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Frontispiece: Aerial view of Otaki river mouth and beach foreshore.

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BEACH MORPHOLOGY AND SEDIMENTS OF THE  
WEST WELLINGTON COAST: WANGANUI TO  
PAEKAKARIKI

A thesis presented in partial fulfilment  
of the requirements for the Degree of  
Master of Science in Geography at  
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by

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1. INTRODUCTION

## 1.1 Introduction

During the past two decades the coastal districts of New Zealand have received increasing attention, in terms of recreation, settlement, pollution and the evaluation of mineral deposits. This trend is clearly in evidence along the west Wellington coast, especially in relation to the pressure of a rapidly increasing population on coastal facilities.

The region considered in this thesis as the west Wellington coast is shown in Figure 1. For the southern coastal section, recently-mooted development proposals include the offshore siting of a Jumbo Jet airport and the establishment of a marina complex, with accompanying breakwater, in the vicinity of Kapiti Island. This southern section has a documented history of incipient erosion since the 1930's, the consequences of which have been accentuated by widespread road, housing and property development on the foredunes. In recent months there has been renewed discussion on groyne and breakwater construction to protect these beaches.

Whether or not these proposals are eventually realised, they have highlighted the fact that, with the exception of work by Donnelley (1959) and Burgess (1971), little basic investigation has been made into the movement of material contributing to foreshore change along the west Wellington coast. The aim of this thesis is therefore to provide further information on the coastal environment and to discuss the possible processes which may contribute to coastal change in the district.

It is hoped also that this work will fulfil a number of related functions.

