from the highlands north of Bluff but the winds would be weakened in strength and dispersed after leaving the valleys and flowing onto the plains which extend for a considerable distance inland of the coast.

Annual rainfall at Bluff Reservoir, near Tiwai Point, is 995 mm which is lower than that experienced on the west coast of the South Island. The rainfall is very evenly distributed throughout the year. Northerly winds are generally associated with dry weather while south or southeasterly flow is often accompanied by rain or drizzle (Sansom 1984). Westerlies also tend to be associated with rain but these are usually heaviest in the west with only scattered showers along the south coast (Sansom 1984). In spite of any rain which may accompanie westerly winds, their strength and frequency creates a high potential for sand movement on any section of the coastline which is exposed to the west.

EAST COAST NORTH ISLAND AND BAY OF PLENTY

Due to the varying outline of the eastern coastline of the North Island, different sections of the coast are sheltered or exposed to winds from different directions. Most of this coast is protected from the full forces of the prevailing westerlies resulting in generally lower wind energy levels and therefore a greater relative importance of local winds. Together these factors lead to a great variation in wind climate along the east coast.

Wind energy varies from intermediate at Marsden Point to low in both the Bay of Plenty and Hawke Bay. Castlepoint on the Wairarapa coastline by contrast has the highest energy of all the stations in this study. The frequency of calm conditions is quite high for the three northern stations, ranging from 11% at Marsden Point to 14.6% at Napier airport. Again Castlepoint is different with only 5% calms. Directional variability is intermediate for all four locations with Marsden Point and Tauranga airport having the highest variabilities. (All rainfall data from New Zealand Met. Service (1979)).

Table 5.4

Location	Total Drift Potential (VUs)	Directional Variability (RDP/DP)	%DP value Onshore	Onshore Drift Potential (VUs)	Onshore Wind Energy
Marsden Point	678	0.31	60%	407	low
Tauranga airport	441	0.36	19%	84	low
Napier airport	351	0.60	13%	46	low
Castlepoint	3389	0.52	24%	813	int

At Marsden Point there is a large percentage of winds from the west but these tend to be in the 4 to 10 knot velocity group. The greatest proportion of effective winds come from the easterly quarter. The strongest winds tend to be from this quarter while winds of 11 to 21 knots come from both the easterly and westerly quarters in similar proportions. Subsequently the resultant for winds >21 knots is 5° more easterly than that of the resultant for winds >10 knots (see Table 4.5)

Marsden Point is partially sheltered from winds from the north and the southwesterly quarter by topography but the proportion of winds from the northwest may be increased by the channelling effect of Whangarei Harbour. The level of wind energy directed onshore is low at this location.

Tauranga in the Bay of Plenty receives even less wind energy. Strong winds are uncommon in this area but when they occur they tend to be in the form of westerlies or southwesterlies despite the considerable topographic shelter provided by the Kaimai, Raukumara and Huiarau Ranges to the west and south. Because of the overall low wind energy of the area these winds dominate in terms of drift potential. Onshore winds tend to be weak although in summer northerly flows may be augmented by sea breezes bringing wind speeds up to 20 knots (New Zealand Met. Service 1982b). The strongest winds affecting the area tend to follow the same pattern as other effective winds producing drift resultants for winds >10 knots and >21 knots that differ by only 1°.

Napier also receives low wind energy due to protection by inland mountains to the north, west and south. Again, winds from the westerly quarter are predominant resulting in a drift resultant that points almost exactly due east. The drift resultant for winds >21 knots differs from this by 1°. Winds from the westerly quarter are channelled along the Heretaunga Plains and through river valleys running between the Ruahine, Kaweka and Ahimanwa Ranges so that winds tend to arrive from the northwest, west and southwest in comparable proportions. Sea breezes in summer can reach speeds of up to 20 knots (Thompson 1987) but as in the Bay of Plenty, onshore winds tend not to be strong so that total drift potential is offshore with the amount directed in an onshore direction being very low. The situation in northern Hawke Bay would be expected to be slightly different as this part of the coastline is exposed to stronger southerly winds. This would create a higher potential for sand drift inland from the coast.

The Wairarapa coastline is also exposed to flow from the south. At Castlepoint strong southerly winds do have a high frequency but this is again overshadowed by the frequency of strong winds from the westerly quarter. In this case, though, it is winds from the northwest which dominate the wind climate. The northwesterlies comprise westerly winds which have been channelled through the topographic low between the Ruahine and Tararua ranges and diverted around the southern the Puketoi Range. Diversion of flow from the east and northeast along the ranges which lie along the Wairarapa coastline result in an increased proportion of north-northeasterlies which are a component of northerly winds in the data used. These northerlies more or less counter-balance the southerlies so that the drift resultant for winds >10 knots points almost directly southeast. The strongest winds follow almost exactly the same pattern with the drift resultant for winds >21 knots deviating from the above by 1°.

The winds funnelled through the topographic low between the Ruahine and Tararua ranges strongly affects the wind climate throughout northern Wairarapa while winds channelled through Cook Strait influence parts of southern Wairarapa (Thompson 1982) and the strength and frequency of these winds mean that while the overall drift potential is high, the potential directed onshore is much less.

Rainfall along the east coast of the North Island tends to be moderate (from around 800 mm at Napier to just over 1300 mm at Tauranga) and the annual distribution is similar to that experienced on the west coast. The greatest frequency of strong winds (those from the north and northeast) experienced at Marsden Point occur during winter. This is also the season of highest rainfall. Rain is common with north and northeast flows in the Bay of Plenty (Quayle 1984). At Napier over 60% of rainfall is associated with wind from the south or southeast but intense precipitation is more likely to take place during east or northeast winds (Thompson 1987). At Castlepoint the onshore southerly winds peak in winter which is also the peak season for rainfall. (All rainfall data from New Zealand Met. Service (1979)).

EAST COAST SOUTH ISLAND

Sheltered from the westerlies by the high altitude ranges of the South Island, the east coast receives low wind energy along most of it's length. Both Christchurch and Oamaru receive low energy but locations such as Cape Campbell would be expected to have a higher level of wind energy due to exposure to strong winds channelled through Cook Strait. The low energy is combined with high variation in wind directions at both stations. Calm conditions exist for 8% and 9% of the time at Christchurch and Oamaru respectively.

Table 5.5

Location	Total Drift Potential (VUs)	Directional Variability (RDP/DP)	DP value Onshore	Onshore Drift Potential (VUs)	Onshore Wind Energy
Christchurch airport	412	0.24	25%	103	low
Oamaru airport	464	0.21	63%	292	low

There are several characteristics of wind climate that are common to most of the east coast. Westerly winds which flow over the mountain ranges may form dry foehn winds which tend to arrive at the east coast as northwesterlies (McGann 1983; New Zealand Meteorological Service 1982). Topography influences wind directions and energy levels due to the presence of the two main peninsulas - Banks and Otago, mountain ranges adjacent to the coast which can deflect flow along their edges, and valleys in those ranges which can channel katabatic and other winds. Another tendency is for the percentage of calm conditions to be highest in winter and lowest in summer. This is due to the sea breezes which commonly develop during the summer months.

The drift roses from Christchurch and Oamaru illustrate these effects. At Christchurch a high proportion of winds are foehn winds (and sometimes katabatic winds) from the northwest (McGann 1983). The frequency of southwest winds is increased by the tendency for strong southeasterlies (from which Christchurch is orographically sheltered) to be deflected around Banks Peninsula (McGann 1983). Sea breezes can be enhanced by the orographic pressure trough created by the ranges to the west, resulting in northeasterlies of up to 16 knots

(McGann 1983). As on the Wairarapa coast, the strongest winds that flow onshore for most of the coastline tend to be from the south. Southerly flows are associated with the passage of cold fronts and these are more common in the south than the rest of New Zealand (see Table 4.1). At Christchurch however, the orientation of the coastline means that southerlies are not onshore winds. Since winds from the northwest and southwest dominate the effective wind climate at that location, the drift resultant is offshore and the amount of energy directed onshore is very low. The drift resultants for all effective winds and for winds >21 knots differ by only 2°.

Foehn winds also approach Oamaru from the northwest but because of the wider barrier to westerlies there compared with Christchurch, the drift potential from this direction in diminished. Strong southwesterlies reach Oamaru airport despite the presence of the Kakanui Ranges and other topographic barriers. This may be partially related to valley systems which tend to run northeast-southwest through these highlands. Northeasterly sea breezes can attain velocities up to 15 knots (New Zealand Meteorological Service 1982) and the drift potential from this direction more than balances the potential from the opposing direction. The drift resultant points almost directly north reflecting the dominance of southerly winds at this location. Oamaru is exposed to winds from this direction but these winds are also enhanced by the tendency for southerly winds to be deflected to flow parallel to the SSW-NNE aligned hills nearby (New Zealand Meteorological Service 1982). However, because northeasterlies are dominant for wind speeds of 11 - 21 knots, but southerlies and southwesterlies are the most frequent for winds >21 knots, the drift resultant for winds >21 knots is 18° more westerly than the resultant for all effective winds (see Table 4.5). As a result of high proportions of effective winds from the northeast and south, the percentage of total drift directed onshore is quite high. However, because this is a low energy site, the potential for drift inland is also low.

Annual rainfall is low at both anemometer sites with around 650 mm at Christchurch and 540 mm at Oamaru. Rainfall amounts increase at the peninsulas and to the far north and far south of the coastline. At Christchurch 75% of the annual rainfall is accompanied by winds from the southwest quarter (McGann 1983) and the peak season for rainfall is winter. The distribution of precipitation through the year at Oamaru is very even but there is a small peak during winter. The frequency of strong southerlies also peaks at this time. (All rainfall data from New Zealand Met. Service (1979)).

ONSHORE DRIFT POTENTIAL AROUND THE NEW ZEALAND COASTLINE

A summary of the values for potential sand drift inland from the coast at the sixteen anemometer sites is shown in Table 5.6. In terms of wind climate only, these values provide an idea of which sections of the New Zealand are most likely to be characterised by transgressive dune development.

Table 5.6

Location	DP Values (vector units)	Wind Energy Level
Napier airport	46	low
Tauranga airport	84	
Christchurch airport	103	
Westport airport	113	
Haast airport	169	
Oamaru airport	292	
Marsden Point	407	
South Head, Kaipara	435	
Ohakea	555	intermediate
Te Horo	643	
Port Taharoa	697	
Castlepoint	813	
Cape Egmont	1007	
Wanganui airport	1855	high
Tiwai Point, Bluff	2069	
Farewell Spit	2242	

Ignoring all other influencing factors then, the locations most favourable for movement of sand inland are Farewell Spit, Tiwai Point and Wanganui. Those least favourable tend to be situated on the east coast of either the North or South Island, or on the west coast of the South Island. It is very likely that the west coast of Northland is a location more favourable for transgressive dune development than is suggested by these figures.

Table 5.6

Location	DP Values (vector units)	Wind Energy Level
Napier airport	46	low
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Castlepoint	813	
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CHAPTER 6

ORIENTATIONS AND DIMENSIONS OF PARABOLIC DUNES IN NEW ZEALAND

INTRODUCTION

The orientations of blowouts and parabolic dunes as seen from aerial photographs are compared with resultant drift potential directions in Table 6.1. The table lists the range of dune orientations as well as the mean orientation and number of dunes at each site. Drift resultant directions are given for all effective winds for each anemometer station. Drift resultant directions using winds that are onshore at each site are listed and compared with the mean dune orientations for those sites. This is also done using strong (>21knots) onshore winds only. (A list of wind directions taken to be onshore at each site, along with the value of onshore drift potential for each site is provided in Table 6.2.)

This method of presentation differs from that used by Landsberg (1956) which listed only the range of dune orientations, the resultant vector directions and the *minimum* discrepancy between the two. This means that at first glance the agreement between orientations and resultants for the New Zealand study (using Frybergers drift potentials) does not seem as satisfactory as for Landsberg's study of dunes in Britain and Denmark. This is not necessarily the case, however, since a resultant direction may differ considerably from the mean dune orientation but fall within the range of orientations at a site. For example, at the Tukituki River site on the east coast of the North Island the onshore drift resultant for all winds >10 knots falls within the range of dune orientations and therefore would have a minimum discrepancy of 0° by Landsberg's method of comparison. However, the same drift resultant differs from the mean orientation value by 21°.

The coarse resolution of most of the wind data used to calculate drift potentials in this study means that a very close correlation between mean orientations and drift resultants would not necessarily be expected. Data from all stations apart from Ohakea were condensed into only eight compass groups. This means that wind directions are averaged over a range of 45° which represents a loss of data quality in terms of precision and this must affect the accuracy of the drift potential diagrams.

It must be noted that the dune orientations used in this study do not include the orientations of every blowout and parabolic dune around New Zealand's coastline. Time constraints, lack of ready access to photographs, the cost of examining photographs (DOSLI currently charges

TABLE 6.1

Location	Dune Orientation Range	Dune Orientation Mean	No. of Dunes	Station	All Winds >10 knots Resultant	Onshore winds >10 knots : Resultant	Onshore winds >10 knots : Discrepancy between resultant and mean orientation	Onshore winds >21 knots : Resultant	Onshore winds >21 knots : Discrepancy between resultant and mean orientation
<u>WEST COAST NORTH ISLAND</u>									
Ahipara	235°-240°	237.5°	2	KS	57°	258°	20.5°	263°	25.5°
Maunganui Bluff	239°-256°	248.0°	5	KS	57°	242°	6.0°	245°	3.0°
Maunganui Bluff	239°-256°	248.0°	5	MP	67°	248°	0.0°	255°	7.0°
Kaipara north head	217°-294°	248.0°	112	KS	57°	251°	3.0°	257°	9.0°
Kaipara south head	208°-257°	237.0°	67	KS	57°	242°	5.0°	245°	8.0°
Te Henga		221.0°	1	PT	247°	234°	13.0°	229°	8.0°
Manakau south head	219°-274°	240.0°	81	PT	247°	245°	5.0°	244°	4.0°
Kaawa Stream		241.0°	1	PT	247°	245°	4.0°	244°	3.0°
Wainui Stream		245.0°	1	PT	247°	245°	0.0°	244°	1.0°
Lake Taharoa (Pain 1976)	212°-250°	232.0°	20	PT	247°	234°	2.0°	229°	3.0°
Manutahi	266°-279°	272.5°	2	WA	273°	274°	1.5°	273°	0.5°
Castlecliff - Whangaehu R.	258°-294°	280.5°	59	WA	273°	274°	6.5°	273°	7.5°
Whangaehu R. - Ohau R.	270°-300°	292.0°	380	OH	291°	295°	3.0°	296°	4.0°
Ohau R. - Te Horo Beach	290°-316°	300.0°	46	TH	303°	307°	7.0°	305°	5.0°
Te Horo Beach - Paraparaumu	292°-343°	312.0°	38	TH	303°	314°	2.0°	310°	2.0°
Raumati South - Paekakariki	300°-343°	324.0°	16	TH	303°	307°	17.0°	305°	19.0°
<u>WEST COAST SOUTH ISLAND</u>									
Farewell Spit : east	278°-287°	283.0°	10	FS	285°	285°	2.0°	284°	1.0°
: west	261°-276°	269.0°	7	FS	285°	285°	16.0°	284°	15.0°
Pilch Point	274°-264°	278.0°	4	FS	285°	293°	15.0°	293°	15.0°
Turimawiwi River	235°-250°	240.5°	12	FS	285°	286°	45.5°	287°	46.5°
Turimawiwi River	235°-250°	240.5°	12	WE	346°	265°	24.5°	293°	52.5°
Okari River	227°-251°	235.0°	9	WE	36°	251°	16.0°	270°	35.0°
Cascade River	231°-251°	250.5°	6	HA	289°	270°	20.5°	270°	20.5°
Barn Bay	232°-256°	239.5°	6	HA	289°	263°	23.5°	264°	24.5°

Location	Dune Orientation Range	Dune Orientation Mean	No. of Dunes	Station	All Winds >10 knots Resultant	Onshore winds >10 knots : Resultant	Onshore winds >10 knots : Discrepancy between resultant and mean orientation	Onshore winds >21 knots : Resultant	Onshore winds >21 knots : Discrepancy between resultant and mean orientation
SOUTH COAST SOUTH ISLAND									
Kawakaputa Bay	252°-259°	256.0°	4	TP	276°	263°	7.0°	264°	8.0°
Oreti River	267°-285°	272.0°	20	TP	276°	273°	1.0°	273°	1.0°
Bluff Harbour	251°-269°	263.0°	8	TP	276°	265°	2.0°	264°	1.0°
Waipapa Point : nth + sth	257°-272°	262.5°	10	TP	276°	265°	2.5°	264°	1.5°
: mid	271°-279°	274.0°	5	TP	276°	274°	0.0°	274°	0.0°
Black Point	275°-283°	278.0°	3	TP	276°	273°	5.0°	273°	5.0°
Haldane Bay	246°-273°	260.0°	10	TP	276°	265°	5.0°	264°	4.0°
Tahakopa Bay	159°-223°	181.0°	16	TP	276°	204°	23.0°	212°	31.0°
Tahakopa Bay	159°-223°	181.0°	16	OA	182°	189°	8.0°	194°	13.0°
Purakaunui Bay	105°-118°	111.0°	5	TP	276°	110°	1.0°	90°	11.0°
Purakaunui Bay	105°-118°	111.0°	5	OA	182°	125°	14.0°	135°	24.0°
EAST COAST SOUTH ISLAND									
Waikouaiti River	87°- 90°	88.5°	2	OA	182°	130°	41.5°	161°	72.5°
Kaitorete Spit	169°-226°	198.0°	45	OA	182°	189°	9.0°	194°	4.0°
Kaitorete Spit	169°-226°	198.0°	45	CA	267°	190°	8.0°	209°	11.0°
Pegasus Bay : north (inld)	134°-159°	147.0°	15	OA	182°	139°	8.0°	150°	3.0°
: south (blwts)	38°- 97°	66.0°	24	OA	182°	60°	6.0°	79°	13.0°
Pegasus Bay : north (inld)	134°-159°	147.0°	15	CA	267°	125°	22.0°	134°	13.0°
: south (blwts)	38°- 97°	66.0°	24	CA	267°	72°	6.0°	76°	10.0°

Location	Dune Orientation Range	Dune Orientation Mean	No. of Dunes	Station	All Winds ≥10 knots Resultant	Onshore winds ≥10 knots : Resultant	Onshore winds ≥10 knots : Discrepancy between resultant and mean orientation	Onshore winds ≥21 knots : Resultant	Onshore winds ≥21 knots : Discrepancy between resultant and mean orientation
EAST COAST NORTH ISLAND									
Great Exhibition Bay	86°-124°	106.0°	12	MP	67°	76°	30.0°	79°	27.0°
Henderson Bay : north	86°-138°	112.0°	2	MP	67°	81°	31.0°	82°	30.0°
: south	5°- 8°	6.5°	2	MP	67°	38°	31.5°	41°	34.5°
Kowhai Beach	89°- 92°	90.5°	2	MP	67°	81°	9.5°	82°	8.5°
Houhora Bay : north	137°-139°	138.0°	2	MP	67°	136°	2.0°	135°	3.0°
: south	72°- 74°	73.0°	2	MP	67°	81°	8.0°	82°	9.0°
East Beach : north	63°- 99°	84.0°	3	MP	67°	81°	3.0°	82°	2.0°
: south	71°- 89°	77.0°	5	MP	67°	64°	13.0°	67°	10.0°
Waipu River	30°- 98°	75.0°	11	MP	67°	76°	1.0°	79°	4.0°
Mangawhai Harbour : inland	16°-104°	76.0°	18	MP	67°	76°	0.0°	79°	3.0°
: blowouts	13°-120°	83.0°	33	MP	67°	76°	7.0°	79°	4.0°
: all	13°-120°	81.0°	51	MP	67°	76°	5.0°	79°	2.0°
Waikawau Bay	40°- 93°	69.5°	4	MP	67°	67°	2.5°	70°	0.5°
Waikawau Bay	40°- 93°	69.5°	4	TA	267°	71°	1.5°	76°	6.5°
Otama Bay	300°-344°	322.0°	2	MP	67°	330°	8.0°	316°	6.0°
Otama Bay	300°-344°	322.0°	2	TA	267°	349°	27.0°	360°	38.0°
Opito Bay	52°- 91°	74.0°	4	MP	67°	76°	2.0°	79°	5.0°
Opito Bay	52°- 91°	74.0°	4	TA	267°	85°	11.0°	59°	15.0°
Hotwater Beach	72°- 99°	91.0°	4	MP	67°	103°	12.0°	102°	11.0°
Hotwater Beach	72°- 99°	91.0°	4	TA	267°	99°	8.0°	90°	1.0°
Katikati entrance	57°- 99°	82.0°	3	TA	267°	57°	25.0°	59°	23.0°
Mt Maunganui	358°- 92°	46.0°	20	TA	267°	50°	4.0°	59°	13.0°
Maketu	24°- 77°	47.0°	10	TA	267°	50°	3.0°	59°	12.0°
Rangitaiki River	1°- 17°	11.0°	5	TA	267°	41°	30.0°	59°	48.0°

Location	Dune Orientation Range	Dune Orientation Mean	No. of Dunes	Station	All Winds >10 knots Resultant	Onshore winds >10 knots : Resultant	Onshore winds >10 knots : Discrepancy between resultant and mean orientation	Onshore winds >21 knots : Resultant	Onshore winds >21 knots : Discrepancy between resultant and mean orientation
EAST COAST NORTH ISLAND									
Whangaparoa River	258°-327°	277.0°	7	TA	267°	275°	2.0°	270°	7.0°
Mahia : west coast	227°-259°	241.0°	16	NA	268°	247°	6.0°	250°	9.0°
: east coast	54°- 92°	76.0°	10	NA	268°	68°	8.0°	90°	14.0°
Whakaki	200°-246°	222.5°	21	NA	268°	214°	8.5°	219°	3.5°
Tukituki River	50°-109°	89.0°	7	NA	268°	66°	21.0°	90°	1.0°
Cape Kidnappers (south)	181°-204°	195.0°	5	NA	268°	204°	9.0°	211°	16.0°

Location	Dune Orientation Range	Dune Orientation Mean	No. of Dunes	Station	All Winds >10 knots Resultant	Offshore winds >10 knots : Resultant	Offshore winds >10 knots : Discrepancy between resultant and mean	Offshore winds >21 knots : Resultant	Offshore winds >21 knots : Discrepancy between resultant and mean
Porangahau River	277°-296°	288.0°	27	NA	268°	291°	3.0°	287°	1.0°
Porangahau River	277°-296°	288.0°	27	CP	321°	326°	38.0°	325°	37.0°

TABLE 5.1

LOCATION	STATION	ONSHORE DIRECTIONS	ONSHORE RESULTANT >10 KNOTS	ONSHORE RESULTANT >22 KNOTS	ONSHORE DRIFT POTENTIAL
<u>WEST COAST NORTH ISLAND</u>					
Ahipara	KS	SW,W,NW	258°	263°	393
Maunganui Bluff	KS	S,SW,W	242°	245°	379
Maunganui Bluff	MP	S,SW,W	248°	255°	113
Kaipara north head	KS	S,SW,W,NW	251°	257°	438
Kaipara south head	KS	S,SW,W	242°	245°	379
Te Henga	PT	S,SW,W	234°	229°	668
Manakau south head	PT	S,SW,W,NW	245°	244°	783
Kaawa Stream	PT	S,SW,W,NW	245°	244°	783
Wainui Stream	PT	S,SW,W,NW	245°	244°	783
Lake Taharoa (Pain 1976, p 174)	PT	S,SW,W	234°	229°	668
Manutahi	WA	S,SW,W,NW	274°	273°	1858
Castlecliff - Whangaenu River	WA	S,SW,W,NW	274°	273°	1858
Whangaehu River - Ohau River	OH	SW,W,NW,N	295°	296°	563
Ohau River - Te Horo Beach	TH	SW,W,NW,N	307°	305°	640
Te Horo Beach - Paraparaumu	TH	W,NW,N	314°	310°	575
Raumati South - Paekakariri	TH	SW,W,NW,N	307°	305°	640
<u>WEST COAST SOUTH ISLAND</u>					
Farewell Spit : east	FS	all	285°	284°	2245
: west	FS	all	285°	284°	2245
Pilch Point	FS	W,NW,N	293°	293°	1569
Turimawiwi River	FS	SW,W,NW,N	286°	287°	1762
Turimawiwi River	WE	SW,W,NW,N	265°	293°	112
Okari River	WE	SW,W,NW	251°	270°	94
Cascade River	HA	SW,W,NW	270°	270°	154
Barn Bay	HA	SW,W	269°	269°	150
<u>SOUTH COAST SOUTH ISLAND</u>					
Kawarapouta Bay	TP	S,SW,W	264°	264°	2031
Oreti River	TP	S,SW,W,NW	273°	273°	2446
Bluff Harbour	TP	S,SW,W	265°	264°	2031
Waipapa Point : north + south	TP	S,SW,W	265°	264°	2031
: mid	TP	SW,W,NW	274°	274°	2368
Slack Point	TP	S,SW,W,NW	273°	273°	2446
Haldane Bay	TP	S,SW,W	265°	264°	2031
Tanakopa Bay	TP	E,SE,S,SW	204°	212°	355
(Tanakopa Bay	OA	E,SE,S,SW	189°	194°)	265
Purakaunui Bay	TP	E,SE	110°	90°	69
(Purakaunui Bay	OA	E,SE	125°	135°)	33
<u>EAST COAST SOUTH ISLAND</u>					
Waikouaiti River	OA	NE,E,SE,S	130°	161°	293
Kaitorete Spit	OA	E,SE,S,SW	189°	194°	265
Kaitorete Spit	CA	E,SE,S,SW	190°	209°	216
Pegasus Bay : north (inland)	OA	E,SE,S	139°	150°	182
: south (blowouts)	OA	NE,E,SE	60°	79°	145
Pegasus Bay : north (inland)	CA	E,SE,S	125°	134°	98
: south (blowouts)	CA	NE,E,SE	72°	76°	33

LOCATION	STATION	ONSHORE DIRECTIONS	ONSHORE RESULTANT >10 KNOTS	ONSHORE RESULTANT >22 KNOTS	ONSHORE DRIFT POTENTIAL
EAST COAST NORTH ISLAND					
Great Exhibition Bay	MP	N,NE,E,SE	76°	79°	495
Henderson Bay : north	MP	NE,E,SE	81°	82°	458
: south	MP	N,NE	38°	41°	200
Kowhai Beach	MP	NE,E,SE	81°	82°	458
Houhora Bay : north	MP	SE,S	136°	135°	97
: south	MP	NE,E,SE	81°	82°	458
East Beach : north	MP	NE,E,SE	81°	82°	458
: south	MP	N,NE,E	64°	67°	404
Waipu River	MP	N,NE,E,SE	76°	79°	495
Mangawhai Harbour : inland	MP	N,NE,E,SE	76°	79°	495
: blowouts	MP	N,NE,E,SE	76°	79°	495
: all	MP	N,NE,E,SE	76°	79°	495
Waikawau Bay	MP	NE,E	67°	70°	367
	TA	NE,E	71°	76°	94
Otama Bay	MP	NW,N	330°	316°	106
	TA	NW,N	349	360	58
Opito Bay	MP	N,NE,E,SE	76°	79°	495
	TA	N,NE,E,SE	85	59	151
Hotwater Beach	MP	E,SE	103	102	296
	TA	E,SE	99	90	69
Katikati entrance	TA	N,NE,E,SE	57°	59°	151
Mt Maunganui	TA	N,NE,E	50°	59°	136
Maketu	TA	N,NE,E	50°	59°	136
Rangitaiki River	TA	NW,N,NE,E	41°	59°	152
Whangaparoa River	TA	W,NW	275°	270°	179
Mania : west coast	NA	S,SW,W	247°	250°	225
: east coast	NA	NE,E	75°	90°	30
Whakaki	NA	SE,S,SW	214°	219°	106
Tukituki River	NA	N,NE,E,SE	68°	90°	46
Cape Kidnappers (south)	NA	E,SE,S,SW	204°	211°	127

LOCATION	STATION	OFFSHORE DIRECTIONS	OFFSHORE RESULTANT >10 KNOTS	OFFSHORE RESULTANT >22 KNOTS	OFFSHORE DRIFT POTENTIAL
Porangahau River	NA	W,NW,N	291°	287°	224
Porangahau River	CP	W,NW,N	326°	325°	2447

KEY TO FIGURES 6.1 TO 6.31

Locations of FIGURES 6.1 to 6.31

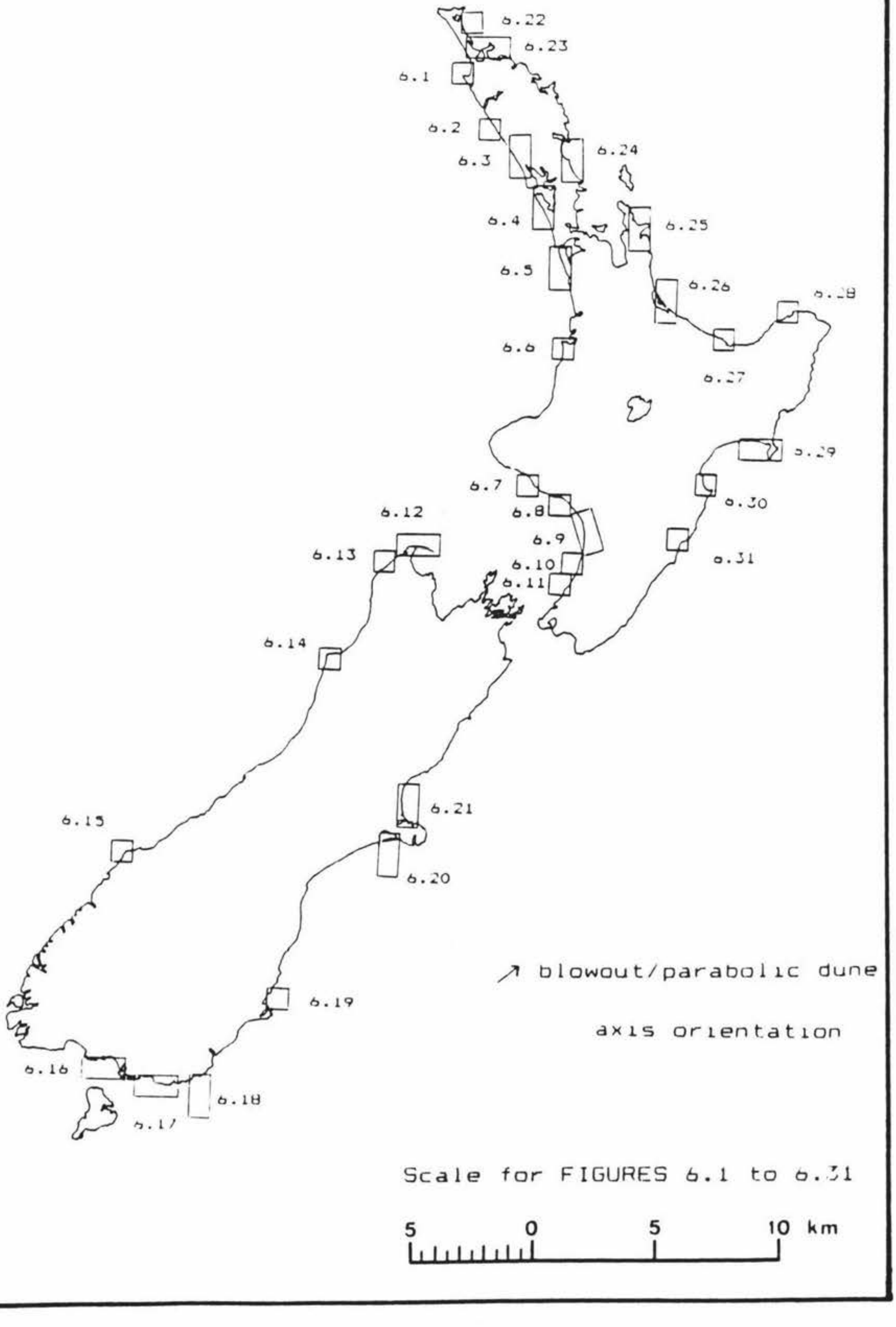


FIGURE 6.1

Ahipara

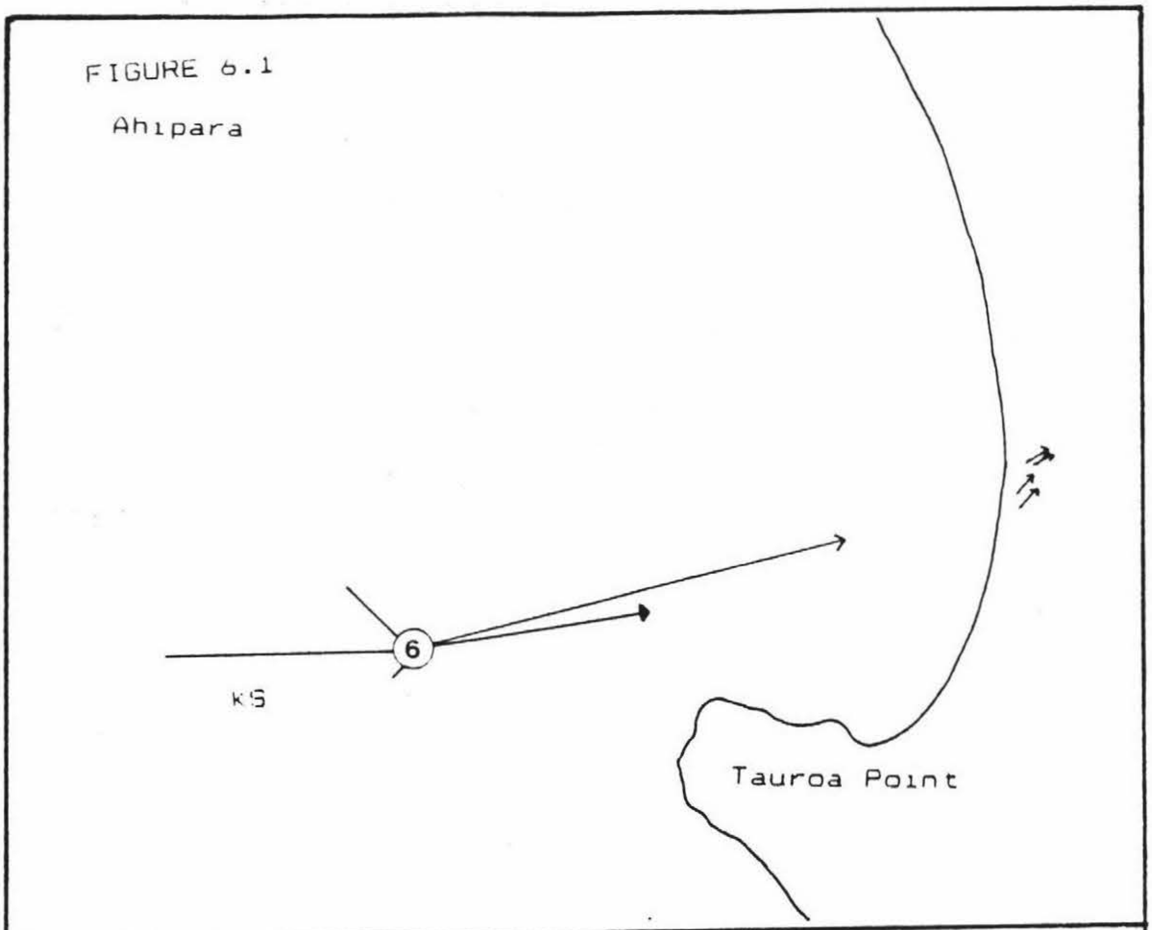


FIGURE 6.2

Maunganui Bluff

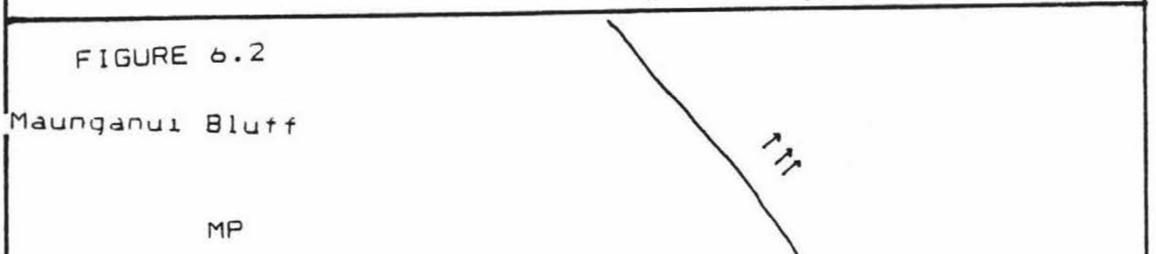


FIGURE 6.3

kaipara north head

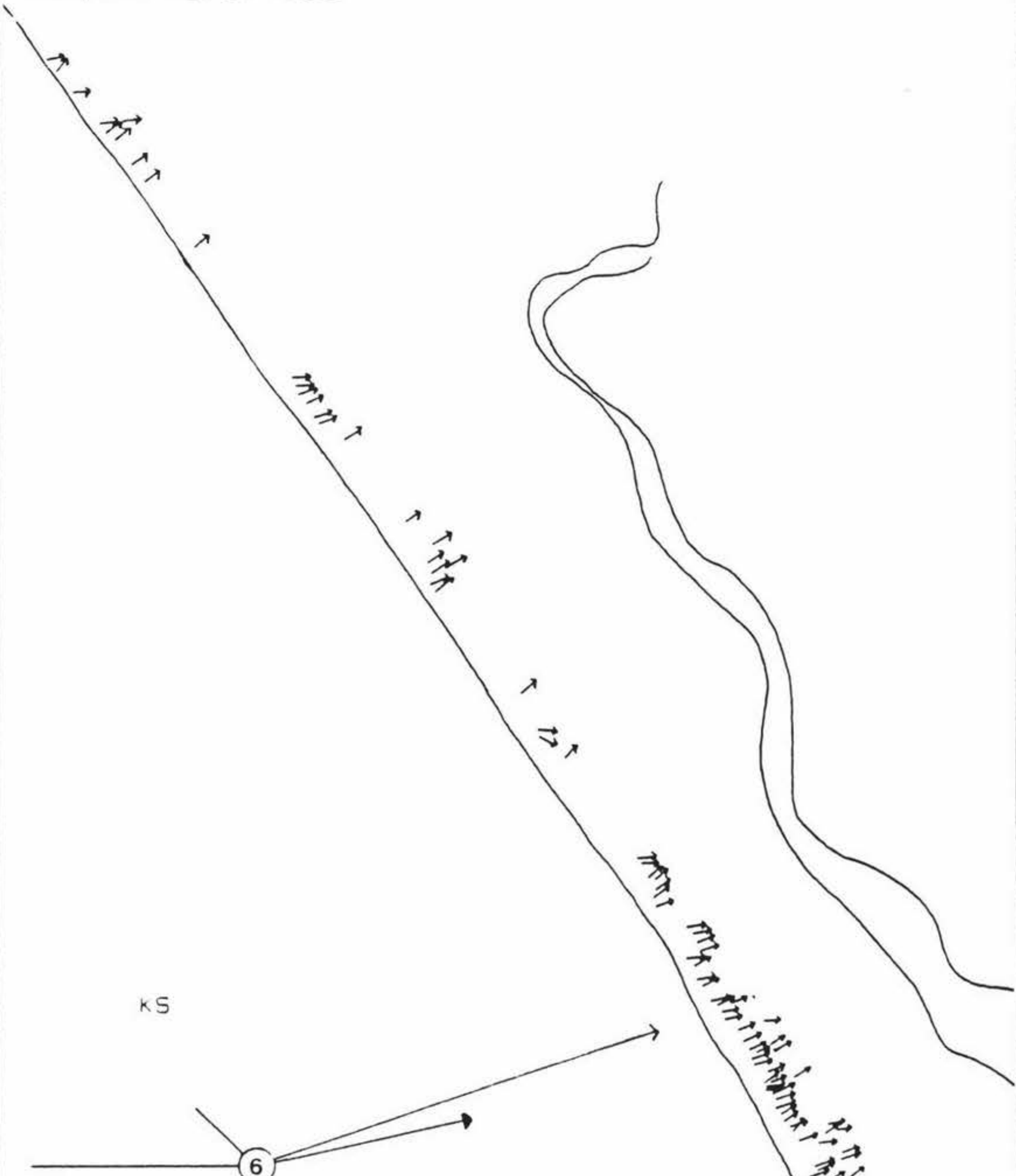
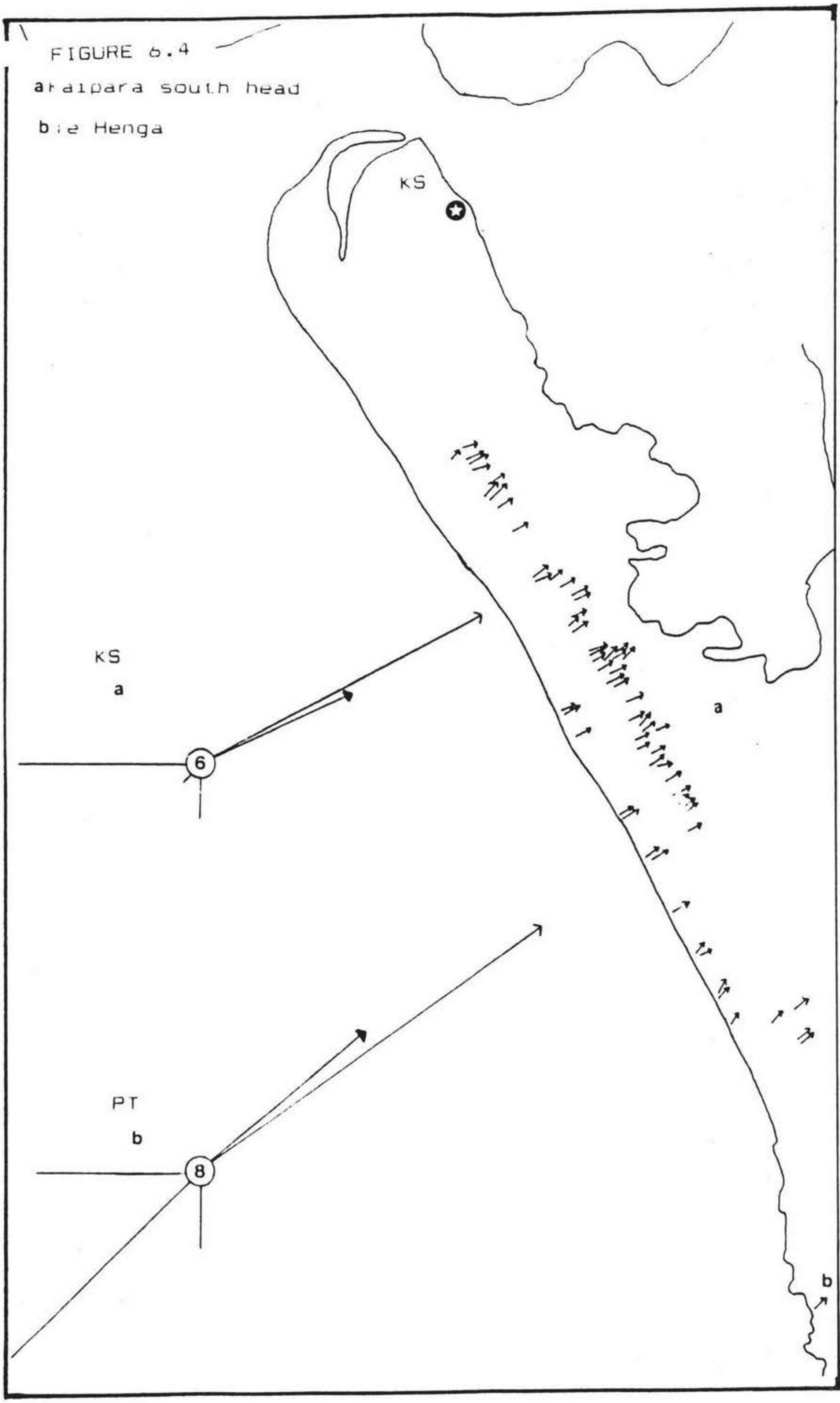


FIGURE 6.4

a Kaipara south head

b Te Henga



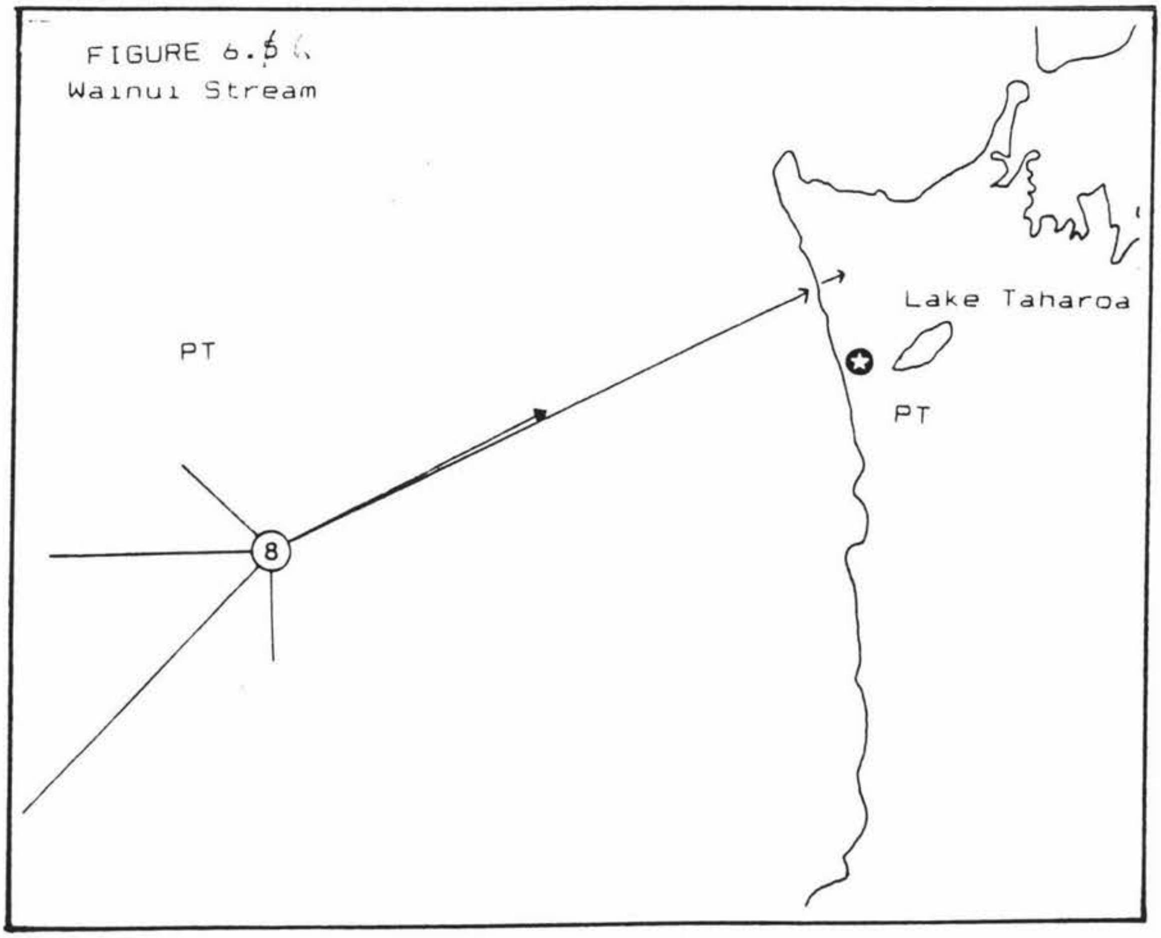


FIGURE 6.~~5~~ 6
Wainui Stream

FIGURE 6.87

Manutahi

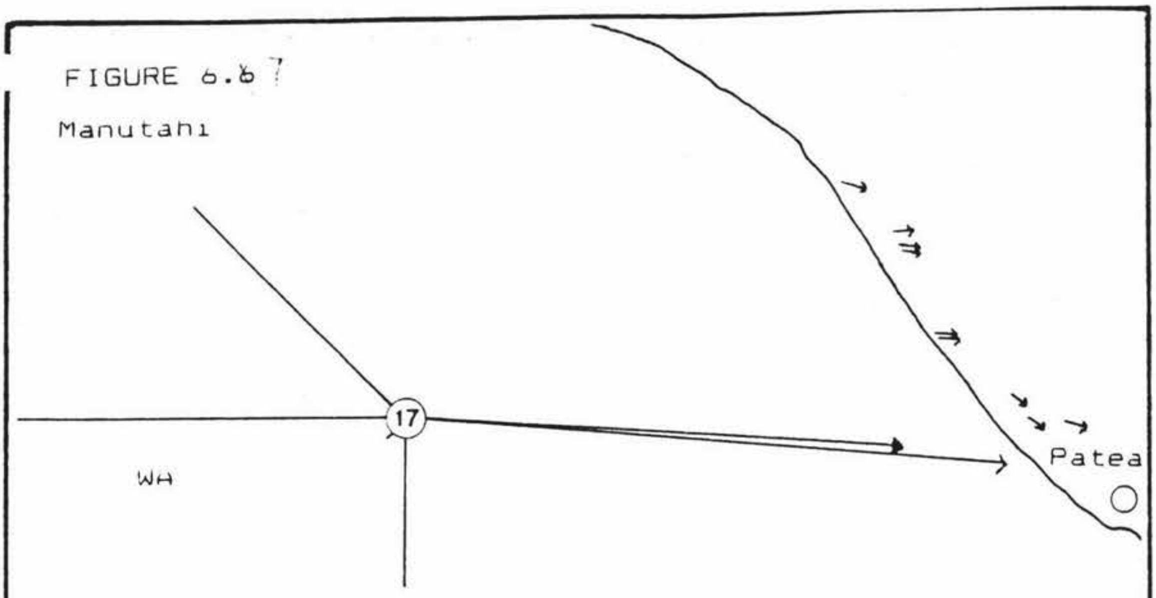


FIGURE 6.78

Castlecliff - Whangaehu River

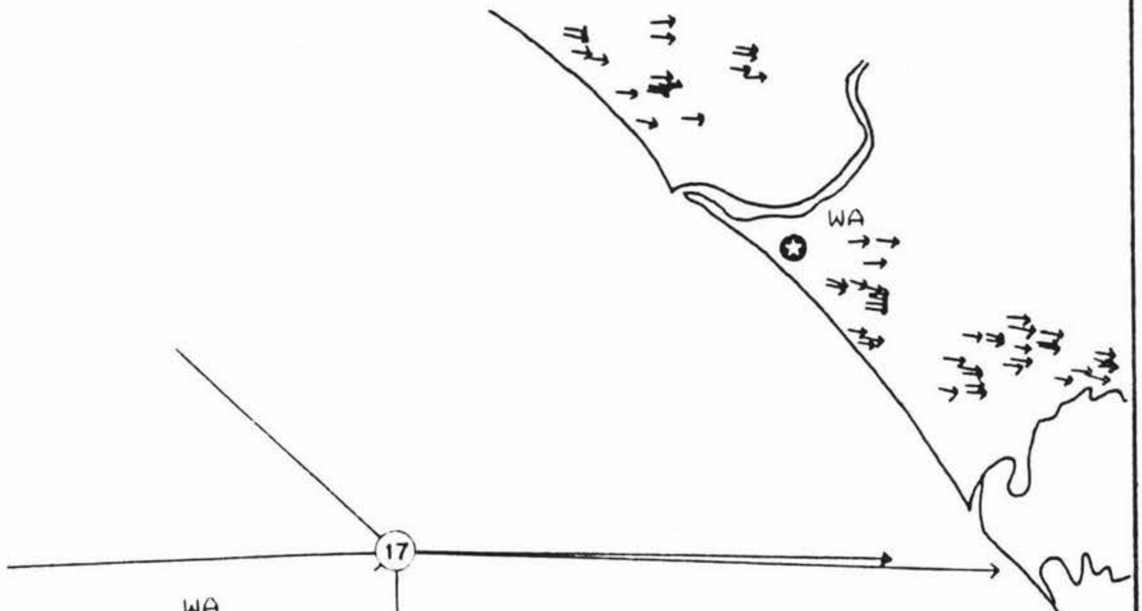


FIGURE 6.~~8~~5

a Manakau south head

b Kaawa Stream

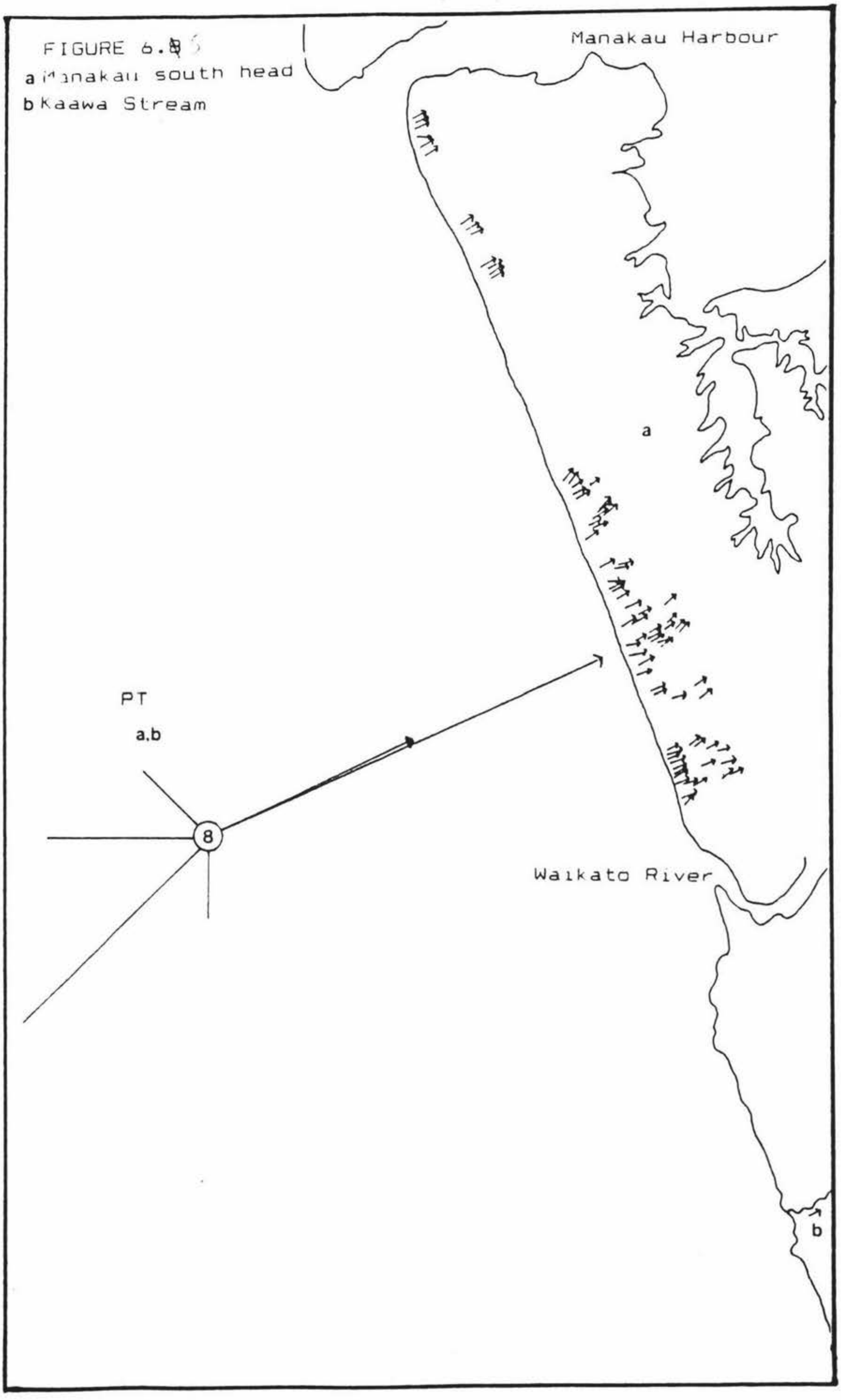


FIGURE 6.9
Whangaehu River - Ohau River

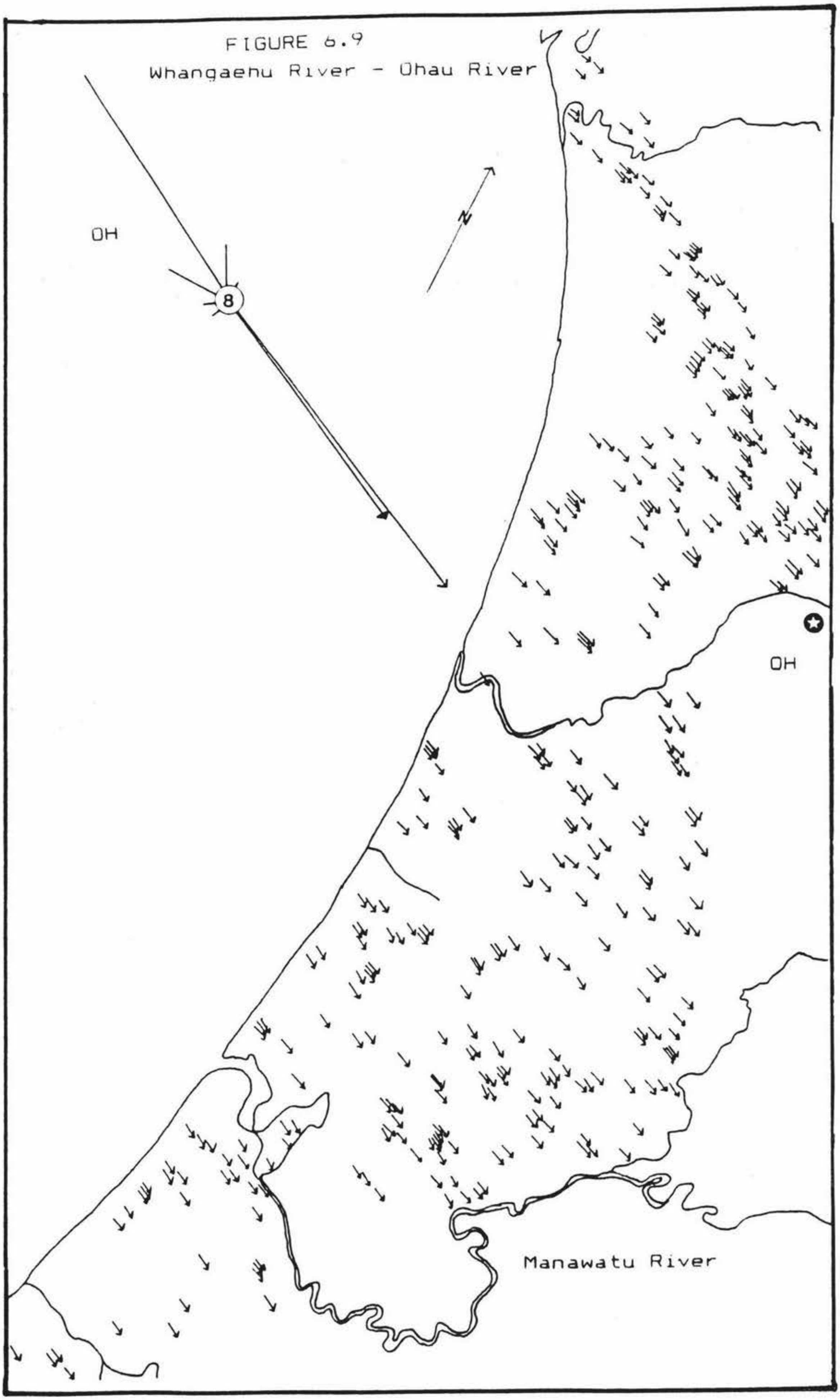


FIGURE 6.10

Ohau River - Te Horo Beach

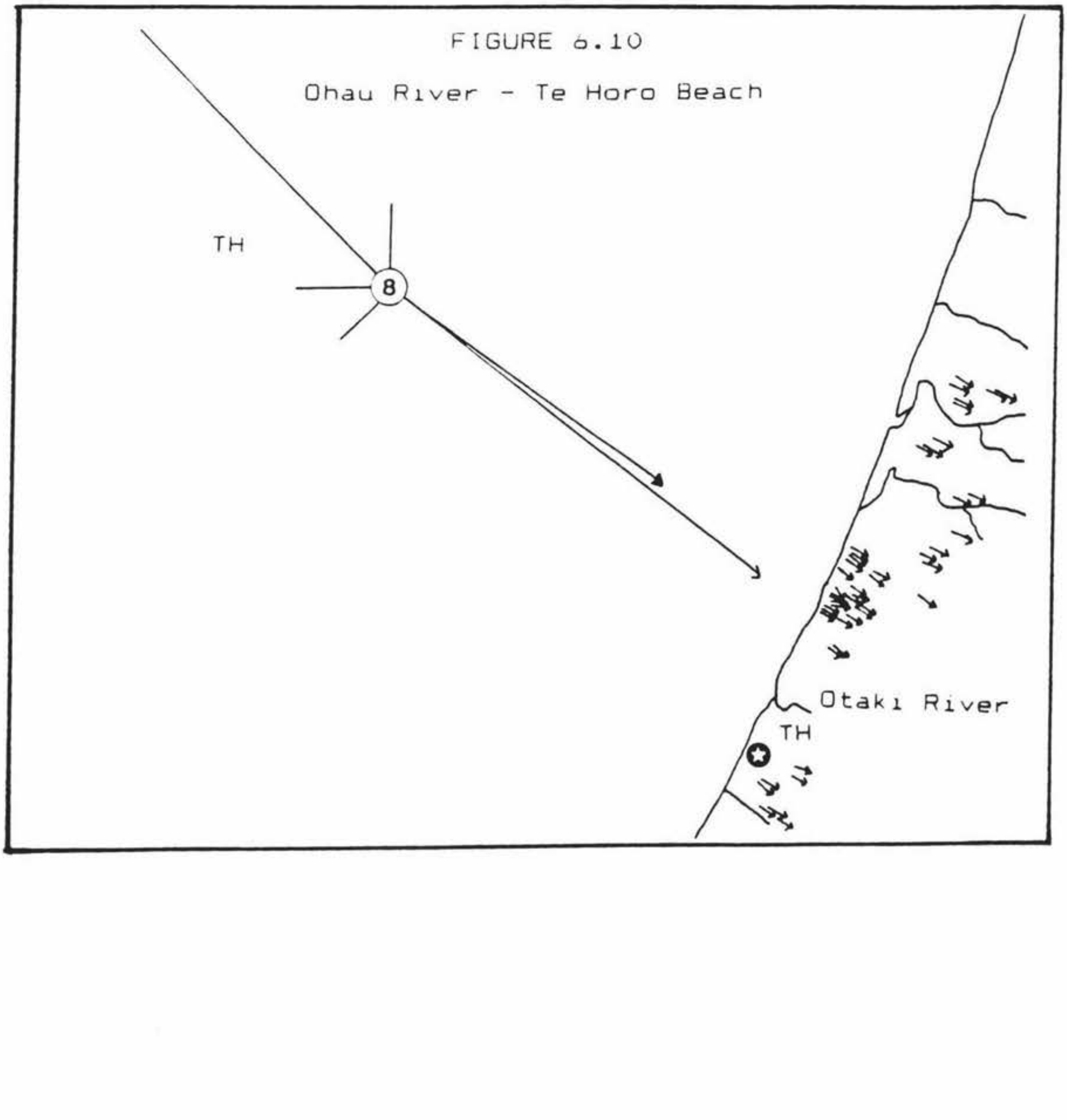


FIGURE 6.11

a Te Horo Beach - Paraparaumu

b Raumati South - Paekakariki

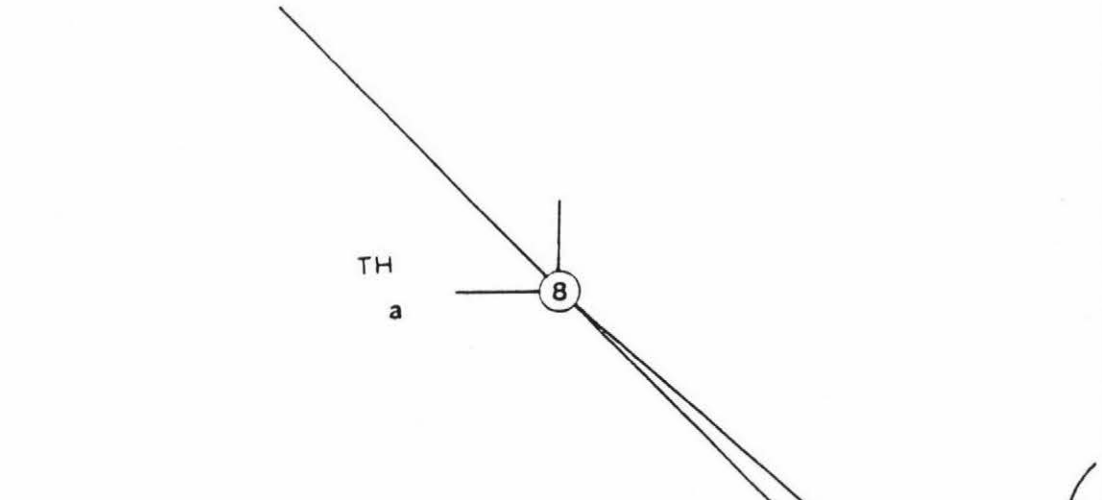


FIGURE 6.12

a Farewell Spit : west

b Farewell Spit : east

c Pilch Point

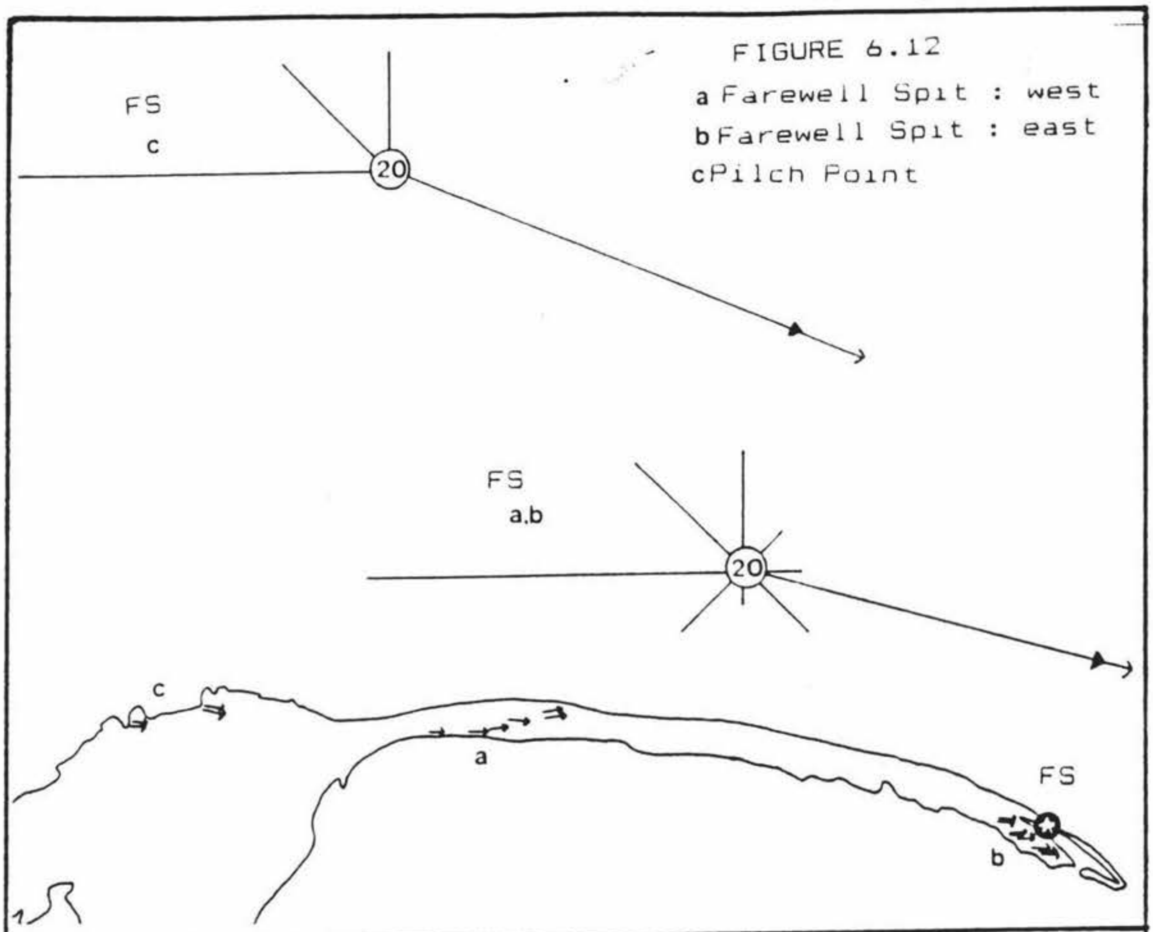


FIGURE 6.13

Turimawiwi River

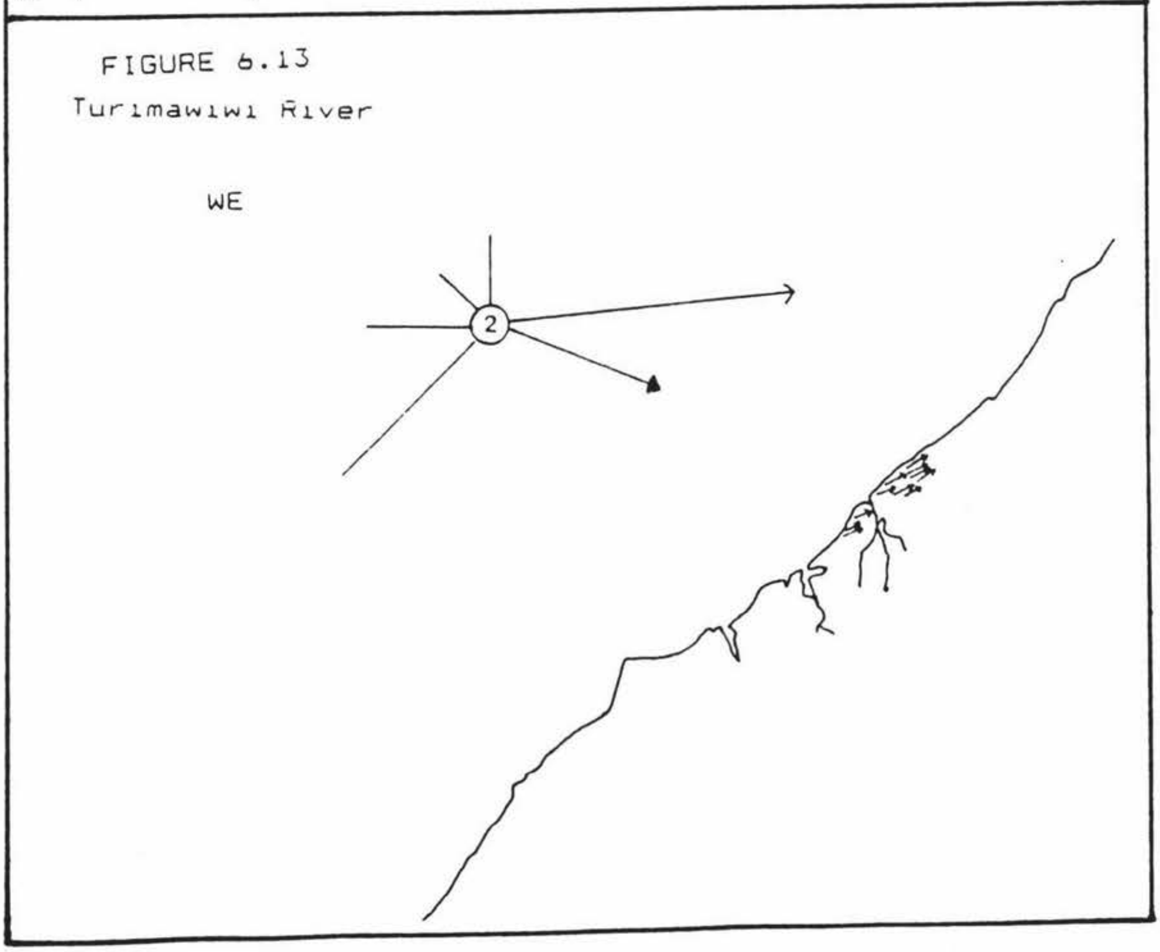


FIGURE 6.14
Okari River

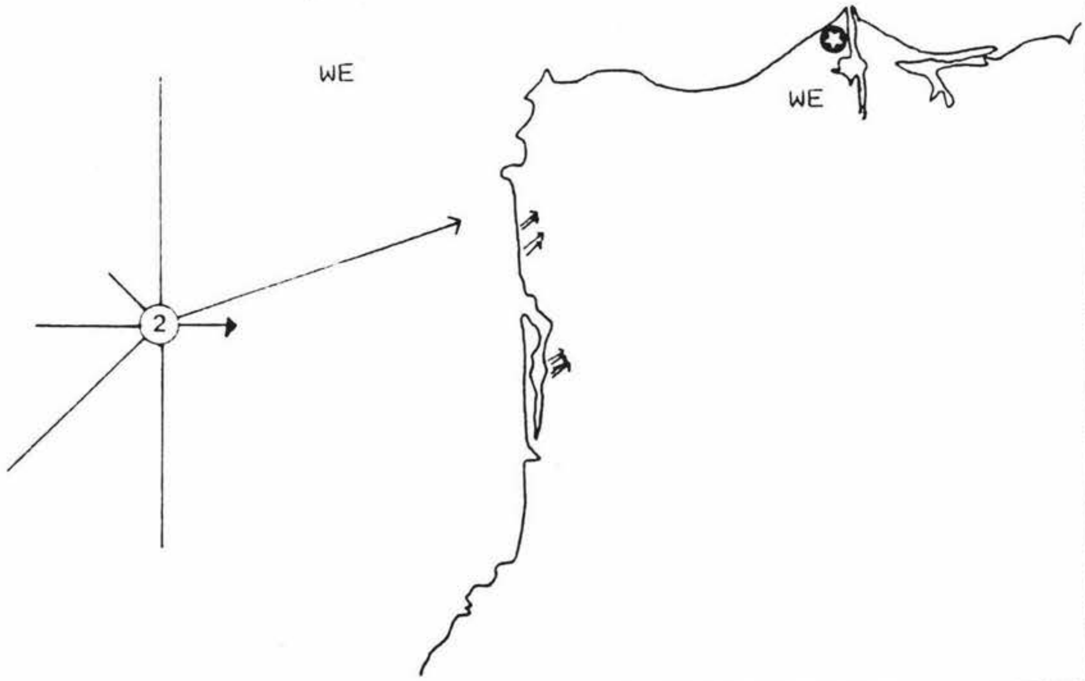
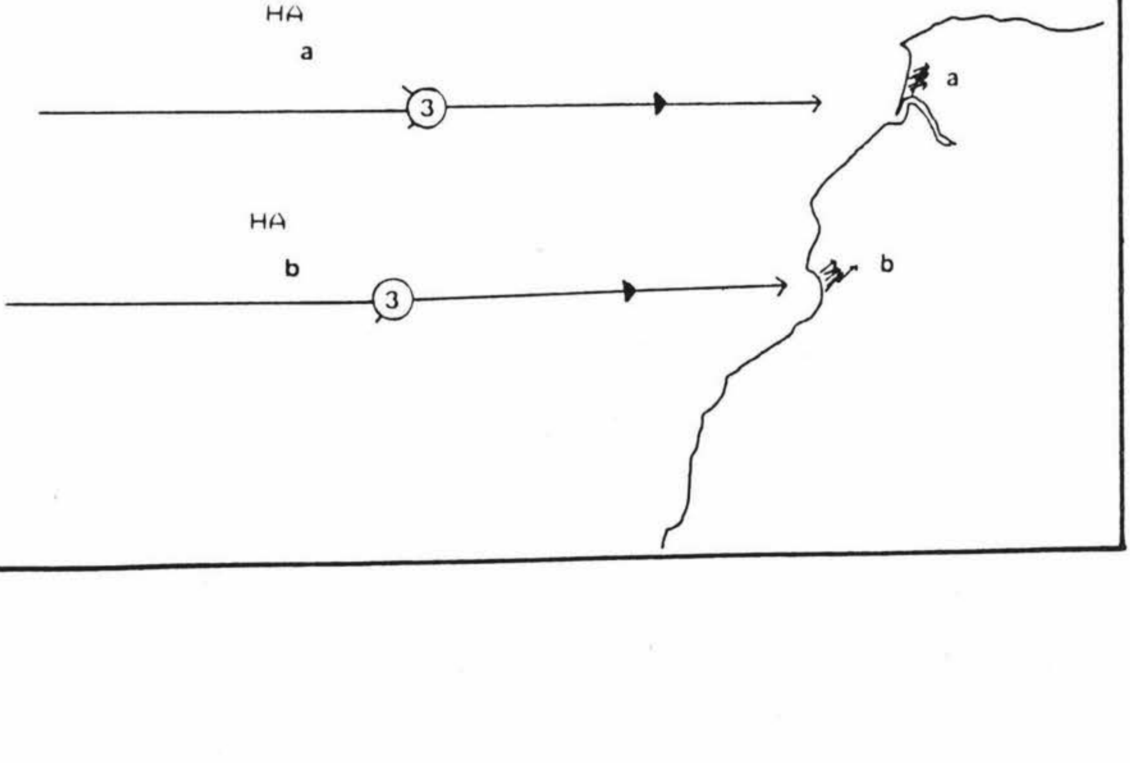


FIGURE 6.15
a Cascade River
b Barn Bay



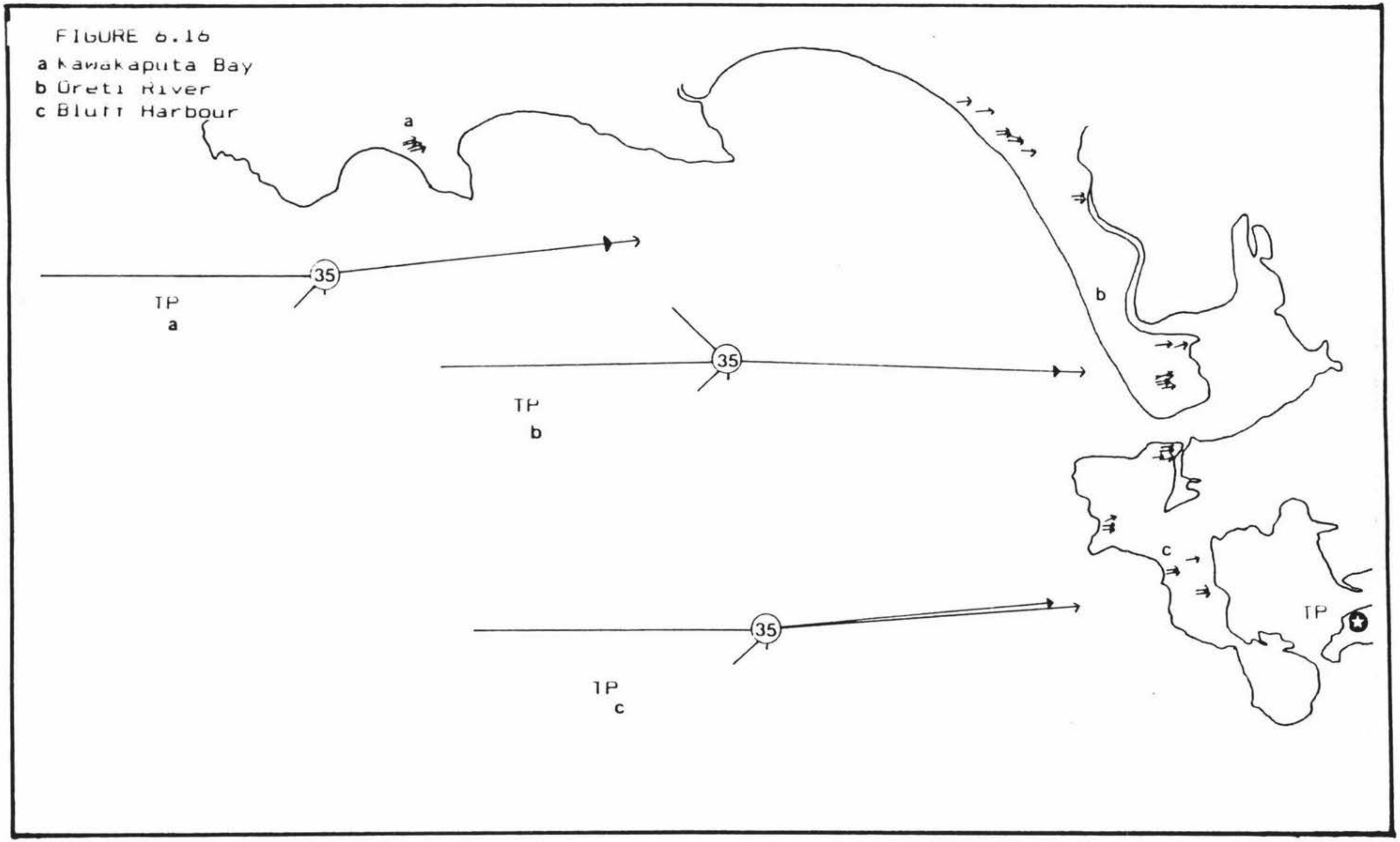


FIGURE 6.16

a Kawakaputa Bay

b Oreti River

c Bluff Harbour

FIGURE 6.17

a Waipapa Point : north + south
b Waipapa Point : mid
c Black Point
d Haldane Bay

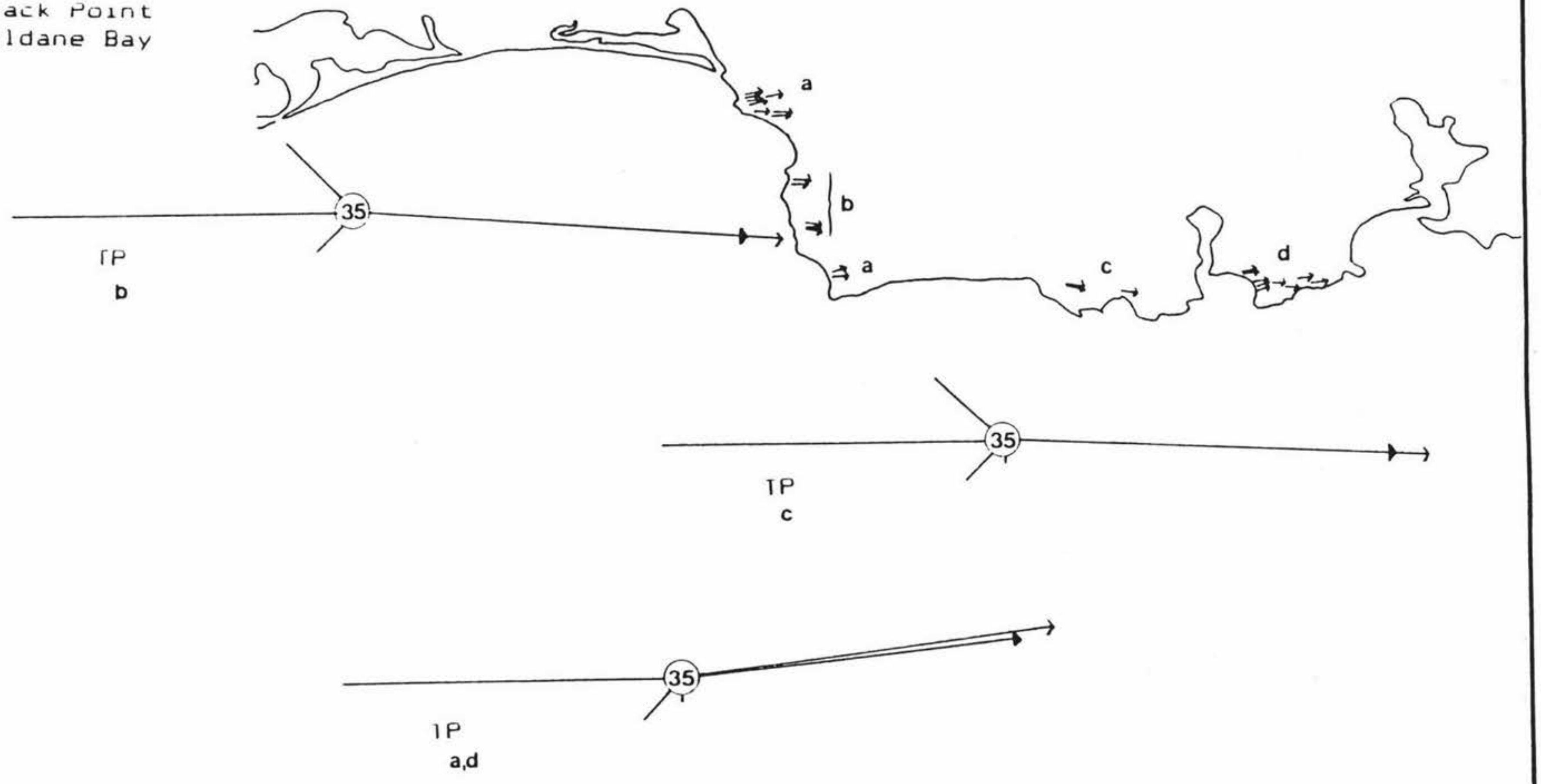
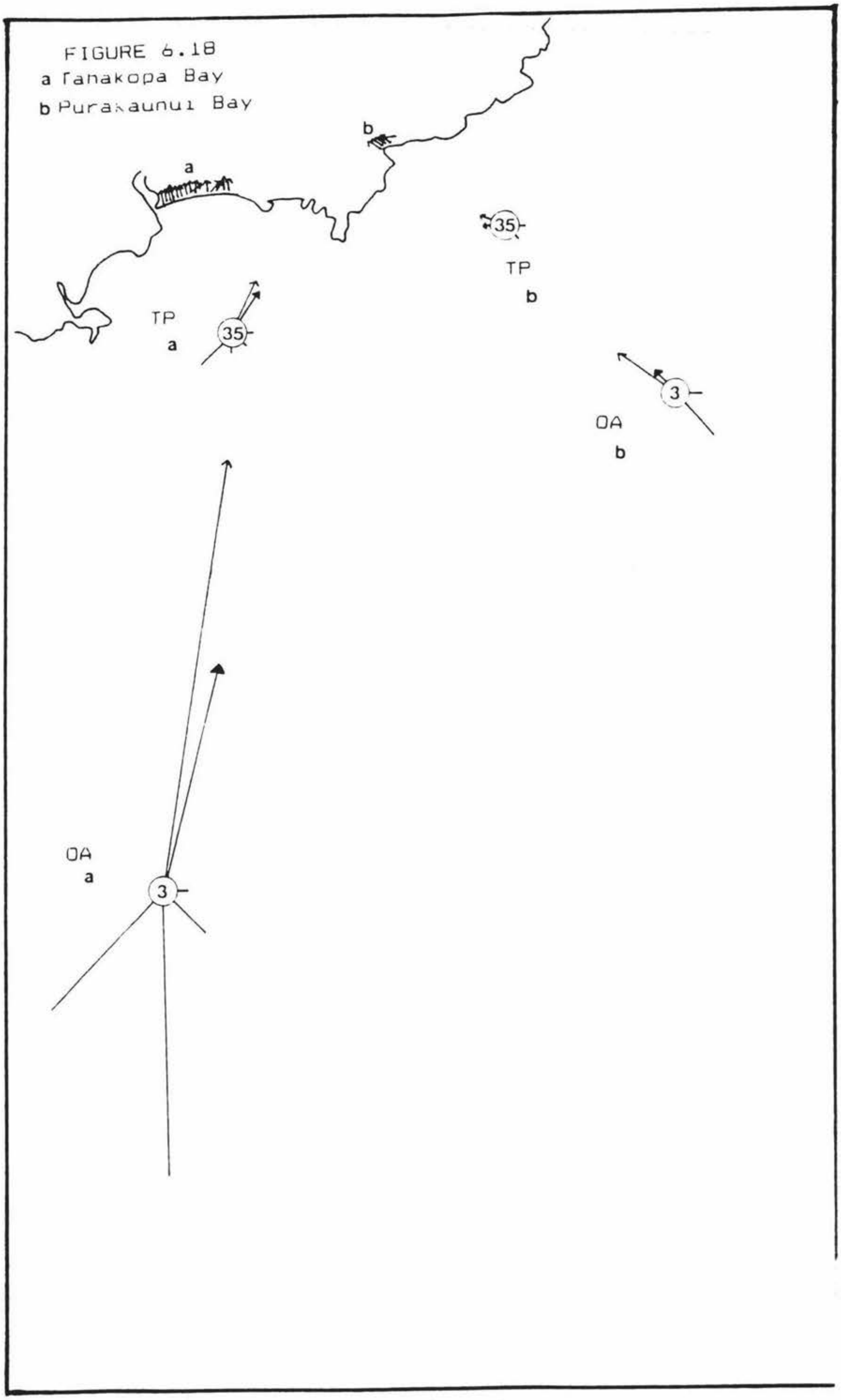


FIGURE 6.18

a Tanakopa Bay

b Purakaunui Bay



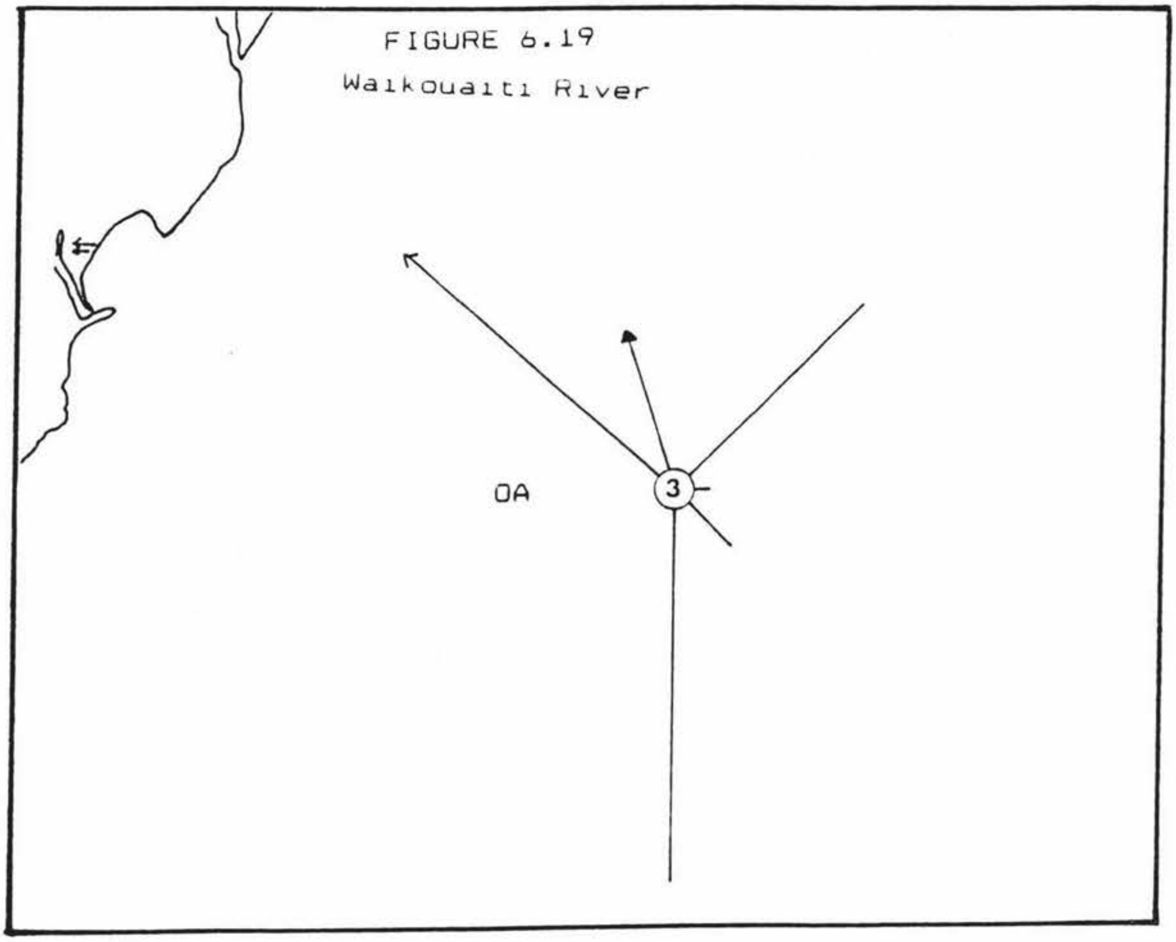
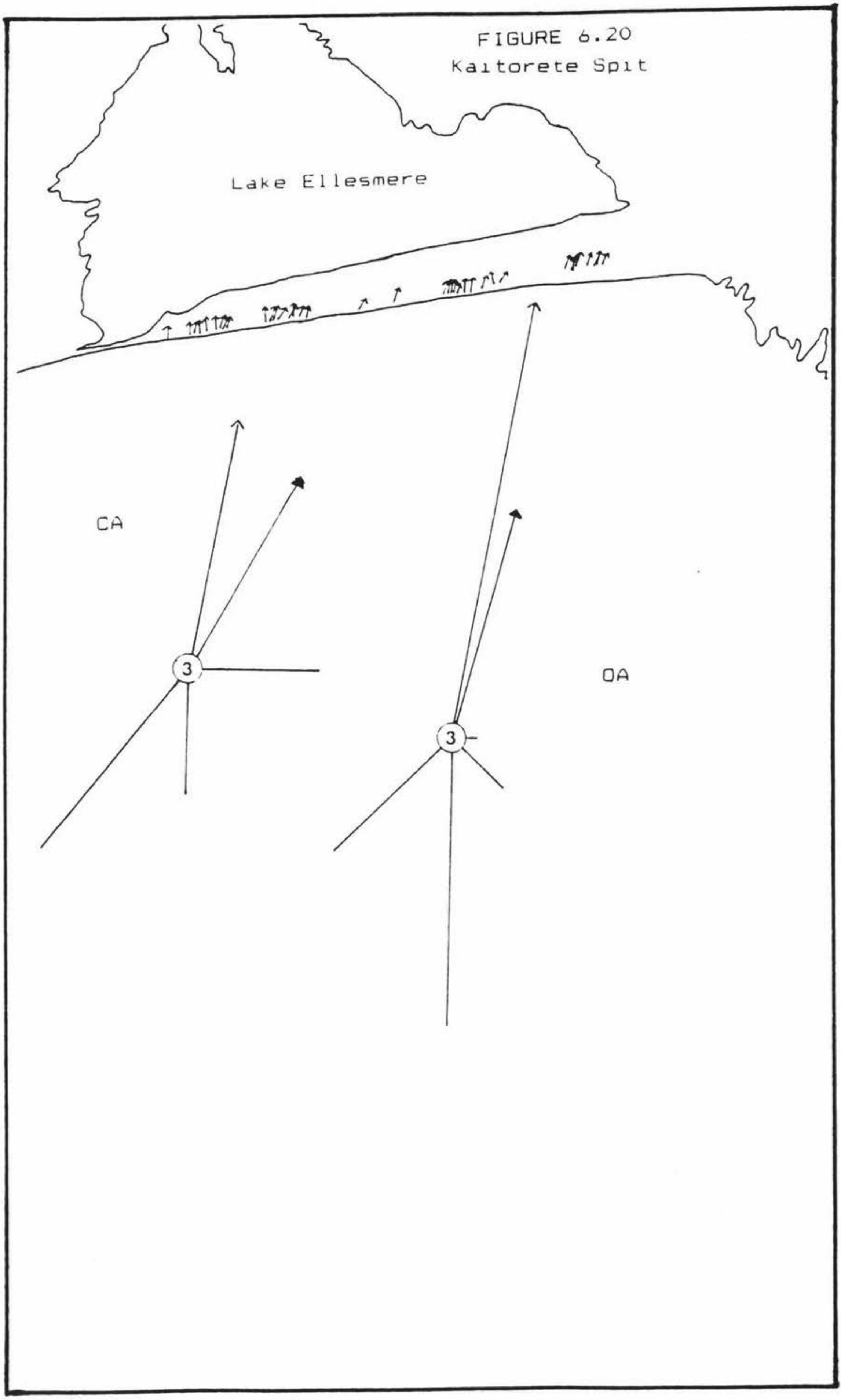


FIGURE 6.19

Waikouaiti River

FIGURE 6.20
Kaitorete Spit



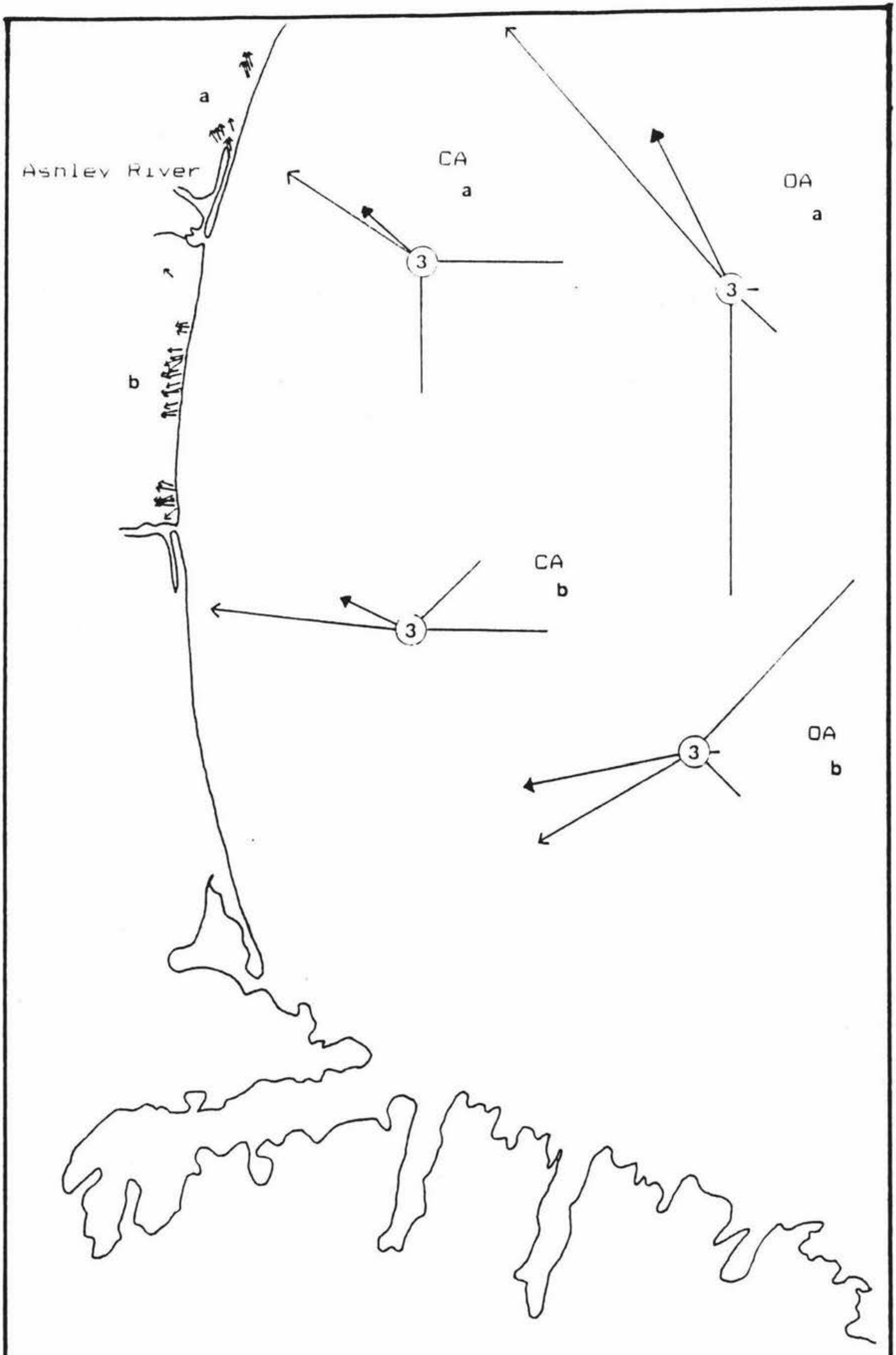
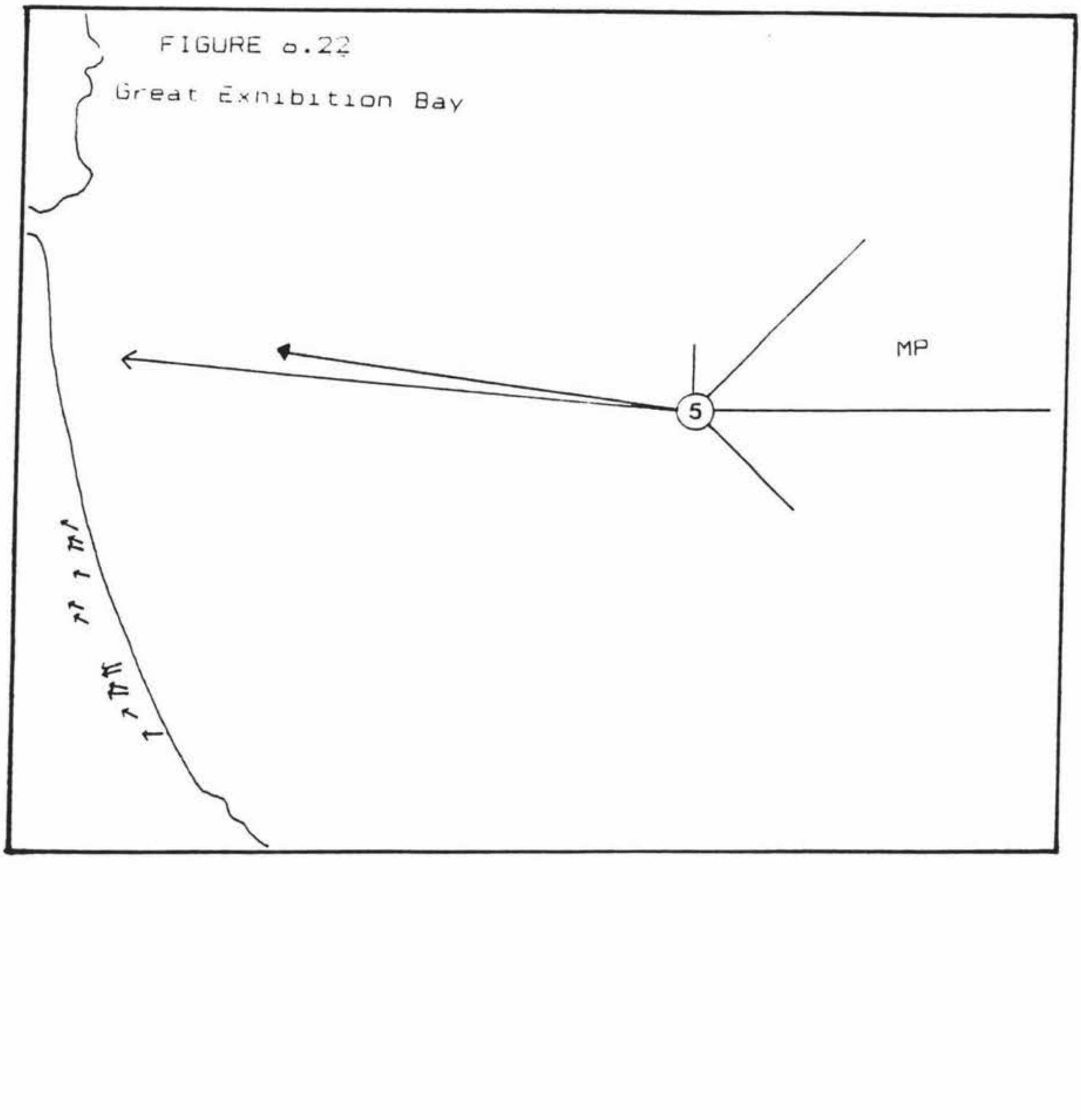


FIGURE 6.21
a Pegasus Bay : north (inland)
b : south (blowouts)

FIGURE 6.22

Great Exhibition Bay



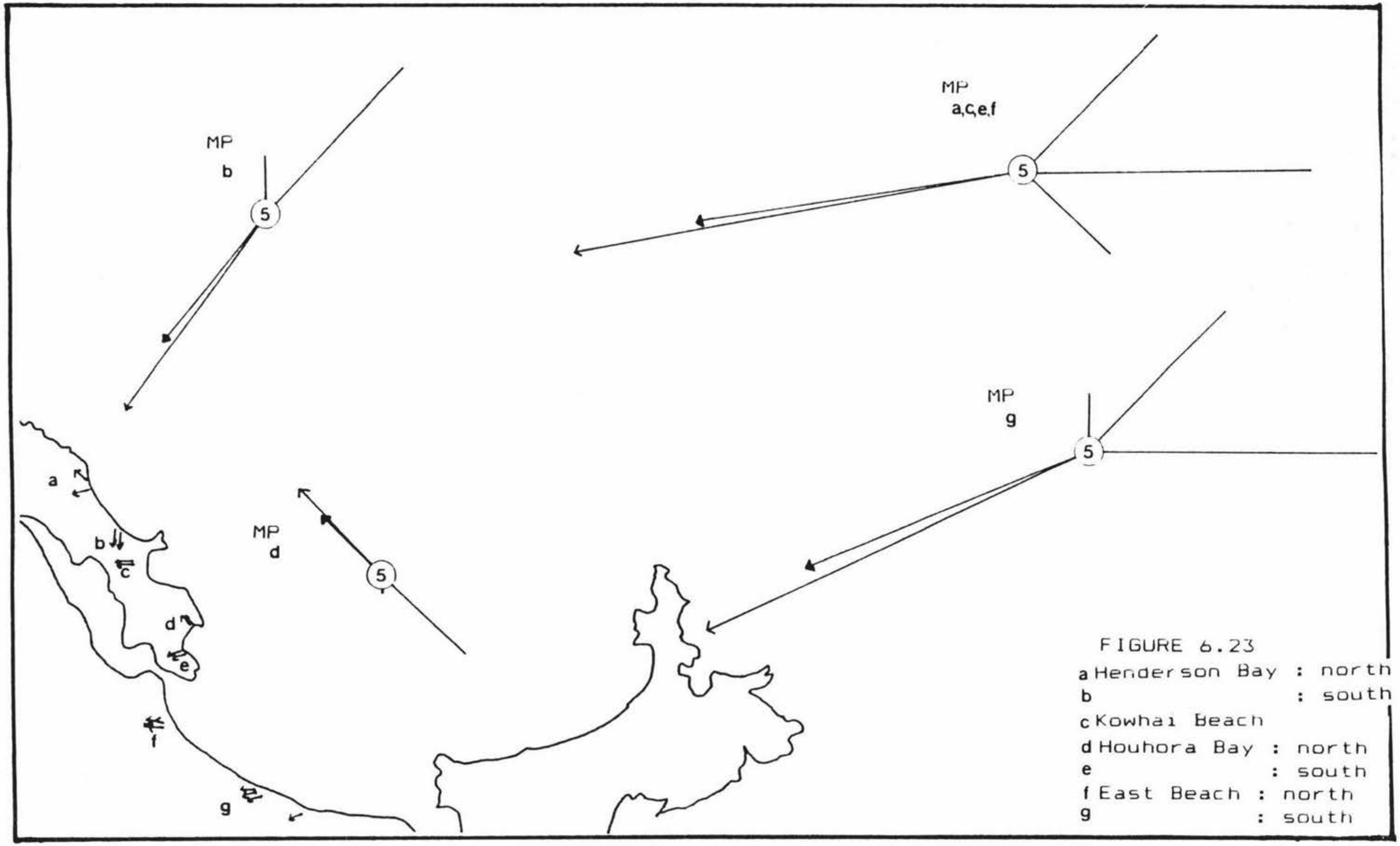


FIGURE 6.23

a Henderson Bay : north
b : south
c Kowhai Beach
d Houhora Bay : north
e : south
f East Beach : north
g : south

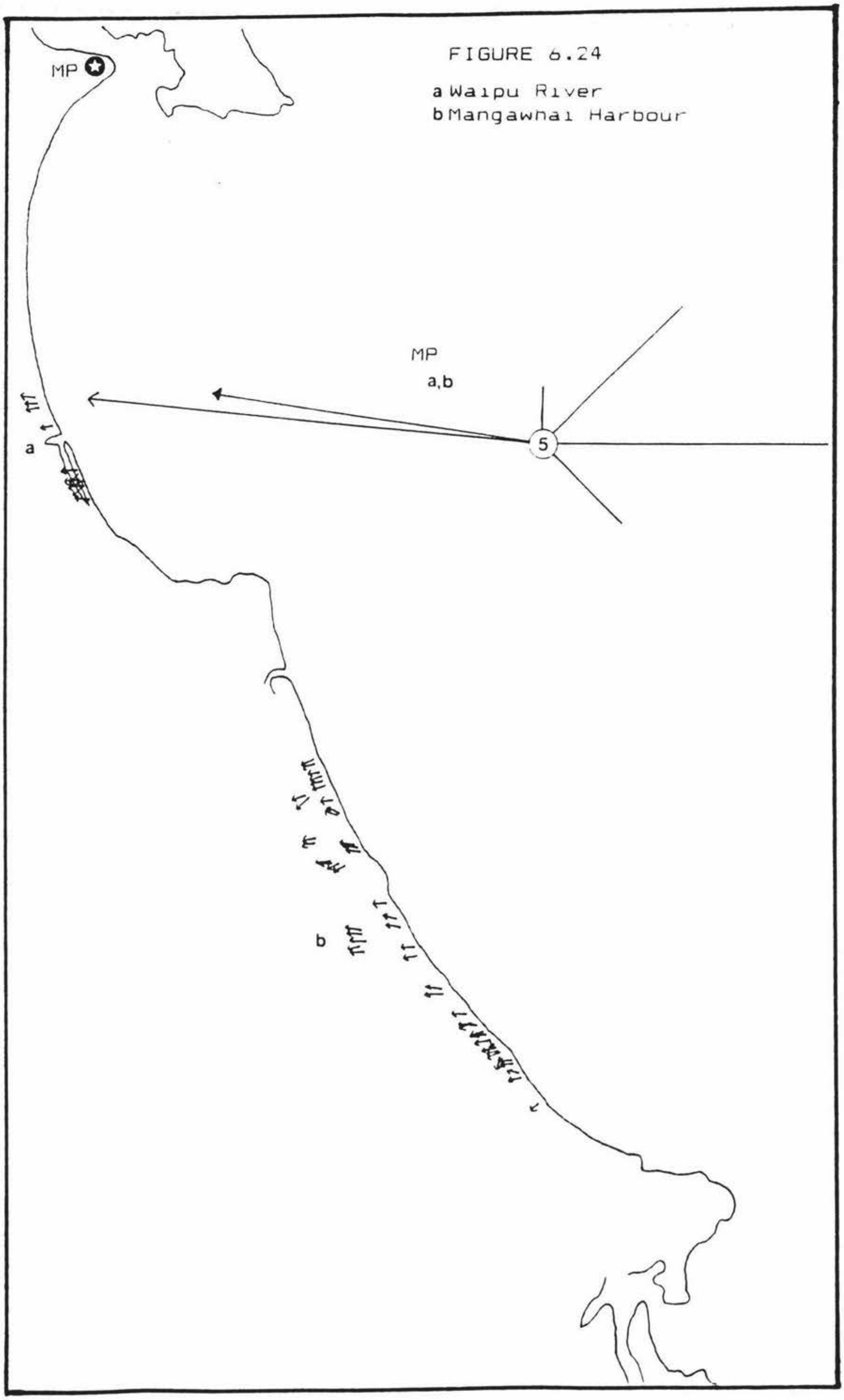


FIGURE 6.24

a Waipu River
b Mangawhai Harbour

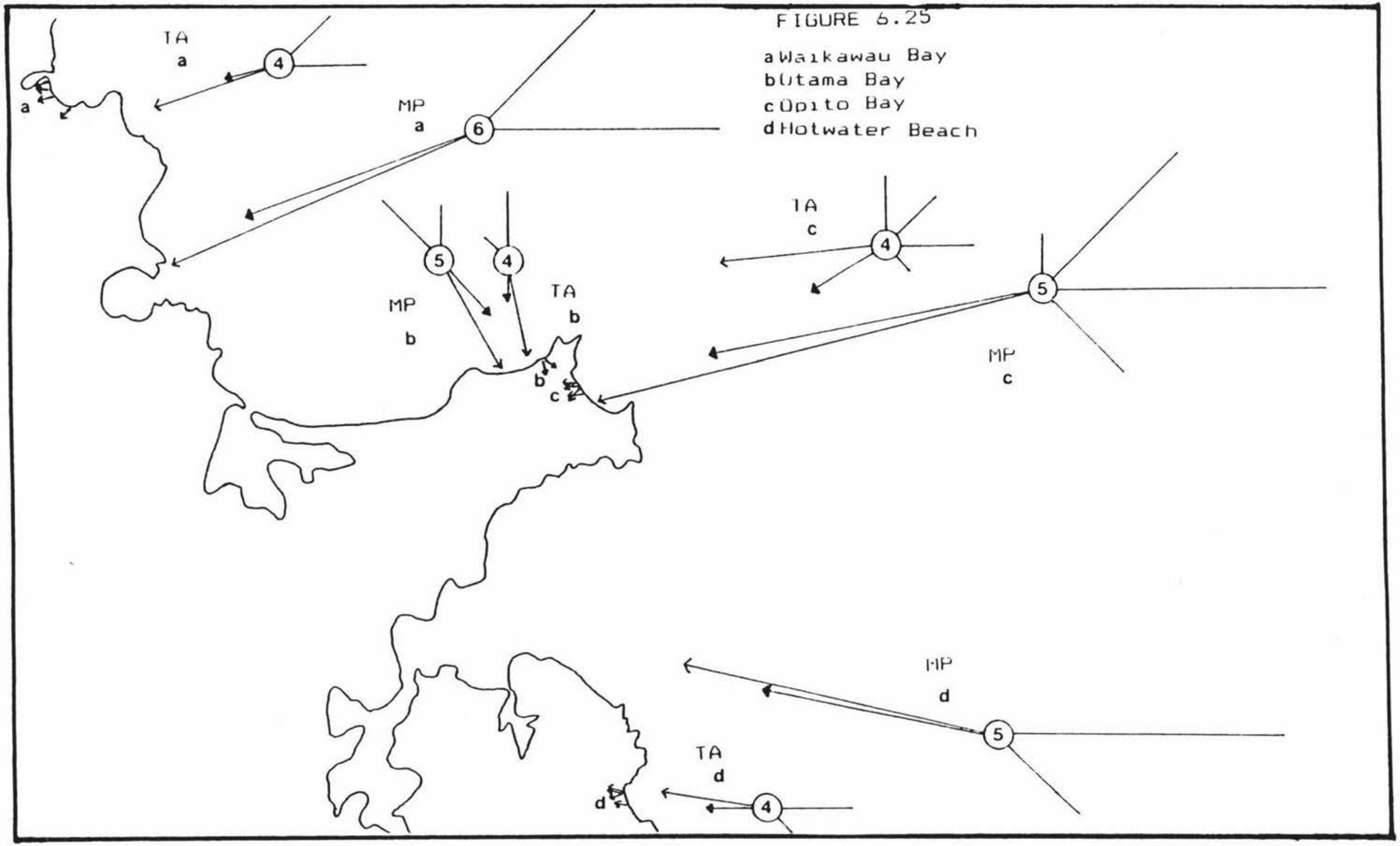


FIGURE 6.25

a Waikawau Bay
b Otama Bay
c Opito Bay
d Hotwater Beach
TA
a
4
MP
a
6
a
5
4
MP
b
TA
b
b
c
TA
c
4
5
MP
c
MP
d
5
TA
d
4
d

FIGURE 6.26

aKatikati entrance
bMt Maunganui
cMaketu

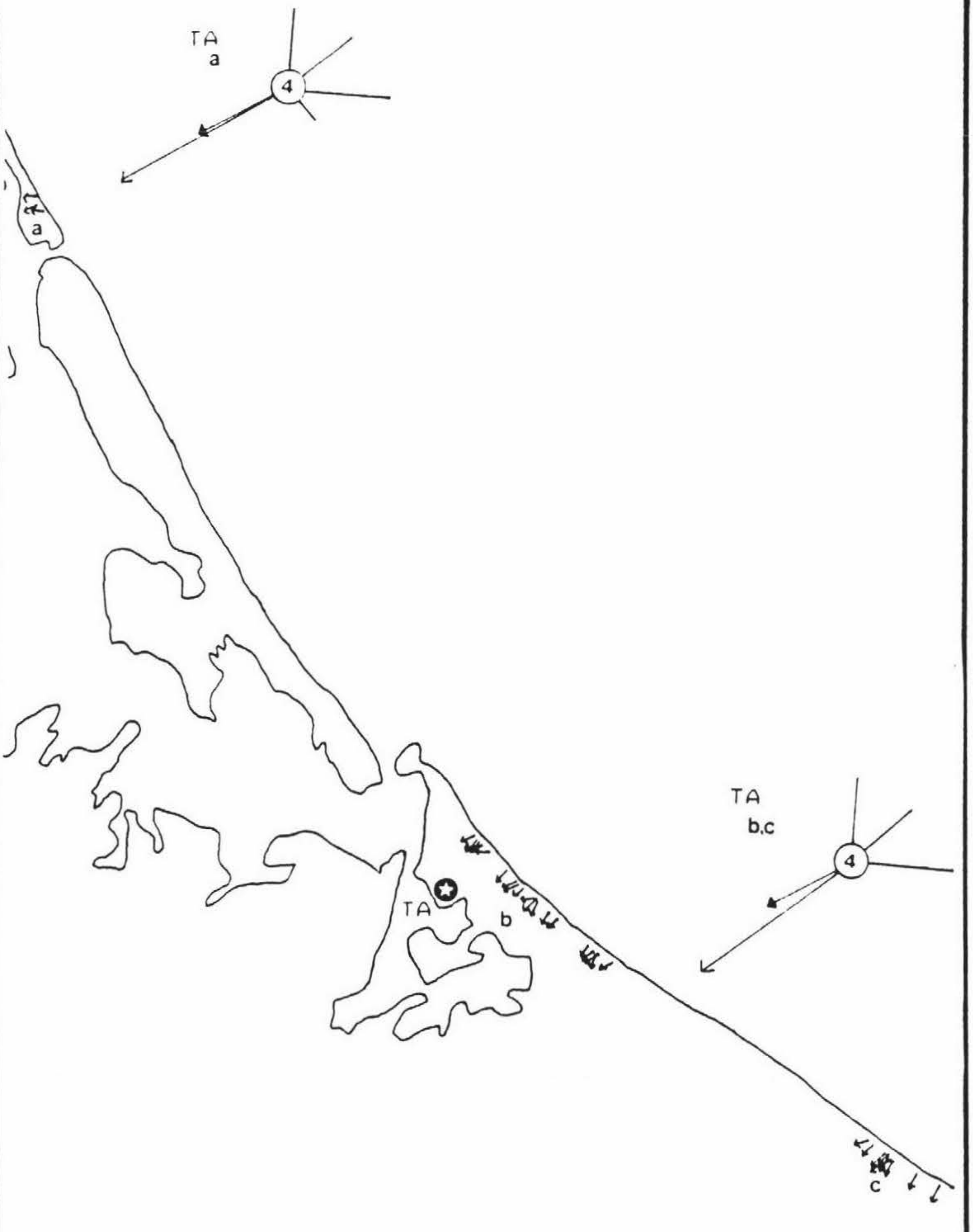


FIGURE 6.27

Rangitaiki River

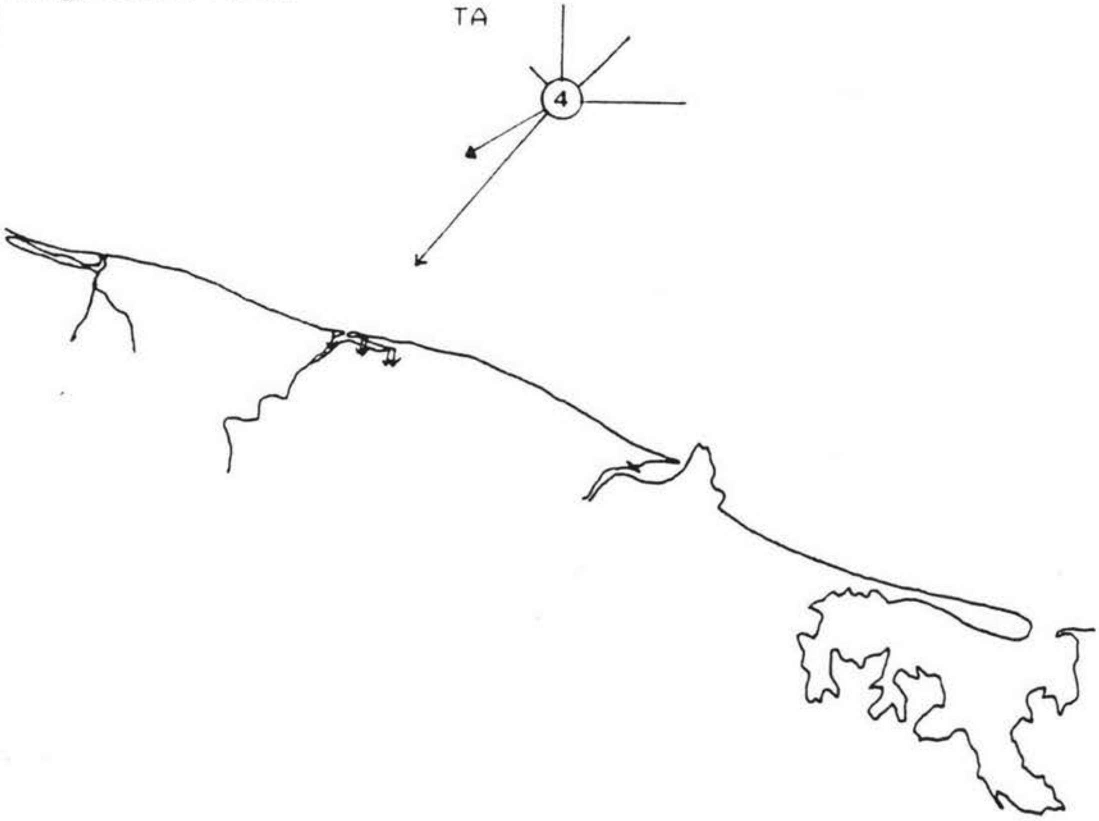
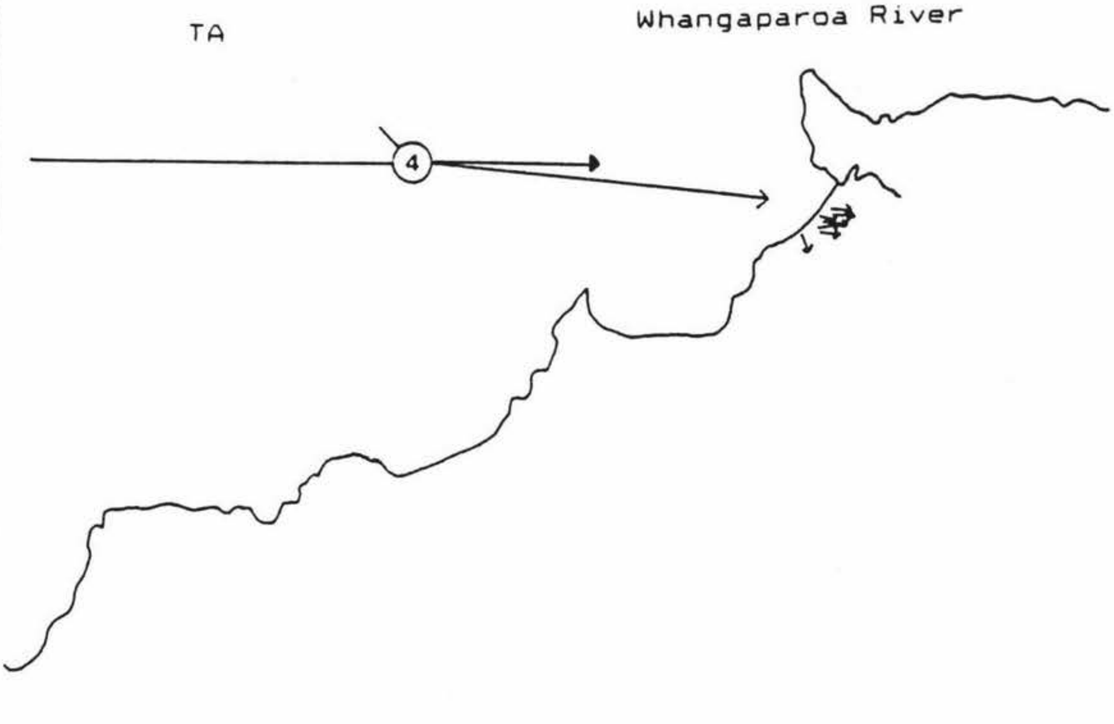


FIGURE 6.28

Whangaparoa River



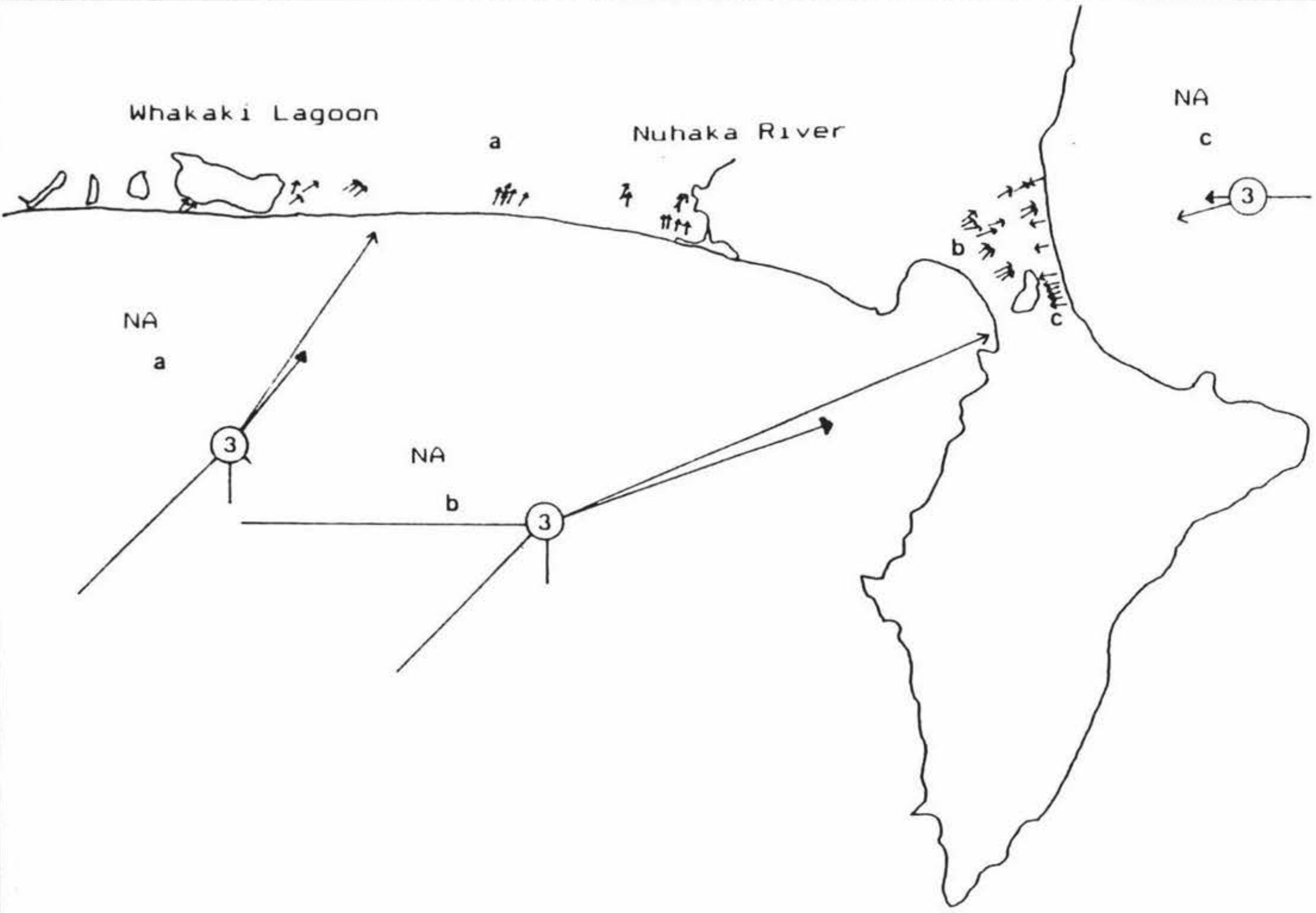


FIGURE 6.29
a Whakaki
b Mahia : west coast
c : east coast

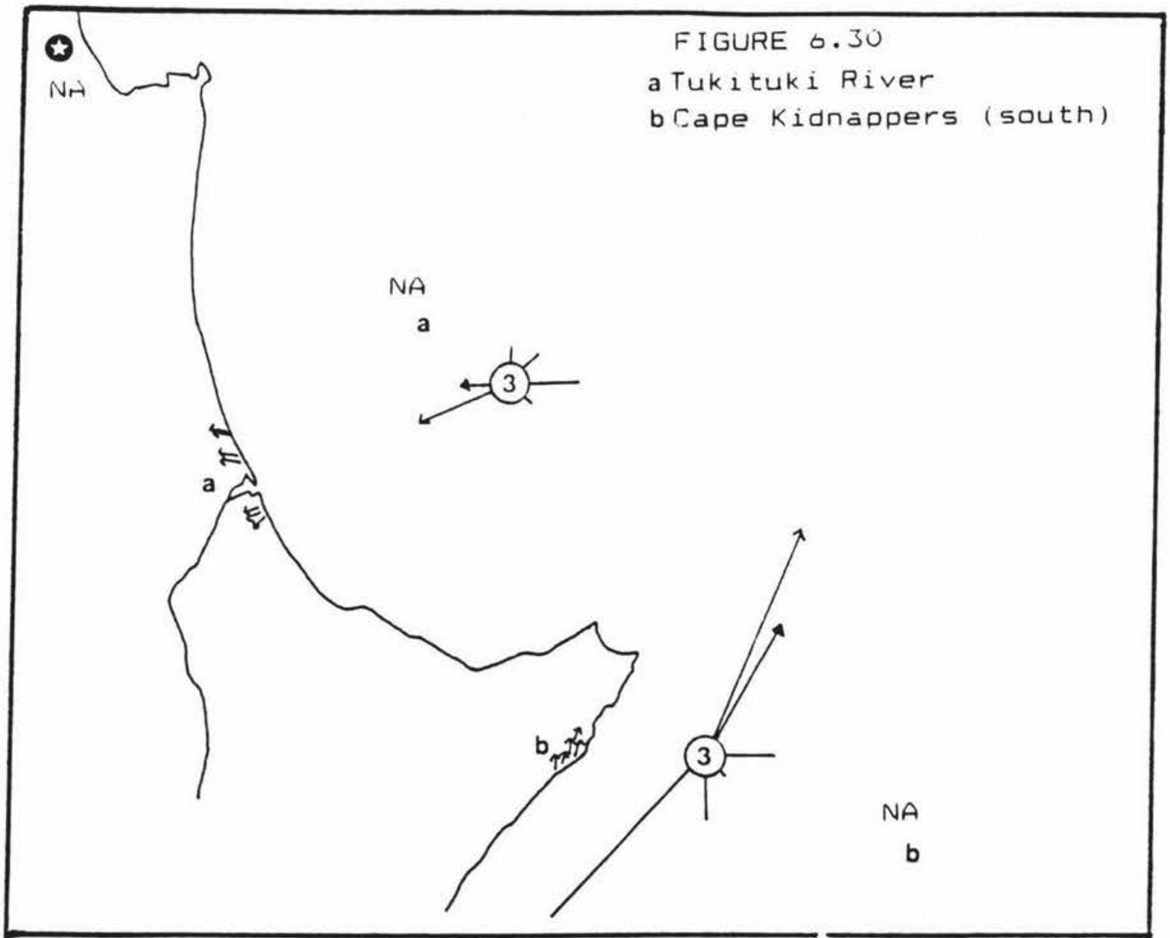


FIGURE 6.30
a Tukituki River
b Cape Kidnappers (south)

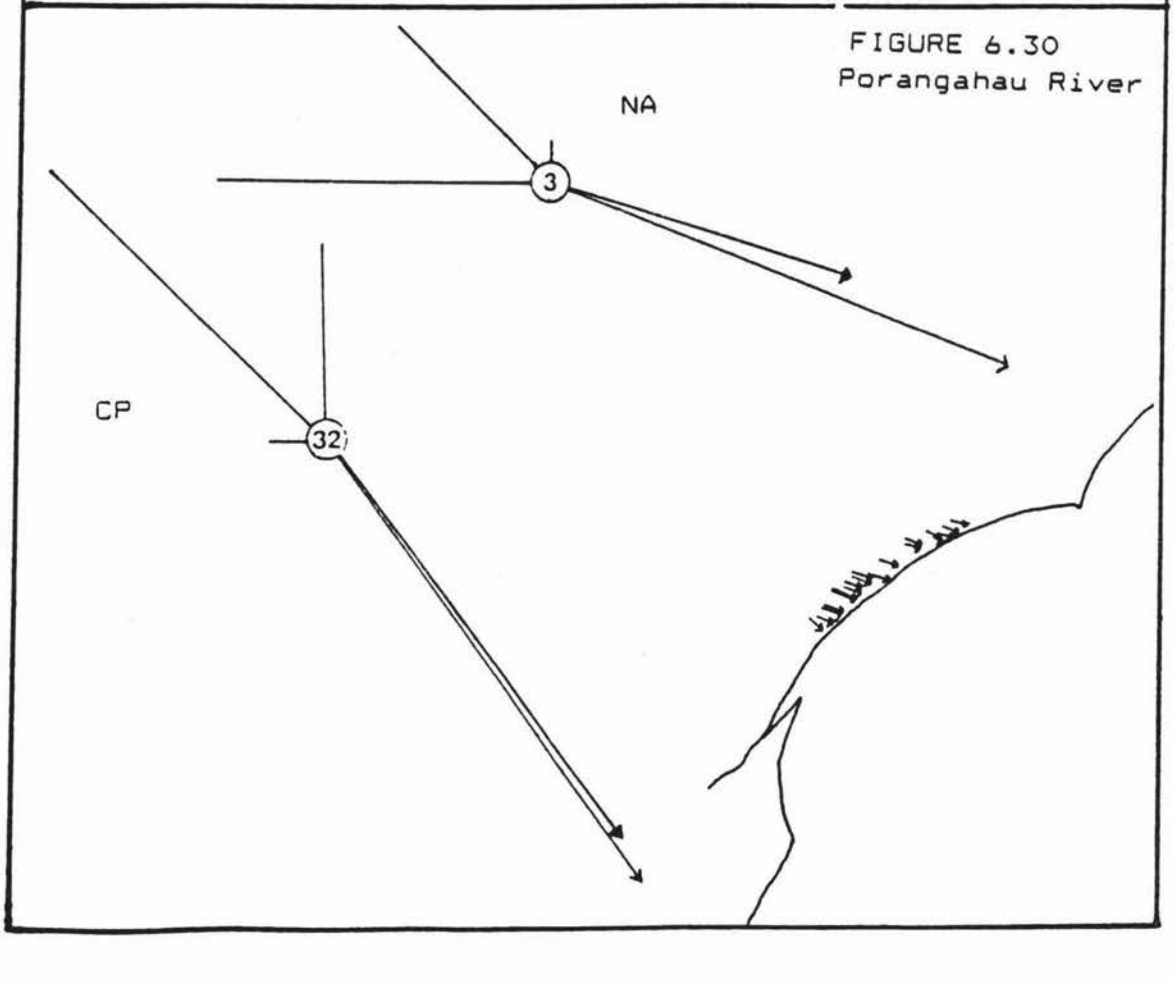


FIGURE 6.30
Porangahau River

$1 per photograph) and inability to inspect almost all sites in the field required that only dunes with clearly orientated axes were used. Even so, many of the orientations taken from blowouts and of sand sheets may be questionable because of the difficulties in accurately judging the direction of movement of sand within such features without information gained through field inspection.

DUNE ORIENTATION

WEST COAST NORTH ISLAND

Most of the sites along this coast show a good agreement between mean dune orientations and both types of onshore drift resultants. The drift resultant for winds >10 knots showed the closest correlation with mean orientation at seven locations while the resultant for winds >21 knots were closer to the mean at six locations. The maximum difference between the directions of the two resultants is only 5° so that there appears to be no significant difference between the two groups of wind speeds with respect to dune orientation.

Although there are some doubts regarding the degree to which the data from the Kaipara anemometer is representative of the long term average wind climate (see Chapter 5), the drift resultants derived from these data explain the orientation of the sand sheet blowouts, tongues of sand and parabolic dunes at Maunganui Bluff, Kaipara North Head and Kaipara South Head. Since Maunganui Bluff is not far from Marsden Point, data from this station was also used to construct drift resultants for that site. The resultants compared well with the orientation values. These results may indicate that while the anemometer data from Kaipara may not accurately reflect the proportion of onshore winds relative to other winds, they may describe the relative frequency of onshore winds reasonably accurately. However, the Kaipara data does not appear to explain the orientations of parabolic dunes near Ahipara very well possibly owing to the proximity of Tauroa Point to the southwest of the dunes. Deflection of southerly winds around this obstacle may result in a higher proportion of southwesterly winds at this location than at Kaipara.

Drift resultants based on data from Port Taharoa fit dune orientations at Manukau South Head well. The single parabolic dune at Te Henga (Bethells Beach) has a slightly more southerly orientation than is predicted by the onshore drift resultants but this may be due to the effect on the local wind climate at Te Henga of topography. This small area of Holocene sand is situated between higher blocks of land to the north and south. This higher ground may result in westerly and southerly winds being funnelled to produce southwesterlies. The parabolic dunes at Kaawa and Wainui Streams compare well to the Port Taharoa resultants. In addition to the single parabolic dune found near the coastline near Wainui Stream, orientations of parabolic dunes described by Pain (1976) were also compared to drift resultants. Pain provided a map of both Holocene and Pleistocene dunes located near Lake

Taharoa. Twenty of the dunes drawn had orientations which could be measured from the map with confidence. The mean orientation of these dunes differed from the orientation of the dune found near the coastline but this would expected since the coast at this location is exposed to winds from the northwest but the dune field farther inland near Lake Taharoa is sheltered from these winds by the higher ground at Albatross Point. Once the northwest component of drift potential was removed from the resultant for the Lake Taharoa dunes drawn by Pain, the drift resultant compared very well with the orientations. This example serves to illustrate that while onshore winds may be of greatest importance for dunes which have the coast as their direct source of sand, the situation maybe more complex where parabolic dunes form farther inland with sand sheets as sediment sources.

The mean dune orientations for locations from Manutahi through to Paekakariki gradually change from westerly to north-northwesterly reflecting the increasing angle of deflection of westerly winds around the South Island as one moves southward along the southwest coast of the North Island. Given that this change in mean orientation is a result of a change in all orientations, it is not surprising that the drift potential directions do not exactly match the mean orientations despite the large numbers of dunes involved. Each group of dunes extends over a substantial stretch of curving coastline and the anemometer stations are not located central to these dune fields. The data fits very well for all locations however, except from Raumati South to Paekakariki. At this site, the drift resultants do fall within the range of dune orientations but are more westerly than dune mean. It is likely that this is due to the presence of Kapiti Island to the northwest. Northwest winds would be partially blocked by the island while some wind from this direction would be deflected around the northern edge of the island. The latter airflow would then be channelled between the island and the hills inland of Paraparaumu resulting in northerly winds. Evidence of the strong effect that Kapiti Island exerts on the wind climate south of Waikanae can be seen in the wind rose for Paraparaumu airport (Goulter 1984).

WEST COAST SOUTH ISLAND

The total area of sand dunes along the west coast of the South Island is small and parabolic dunes or blowouts with measurable orientations were found at only six locations. Much of the west coast consists of eroding cliffs with a lack of flat topography for sand to transgress over readily. Where sand has accumulated in the past the rate of sand supply tended not to be great enough to overwhelm sand binding vegetation and lead to blowouts, climbing dunes or dune sheets. Most of this coastline is characterised by very low onshore drift potential so that once foredune vegetation has been established, blowouts caused by wind action alone would be rare. As a result, in many areas where sand has accumulated a series of foredunes have built out. Examples of areas of relict foredunes can be found near the mouth of the Little Wanganui River (south of Karamea), Birchfield and Charleston (north and south of Westport respectively), Lake Mahinopua (south of Hokitika), Totara River mouth (near Ross), Three Mile Beach (south of Awarua Point) and at Jackson Bay near Haast.

Thirty kilometre long Farewell Spit, at the northern tip of the South Island, is exposed to high wind energy. Most of the spit is covered by sand dunes with some reaching heights of over 20m. Sevon (1966, p73) commented that 'the prevailing wind at Farewell Spit is southwesterly' and that 'such a distribution of wind seems in opposition to a theory of bulk sand movement from north to south across the spit'. The resultant drift potential for Farewell Spit is in fact from the WNW which explains this movement. Most of the sand on the spit takes the form of sand sheets which are either mobile or fixed by vegetation. A few vegetated parabolic dunes exist at the eastern end of the spit along with some vegetated linear ridges (which are paired in a way to suggest that they may be the remnants of parabolic dunes). These ridges and dunes have a mean orientation of 283° which compares well with the drift resultant direction for Farewell Spit (285°). The anemometer for Farewell Spit is located close to these dunes and so a good correlation between the data and orientations would be expected.

This is not the case however, with the dunes and blowouts at the western end of the spit. Only two vegetated parabolics were found there and all other orientations were taken from blowouts at the edges of unfixed sheets of sand. Paradoxically, while the sand sheets are moving from the northern side of the spit to the southern, some of the blowouts and dunes at western end of the spit appear to be moving towards the northeast from within the body of the spit. This has lead to a mean orientation value of 269° (from almost due west). This is not inconceivable since the source of sand for these dune forms is the sand sheets rather than the ocean beach to the north. The wind climate at this end of the spit may be dissimilar to that at the eastern end owing to the presence of hills of greater than 1000m to the southwest. This topography would be expected to cause an increase in southwesterly winds received at the eastern end of Farewell Spit as winds flow along the eastern flanks of the Wakamarama Ranges and adjacent foothills. In addition to the differences in wind conditions at either end of the spit, the movement of sand dunes at the western end would involve a greater degree of interaction with vegetation and dune lakes which may influence the direction in which the dunes travel.

Dunes at Pilch Point, to the east of Farewell Spit, are also exposed to a high level of onshore wind energy. Sand has blown from the bay to the west of Pilch Point and from Wharariki Beach in an eastward direction. Dunes from the western embayment have been channelled through a topographic low between Pilch Point and hills to the south and have reached the embayment on the other side of Pilch Point. Dunes from Wharariki Beach are large (up to 500m in length) vegetated parabolics. The drift resultants based on data from Farewell Spit do not explain the orientations of these dunes very well, probably because the Pilch Point area is more openly exposed to wind from the west than Farewell Spit, resulting in dunes orientated in a more westerly direction than predicted by the anemometer data.

Data from the Farewell Spit anemometer suggests that the coastline at the mouth of the Turimawiwi River receives high wind energy. This may not be the case in reality since onshore winds affecting the coastline from Kahurangi Point to Lake Otuhie are likely to be influenced by the close proximity of the Wakamarama Ranges to the southeast. These ranges would be expected to lead to the develpoment of a buffer zone during strong onshore wind conditions similar to that created by the Southern Alps further south. Southwesterlies, deflected along the western flanks of the ranges, would be expected to be the dominant onshore winds at this location. Dunes (some up to 750 m long) and blowouts to the north and south of the Turimawiwi River mouth are orientated from the southwest in response to this wind climate. Owing to the effects of topography on the wind climate at this location, the data from Farewell Spit does not represent drift directions very well with the difference between mean dune orientation and drift resultant being 45.5°. Data from Westport airport explains dune orientation at this site slightly better but the drift resultants are still more northerly by greater than 20°.

Probably the largest area of coastal sand to be found on the west coast of the South Island apart from Farewell Spit is that at the mouth of the Okari River to the south of Cape Foulwind. A lagoon has formed behind a sand spit which is capped by young sand dunes (Nathan 1975). Some parabolic dunes with lengths between 50 and 100 m are located in areas of older Holocene dunes (Nathan 1975) to the north and east of the spit. These dunes are likely to be exposed to greater levels of wind energy from the southwest than is the case at Westport, which probably accounts for the fairly large discrepancies between the drift resultants based on the Westport airport data and the dune orientations at the Okari River mouth. For the same reason the very low drift potential value of 94 vector units calculated from the Westport data is probably an underestimate of the true level of onshore wind energy for the Okari River site.

At the mouth of the Cascade River, near Cascade Point, there are a number of blowouts which range in length from around 75 to 275 m. Both blowouts and parabolic dunes of similar scale are present in Barn Bay to the south. Neither of these dune areas have a very satisfactory agreement between dune orientation and drift resultants based on wind data from Haast. This is a similar situation to that pertaining to the Okari River dunes and Westport wind data. Again the anemometer site at Haast is partially sheltered from southwesterly winds while the dune sites are openly exposed to these winds resulting in dune orientations which are more southwesterly in direction than the drift resultants.

SOUTH COAST SOUTH ISLAND

The south coast of the South Island is characterised by a series of embayments which act as sediment traps. This, together with the high onshore wind energy the area receives, has resulted in the development of parabolic dunes at a number of sites along this coastline. All the dunes from Kawakaputa Bay to Haldane Bay involve the movement of sand eastward from west facing coasts. The orientations of these dunes range from 246° to 285° reflecting the overwhelming predominance of westerly winds received along this stretch of coastline. Accordingly, drift potential directions based on data from Tiwai Point fit the mean orientations of these dunes very well. At two of these sites however, the drift resultants fall outside the range of orientation values. The dunes at Kawakaptu Bay are orientated in a more southwest direction than the drift resultants. This is likely to be due to deflection of some westerly winds into Kawakaptu Bay resulting in southwesterly airflow where the dunes are located at the head of the embayment. Dunes at Black Point, on the other hand, are orientated in a more northwesterly direction than the drift resultants for that site. Hills to the north may affect the local wind pattern by deflecting westerly winds so that they flow in a more northwesterly direction.

Tahakopa Bay and Purakaunui Bay are not directly exposed to westerly winds owing to their location on the coastline and to topographic sheltering. As a result the levels of onshore wind energy are much lower at these locations than the rest of the south coast. Purakaunui Bay's drift potential is particularly low since it is not exposed to southerly winds either. Orientations at these sites were taken from blowouts ranging from 25 to 75 m in length. At Tahakopa Bay the sand is being blown into a large area of forest resulting in a wide range of orientation values. Drift resultants using data from both Tiwai Point and Oamaru airport all fall within this range but the Oamaru resultants come the closest to the mean orientation for the blowouts. The blowouts at Purakaunui Bay are more uniform in their orientations. Only the Tiwai Point drift resultant for winds >10 knots falls within this range. The topography in the vicinity of Purakaunui Bay is quite complex with hills over 200m to the north and southwest, and a series of coastal cliffs up to 180 m high to the east (NZMS 1 S184). This may mean that winds in this area are modified to the extent that the wind climate is very localised and quite dissimilar to that at either Tiwai Point or Oamaru.

EAST COAST NORTH ISLAND AND BAY OF PLENTY

Wind climates along these coastlines are characterised by greater spatial variability than the west coast of the North Island. Since data from only four anenmometer stations are used to describe the drift potential at a large number of widely distributed sites, the computed drift resultants differ from the dune orientations by quite a large margin at many of these sites. In thirteen cases the resultant of winds >21 knots has an orientation closest to the mean dune orientation while the >10 knots resultant comes closest in fifteen cases. In many instances the orientations of the two onshore drift resultants only differ by a few degrees but at some sites the difference is as high as 26° (Opito Bay, Tauranga airport resultants).

This coastline may be divided into sections according to proximity to the anemometer stations used. The locations from Great Exhibition Bay to Mangawhai Harbour are located along the eastern coast of Northland and are therefore taken to be covered by the Marsden Point wind data. The sites along the eastern coast of the Coromandel Peninsula (Waikawau Bay to Opoutere Beach) are exposed to similar wind directions as those along the Northland east coast but many of these sites are located closer to the more sheltered anemometer at Tauranga airport. Thus all dune orientations along the Coromandel coastline have been compared to both Marsden Point and Tauranga airport drift resulants. Tauranga airport data is used for all Bay of Plenty dune sites (Katikati entrance to Whangaparoa River) and Napier airport data for all Hawke Bay sites (Mahia to the Tukituki River) as well as the Cape Kidnappers site. The orientations of the rather unusual parabolic dunes at Porangahau (to the north of Cape Turnagain) are compared to drift resultants derived from Castlepoint wind data although these do not involve the use of onshore winds.

The agreement between resultants and mean dune orientations along the Northland coast are reasonably good except at Great Exhibition Bay and Henderson Bay. One explanation for the poor correlations may be that the Marsden Point wind data does not reflect wind conditions at these sites. The orientation of the coastlines at Great Exhibition Bay and Henderson Bay are very similar to the coastline at Mangawhai Harbour to the south, and the Marsden Point resultants correlate well with the dune orientations there. If the explanation were related to the large distance between the bays and Marsden Point, one would expect a poorer correlation than is the case at nearby Kowhai Beach and Houhora Bay. An alternative explanation may involve inaccurate determination of the orientation of the dunes because parabolic dunes were not well developed and orientations for these locations are taken from blowouts at the edges of sand sheets and from sand sheet lobes themselves.

All of the other locations along the east coast of Northland also involve blowouts from either the edges of sheets or, in the case of some of the blowouts at Mangawhai Harbour, the contemporary foredune. The orientation of these blowouts correlates reasonably or very well with the drift resultants at all locations with the greatest discrepancy between the >10 knots drift resultant and the mean orientation being 13° at the southern end of East Beach.

Along the Coromandel coast dune orientations compare well with drift resultants constructed from either the Marsden Point data or the Tauranga airport data. All orientations along this stretch of coastline were taken from small blowouts of between 12 m and 50 m in length.

The orientations of the four blowouts at Waikawau Bay agree well with onshore resultants from both the Marsden Point and the Tauranga anemometer data. The Marsden Point resultants are closest to the blowout orientations at both Otama and Opito Bays but the Tauranga drift resultant lies within the range of orientations for the latter site. The Tauranga resultant best explains orientations of blowouts at Hotwater Beach. This indicates that the Marsden Point data best describes the wind climate of the northern part of the east coast of the Coromandel Peninsula while the Tauranga data best relects that of the southern part.

Estimating the level of onshore drift potential at the sites on the Coromandel Peninsula is difficult because of the different amounts of wind energy received at the two anemometer stations. The Marsden Point data indicates that these sites are exposed to onshore drift potential equivalent to between 106 and 495 vector units while the Tauranga airport data indicates levels equivalent to between only 58 and 151 vector units. However, any values of less than 550 vector units are considered to be low levels of wind energy (see Chapter 4).

Most of the orientations in the Bay of Plenty coastline were taken from blowouts of 25 m to 125 m in length. The exception is the site at the Whangaparoa River just south of Cape Runaway where the orientations of five parabolic dunes were also measured. These dunes vary in length from around 100m to 225m. All sites are again exposed to only low levels of onshore wind energy. This may be misleading in the case of the Whangaparoa River site, however, since this coastal area is exposed to west while the coast near the Tauranga airport, from which the wind data was taken, is not openly exposed to winds from this direction. Therefore the level of wind energy at this site might be expected to be higher than that indicated by the Tauranga data.

Drift resultant directions explain the directions of the dunes at this site well, however, and this is also the case at Mount Maunganui and Maketu. In contrast, the discrepancies between dune orientations and drift resultants at the Katikati entrance and near the mouth of the Rangitaiki River are over 20°. The orientations for the Katikati entrance were taken from three blowouts, the largest of which (around 125m long and around 75m wide) has an orientation of 57° which is also the direction of the drift resultant for onshore winds >10 knots for this location. The other blowouts are much smaller (around 25m long) and have orientations which appear to be more southwesterly than the drift resultant. It is possible that the small blowouts may have been generated by one storm event and that at the time the photograph was taken, there had not been sufficient time for the orientation of the blowouts to adjust to average wind conditions.

The blowouts near the mouth of the Rangitaiki River have orientations ranging from 1° to 17° while the onshore drift resultant directions are 30° and 48° for winds >10 knots and >21 knots respectively. This may be a result of greater sheltering from easterly winds (provided by the Raukumara Ranges) at this location than is the case at Tauranga. If the easterly component is removed from the construction of the onshore drift potential for the Rangitaiki River site the drift resultants for both wind speed groups have directions of 22° which is closer to the mean orientation of the blowouts.

The dunes in or near Hawke Bay include parabolics at the west coast of the Mahia tombolo, Whakaki and Cape Kidnappers where the coastline is exposed to southerly winds. The parabolic dunes on the west coast at Mahia have in some cases traversed the narrowest point of the tombolo, reaching the eastern coast. The longest of these is about one kilometre long and approximately 175m wide. A number of others are about 120m long and 50m wide. The largest parabolic at Cape Kidnappers is about 600m long and 125m wide. The parabolics at Whakaki tend to be short and wide by comparison with one example being around 75m long and 100m wide. One large dune measures approximately 625m long by 400m wide. On the eastern coast of the Mahia tombolo and at the Tukituki River where the coast is sheltered from these stronger winds, only blowouts occur. These are much smaller with lengths of 100m at Mahia and 25m at the Tukituki River being typical. (For further comment on this see the section on Dune Dimensions below).

In all cases the onshore drift resultant for winds >10 knots falls within the range of dune orientations. Despite this, due to the very large range of orientations, the difference between that resultant and the mean orientation for the dunes at the mouth of the Tukituki River is 21°. The mean orientation of the blowouts at this location is almost exactly equal to the drift resultant for onshore winds >21 knots. Interestingly the drift resultant for winds >21 knots for both Mahia east and the Tukituki River is from 90° since the only strong onshore wind at these locations which is frequent enough to be represented in the data as a per thousand occurance is from the east.

At all locations apart from the Tukituki River the drift resultants compare well with the mean dune orientations.

Sand dunes located in the vicinity of the mouth of the Porangahau River differ from all the other dunes examined in this study in one important aspect. While all the other dunes investigated have formed as a result of winds blowing sand in an inland direction, this is not the case at Porangahau. Instead the parabolic dunes at this site are moving *toward*, and some some cases reaching, the coastline. The sources of sand for these dunes are sand hills which lie between approximately one and two kilometres from the shore. The parabolic dunes, the largest of which is approximately 1.3 km long and 120m wide, have traversed over a series of low lying relict foredunes. According to Mr Mike Sugden, Head Stock Controller of a farm in the area, this land was first farmed around 1850 using a swamp plow before drainage channels were subsequently constructed. It is possible that drainage of the land, together with removal of any covering of natural vegetation which may have been present, could have lead to the initiation of dune movement. Mr Rob Bruce, who owns farm land in the area, and Mr Sugden agree that the strongest winds which affect this location are westerlies and that these are not infrequent in occurence. Mr Bruce reports having observed considerable sand movement on the dunes during winds of 60 to 65 knots. At present, however, many of the dunes are being stabilised through the planting of pine trees on the eroding sand hills which supply sand to the parabolics, and the planting of vegetation such as barley grass on to the low lying noses of the dunes. (M. Sugden and R. Bruce pers. comm.).

It is apparent that onshore winds can explain neither the formation nor the orientation of the parabolic dunes found at Porangahau. Therefore offshore winds were used to calculate the drift potential in this case. Owing to the location of Porangahau approximately midway between Napier and Castlepoint, data from both of these anemometer stations were used for calculations.

Westerly winds funnelled through the topographic low between the Ruahine and Tararua ranges dominate the wind climates at both Castlepoint and Porangahau. While these modified winds tend to arrive at Castlepoint as northwesterlies, they form westerly winds at Porangahau. Because of this, the mean orientation of dunes at Poranagahau is 38° more westerly than that predicted by the Castlepoint data. The Napier airport drift resultants fit the mean orientation value very closely indicating that offshore winds of different directions occur in similar proportions at Napier and Porangahau. The level of wind energy may be higher than that indicated by the Napier figure, though, because winds from the westerly quarter would be expected to be stronger on average at Porangahau (for the reason mentioned above) than those received at Napier. The drift potential at Porangahau may be closer to that indicated by the Castlepoint data.

EAST COAST SOUTH ISLAND

The values of onshore drift potential received at locations along this coastline are fairly low and are comparable to those of the east coast of the North Island. The number of dune locations is much fewer, however, mainly due to coastal topography and lack of sand supply. There is an area of sand near the mouth of the Waikouiti River (north of the Otago Peninsula) but only two parabolics with measurable orientations were found. The correlation between the orientations and the onshore drift resultant using Oamaru wind data is very poor with the resultants being more than 40° more southerly than the orientations. This may be explained by the presence of the Otago Peninsula to the immediate south of Waikouiti. This high topography would shelter the bay from a high proportion of southerly winds which are received at Oamaru.

A series of relict foredunes exists on Kaitorete Spit. Blowouts from some of these and from the contemporary foredune have quite a large range of orientations. Drift resultants based on data from Oamaru and Christchurch all fall within this range of values and also reasonably close to the mean orientation. While the data from the two anemometer stations agree fairly closely with regard to both drift resultants and drift potential at this location, this is not the case further north at Pegasus Bay. In this instance there are two areas of blowouts - one to the north and one to the south of the Ashley River mouth - and each group is characterised by quite different orientations. The northern blowouts have formed from, and strongly modified, foredunes between 350m and 1km from the coast. These blowouts are orientated in a south-southeasterly direction while blowouts of to the south of the Ashley River have formed from the contemporary foredune have orientations mainly from the east-northeast. This difference in orientations is probably related to the fact that while the section of coastline between the Ashley and Waimakariri Rivers is openly exposed to winds from the southeast through to the northeast, the coastline north of the Ashley River is sheltered from northeast winds.

The nearest anemometer station to these blowouts is that at the Christchurch airport. The drift resultants based on data from this station do not fit the orientations of the northern blowouts very well, probably because the anemometer site is sheltered from southeast flow while the blowouts are openly exposed to these winds. Data from Oamaru airport provides drift resultants which explain the orientations of these blowouts more satisfactorily. Resultants from both stations have directions which are close to the orientations of the blowouts to the south of the Ashley River.

LANDSBERG WIND RESULTANTS

Since most wind resultants constructed using Landsberg's method were the same or very close to the Fryberger drift potentials for winds >10 knots (see chapter 4), it was assumed that onshore wind resultants would also agree with onshore drift resultants and therefore the former were not used. There are two stations, however, for which the Landsberg and Fryberger resultants do not agree. These are the Wanganui airport and Westport airport stations where the resultants differ by 7° and 15° respectively. The onshore wind vectors using Landsberg's method were computed for the dune sites discussed above to see if the Landsberg resultant came closer to the dune orientations than the Fryberger drift resultants. Using the Wanganui airport data the onshore Landsberg vector for the Manutahi and Castlecliff to Whangaehu River sites is from 273° which differs from the Fryberger resultant for winds >10 knots by only 1° and is the same as the resultant for winds >21 knots. For the Westport airport data the Landsberg vectors for onshore winds at the mouth of the Turimawiwi River and the Okari River are 267° and 256° respectively. These differ from the Fryberger resultants (for winds >10 knots) by 2° and 4° for the two sites and in both cases the Fryberger resultants are closer to the mean orientation values.

DUNE DIMENSIONS

DUNE SIZE

One of the primary factors influencing the height of parabolic dunes is the size of vegetation over which the dunes encroached. In the Manawatu region for example, some Foxton phase dunes which transgressed over native forest reached heights of around 20m while younger dunes which have migrated over pasture are much lower (Shepherd 1987). Where sand is encroaching on forest it will pass around or over the trees depending on which is the easiest path. This is illustrated by a transverse dune near Himitangi Beach which is presently moving over an area containing a block of pine trees. Owing to the relatively small size of the forest much of the sand is being blown around it (Shepherd 1987). Any orientation of sand bodies bypassing such an obstacle would not reflect the drift potential direction of the area alone. At Tahakopa Bay, where sand is being blown into forest which extends across the length of the embayment, blowout orientations have a range of 64°. This may be a result of sand being transported through the easiest path at each site. The same effects would be expected where sand dunes interact with topographical obstacles. On the southern barrier at Kaipara Harbour, sand advancing inland encounters a dissected cliff. Where the cliff face is not too steep sand has piled up against it forming climbing dunes. Where sand has been transported to the top of the cliff, cliff-top dunes (often parabolic) have formed. However, where gulleys exist, wind tends to be funnelled through these gaps in the cliff face (Brothers 1954). Dunes confined within the gulleys have constraints imposed on their direction of movement and are exposed almost exclusively to winds that flow along the length of the gulley. This may explain the 49° range of dune orientations found at the southern Kaipara barrier.

DUNE SHAPE

Dune size appears to be related to levels of onshore drift potential. Dune shape, on the other hand, is to some extent dependent on the directional variability of effective winds. Jungerius and Verheggen (1981) found that blowouts in the 'De Blink' area of the Netherlands are widened as a result of undermining and consequent mass wasting of the walls of the blowouts. A blowout of the foredune on the Manawatu coastline has been observed by the author during strong wind conditions. At that time the wind was blowing onshore in a direction oblique to the orientation of the blowout. This lead to the removal of sand from the wall that was facing the wind and deposition of sand on the opposite side of the blowout. The sand could not be blown to the top of the latter and leave the blowout because of the steep angle of the wall (around 30°, the angle of repose for dry sand). However, continued removal of sand from the exposed wall of the blowout would be expected to result in the process of underminig and wall recession described by Jungerius and Verheggen (1981). It follows from this that the greater the variation in effective wind directions at a site, the greater the degree of lateral wall recession and therefore the rounder, or less elongate, the shape of the blowout that will develop. The same would also be expected to apply to the development of the shape of parabolic dunes. Davies (1980) notes that 'where the direction of strong winds is relatively constant, transgressive dunes are often markedly linear' (p 164) whereas parabolic dunes with high width/length ratios are more likely to develop where there is a great variation in strong wind directions. Davies also suggests that a such a variation in wind directions may lead to coalesence of dunes, producing transgressive dune sheets.

The table below provides a summary of the theoretical relationships between levels of onshore drift potential and directional variability of wind, and dune size and shape. (In this diagram it is assumed that sand supply is sufficient for these dunes to develop.)

Table 6.3

	Increasing Values of Onshore Drift Potential →	
Decreasing Directional Variability of Wind ↓	small, rounded blowouts	blowouts and parabolics with higher width/length ratios; sand sheets
	small, more elongate blowouts	elongate parabolic dunes; linear ridges

In order to assess whether these relationships hold for New Zealand dune sites, the directional variability and onshore drift potential values (see Chapter 5) for each of the anemometer sites that were used to represent dunes sites are shown in a similar diagram below.

Table 6.4

		Levels of Onshore Drift Potential →		
		low	int	high
Levels of Directional Variability ↓	high	Westport, Kaipara SH, Haast, Oamaru Christchurch		
	int	Marsden Pt, Tauranga, Napier	Ohakea, Port Taharoa, Te Horo	Farewell Spit, Wanganui, Tiwai Pt (Castlept-*offshore*)
	low			

Comparing the two tables, it would be expected that the majority of well developed parabolic dunes would be found along the south coast of the South Island, the northwest of the South Island, the west coast of the North Island and and at Porangahau, and indeed this is the case. (Note that the position of Kaipara South Head on the table is probably not correct: refer to Chapter 5.) It is also true that dunes found along the south coast of the South Island and the west coast of the North Island are more elongate, and therefore have clearer orientations, than most parabolic dunes or blowouts located on the east coasts of either Island or on the west coast of the South Island. For example, many dunes in the Manawatu and at Bluff Harbour, Waipapa Point and Porangahau have width/length ratios of less than 1:3. By comparison, some dunes at Kaitorete Spit, Whakaki and the Okari River have width/length ratios of greater than 1:1.

The parabolic dunes that were found to have the highest width/length ratios in this study are those located near Whakaki in northern Hawke Bay where southerly winds have been dominant in forming the dunes but westerlies, which flow alongshore in this location, may have influenced the shape of the dunes. The exposure to southerly winds at this site means that the onshore drift potential is likely to be higher than at the Napier anemometer site.

Whilst the division between areas of parabolic dunes of different dimensions appears to be accounted for reasonably well by these tables, the locations of sand sheets are not so well explained. The main areas of active sand sheets are found in the northern part of the North Island and Farewell Spit in the South Island, and areas which have been characterised by sand sheets in the past include the Manawatu and Wanganui regions. However, the positions of the Marsden Point, Port Taharoa, Farewell Spit, Ohakea and Wanganui on the second graph do not correspond to the high values of directional variability of wind that the first graph predicts. In fact, the sand sheets in these areas (except the east coast of Northland) have tended to be sources of well developed parabolic dunes. This indicates that levels of onshore drift potential and directional variability of wind are not the main variables determining whether sand sheets will develop at a location. Rates of sand supply and the extent of vegetation destruction at the foredune (which is more likely to be complete where onshore wind energy is highest) are likely to be factors of greatest importance.

The other variable that may influence the development of sand dunes is the topography over which the sand is transported. Sand movement's relationship to topography is similar to it's relationship with vegetation. As Cook (1986, p 135) notes : 'Transgressive dune growth can be seen as a balance between sand supply and vegetation resistance.' The same applies to topography for where sand supply (and drift potential) are great enough, topographic features will not halt the movement of transgressive sand dunes. However, the shape, size and orientation of the dunes may be affected as sand piles up to climb cliffs or bush, moves across series of relict foredunes or is diverted into valleys. Where sand supply is not great enough, cliffs and barriers may halt dune movement.

Within any region the relative importance of controlling variables may change from one location to another, with the result that variations in dune morphology between locations, and even between individual dunes, commonly occur.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Many factors have influenced the location of coastal dunefields in New Zealand. The most important factor has probably been the supply of sand to coastal areas but this variable is controlled by a host of other factors including sea level change, wave climate, location of rivers and local geology. The most important factors affecting the development of transgressive dunes at the coast are sand supply, vegetation cover and levels of wind energy.

The sections of coastline that are openly exposed to the prevailing westerly winds are correspondingly characterised by the highest levels of onshore drift potential. The highest values of onshore drift potential are those computed for locations on the west coast of the North Island, and the northwest and south coasts of the South Island (see Table 6.2). The most extensive transgressive dune fields are located on the west coast of the North Island because of the combination of high drift potential, abundant sand supply and relatively flat coastal hinterland along much of this coast. Coastlines which are exposed to low levels of onshore drift potential, such as the east coast of the Coromandel Peninsula and the Bay of Plenty, do not tend to be characterised by high levels of transgressive activity.

However, given that sand movement in the form of blowouts and small sand sheets has occurred in areas of low levels of onshore drift potential (eg: Bay of Plenty and east coast of Northland) and that undisturbed sequences of relict foredunes still exist in areas characterised by high levels of onshore drift potential (eg: north of Bluff Harbour), wind cannot be said to be the only factor leading to transgressive dune development.

FIGURE 7.1 is reproduced from Hack (1941) and shows how these variables control the developlment of major sand dune types. FIGURE 7.2 is a diagram which is similar to Hack's but looks at the relationship between sand supply, vegetation cover, wind energy and *coastal* dune type, based on observations of New Zealand coastal dunefields [it should be noted that this diagram cannot represent all possible combinations of coastal conditions due to it's shape. For example, a combination of high sand supply and high onshore wind energy cannot be represented in FIGURE 7.2].

The destruction of coastal vegetation was widespread in most parts of New Zealand following the arrival of Europeans. This means that at some stage nearly every section of the New Zealand coastline was characterised by conditions favourable to transgressive dune

FIGURE 7.1

Relationship of the three main dune forms to vegetation, sand supply and wind (from Hack 1941)

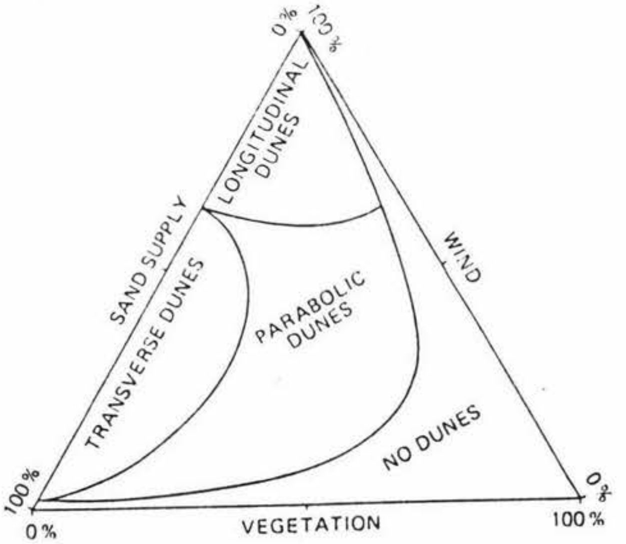
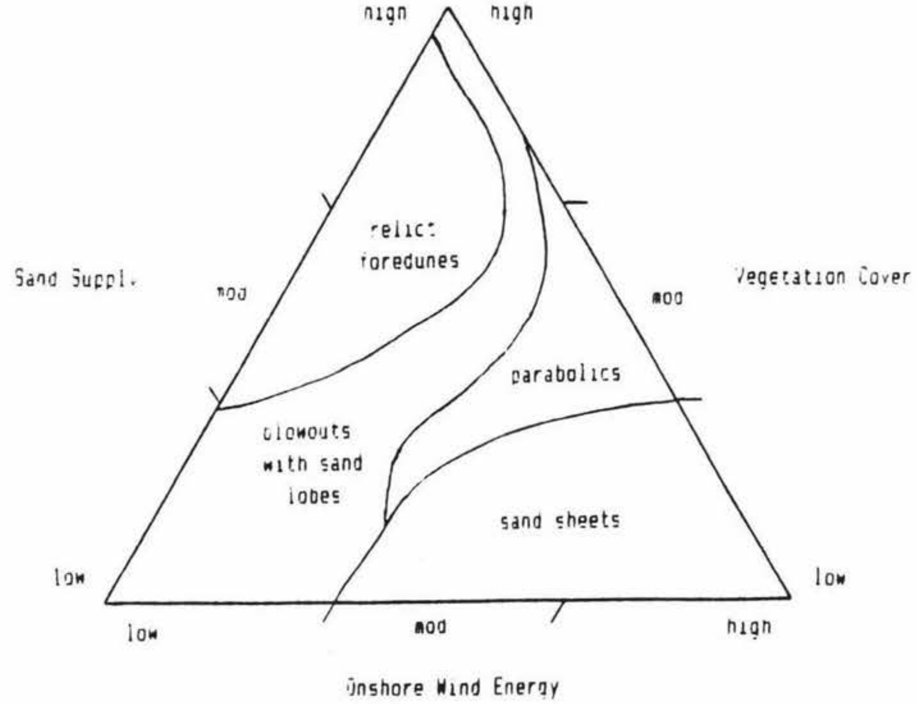


FIGURE 7.2

Relationship of four main coastal dune forms to vegetation, sand supply and onshore wind energy



development in terms of one important variable. Since the turn of the century efforts have been made to introduce a variety of vegetation types to dune areas in order to arrest transgressive dune activity. Pine plantations have been particularly successful in stabilising sand sheets at locations such as Santoft in the Manawatu. Introduction of marram to foredunes has helped to prevent blowouts in many areas but where sand supply and onshore winds are great enough, as is the case along much of the west coast of the North Island, blowouts still occur owing to the heights to which marram dunes may grow.

While the location and type of dune depend on a number of variables, the morphology of parabolic dunes appears to be controlled mainly by wind characteristics. Orientations of blowouts and parabolic dunes in most of the sites studied have been found to correlate well with the wind vector resultants of Landsberg (1956) and the drift resultants of Fryberger (1979), provided that only the winds that blow from the source of sand toward the dunes are used in computations. In some cases the correlation is less than satisfactory but this may be due to a lack of anemometer data which can accurately represent wind conditions at some of the dune locations. This is more frequently the case on coasts which are leeward to the prevailing westerlies where onshore winds tend to be more local in nature. Winds are also more localised along much of the west coast of the South Island, owing to the modification of westerly winds by the Southern Alps.

Correlations between dune orientation and drift resultants for winds >10 knots tended to be marginally better than those between orientations and resultants for winds >21 knots. It is not known whether this difference is statistically significant.

From the work done in this thesis, it would appear that the size and shape of parabolic sand dunes are primarily dependent on levels of onshore drift potential and the directional variability of geomorphically effective winds. High values of onshore drift potential and low variability in the direction of winds tend to produce more elongate parabolic dunes while rounder dunes are formed where winds are less unidirectional. Where onshore drift potential is low, sand cannot be moved very far inland and so dunes do not develop elongate shapes.

Although this study has provided some insight into the topics discussed above, there is scope for more detailed research into the morphology of parabolic dunes and dunefields in New Zealand. Some of the smaller dunefields, many of which have not been studied at all by geomorphologists, warrant investigation. Detailed studies of individual dune areas and comparisons between both individual dune morphology and between types of dunefield would allow many of the relationships discussed in this thesis to be further clarified.

Appendix 1 : Anemometer Stations

	Station	Height above MSL	Location	Data Period	Number of Months
A54640	Marsden Point	3m	35 50S 174 16E	Jan 1969 - Dec 1978	120
A64422	South Head, Kaipara	24m	36 28S 174 16E	Jun 1966 - Apr 1968	22
B76621	Tauraunga airport	4m	37 40S 176 12E	Apr 1961 - Dec 1978	213
C84173	Port Taharoa	27m	38 10S 174 42E	Jan 1980 - May 1981	17
E93271	Cape Egmont	8m	39 17S 173 45E	Jun 1970 - Mar 1977	82
	Napier airport	2m	39 28S 176 52E	1949 - 1978	360
E95903	Wanganui airport	9m	39 58S 175 01E	Jan 1965 - Dec 1969	60
	Ohakea	22m	40 12S 175 22E	Jan 1960 - Dec 1972	156
E05700	Te Horo	9m	40 46S 175 05E	Jan 1972 - Dec 1976	60
D06921	Castlepoint	3m	40 54S 176 13E	Jan 1962 - Dec 1970	108
F03501	Farewell Spit	3m	40 33S 173 01E	Apr 1961 - Dec 1978	213
F11752	Westport airport	2m	41 44S 171 35E	Jan 1949 - Dec 1978	360
	Christchurch airport	30m	43 29S 172 33E	1960 - 1978	228
F39801	Haast	4m	43 52S 169 00E	Apr 1961 - Aug 1976	185
I41901	Oamaru airport	30m	44 58S 171 05E	Apr 1961 - Aug 1977	197
I68533	Tiwai Point, Bluff	5m	46 35S 16823E	Feb 1971 - Dec 1977	83

Wind rose data from all stations except Napier airport and Christchurch airport were supplied by the New Zealand Meteorological Service in the form of wind rose tables. Data for Napier Airport were derived from N.Z. Met. Service Misc. Pub. 171(20), table 2, page 10. Data for Christchurch airport were taken from N.Z. Met. Service Misc. Pub. 171(3), table 2, page 12.

Appendix 2 : Anemometer groups A and B

Station	Hs (m)	Ha (m)	RC	V(10) m/s	V(10) knots	Frequency >28 knots (per 1000)	Group
Oamaru airport	30	6	3	4.4	9	2	A
Westport airport	3	10	6	3.5	7	2	A
Haast	3	10	3	3.4	7	3	A
Napier airport	2	10	3	3.7	7	3	A
Christchurch airport	30	10	3	4.0	8	4	A
Tauranga airport	4	10	3	4.6	9	4	A
Te Horo	5	10	3	5.1	10	9	A
Marsden Point	3	10	3	4.9	10	11	A
Port Taharoa	27	6?	?	?	?	11	A
South Head, Kaipara	24	10?	?	?	?	13	A
Cape Egmont	21	10	2	6.5	13	22	B
Wanganui airport	9	10	2	6.5	12	27	B
Farewell Spit	3	6	4	6.6	13	50	B
Tiwai Point, Bluff	4	14	4	5.3	10	65	B
Castlepoint	6	10	3	6.7	13	94	B
(Ohakea	47	22	5	3.9	8)		

Where Hs (m) is height of anemometer above mean sea level in metres
Ha (m) is height of anemometer above ground level in metres
RC is roughness class. 2 : Smooth, open, flat sites. Typical of plains with few trees or buildings.
3 : A locally flat open site with few trees and buildings some distance away. Typical of large urban airports with the anemometer well exposed amongst the runways.
4 : Flat sites with moderate local roughness. Typical of sites with some bushes, trees or small buildings in the vicinity. Farmland.
5 : Flat sites with bushes and trees nearby, but few buildings.
6 : Flat farmland with some shelter belts and scattered farm buildings, near small town or outer suburbs. (Cherry 1987)
and V(10) m/s and knots are the mean wind speeds adjusted to a height of 10m above ground level

Sources : anemometer heights, roughness classes and wind speeds in m/s from Cherry 1987 except for Port Taharoa and South Head, Kaipara. Wind speeds in knots from Reid 1981. Frequency of winds over 28 knots from N.Z. Met. Service. Wind speed in m/s for Tauranga airport derived from Reid since his data was based on a longer record than Cherry's.

Appendix 3 : Wind speed conversions

1 knot = 1.152 mph
= 0.515 m/s
= 1.85 km/hr

1 m/s = 1.94 knots
= 2.24 mph
= 3.60 km/hr

1 mph = 0.868 knots
= 0.447 m/s
= 1.609 km/hr

1 km/hr = 0.541 knot
= 0.621 mph
= 0.278 m/s

Appendix 4 : Beaufort wind scale

BEAUFORT SCALE

			Speed (knots)
0	Calm	Smoke rises vertically	< 1
1	Light air	Smoke of leaves indicate movement, otherwise almost calm	1 - 3
2	Light breeze	Wind felt on face, leaves rustle, etc.	4 - 6
3	Gentle breeze	Flag extended; leaves and twigs in constant motion	7 - 10
4	Moderate breeze	Small branches moved; dust and litter raised	11 - 16
5	Fresh breeze	Small trees begin to sway	17 - 21
6	Strong breeze	Large branches in motion; whistling in telephone wires	22 - 27
7	Near gale	Whole trees in motion; inconvenience experienced in walking	28 - 33
8	Gale	Twigs broken off; walking impeded	34 - 40
9	Strong gale	Slight structural damage	41 - 47
10	Storm	Widespread damage	48 - 55
11	Violent storm	Severe damage results	56 - 63
12	Hurricane	Severe damage results	64 +

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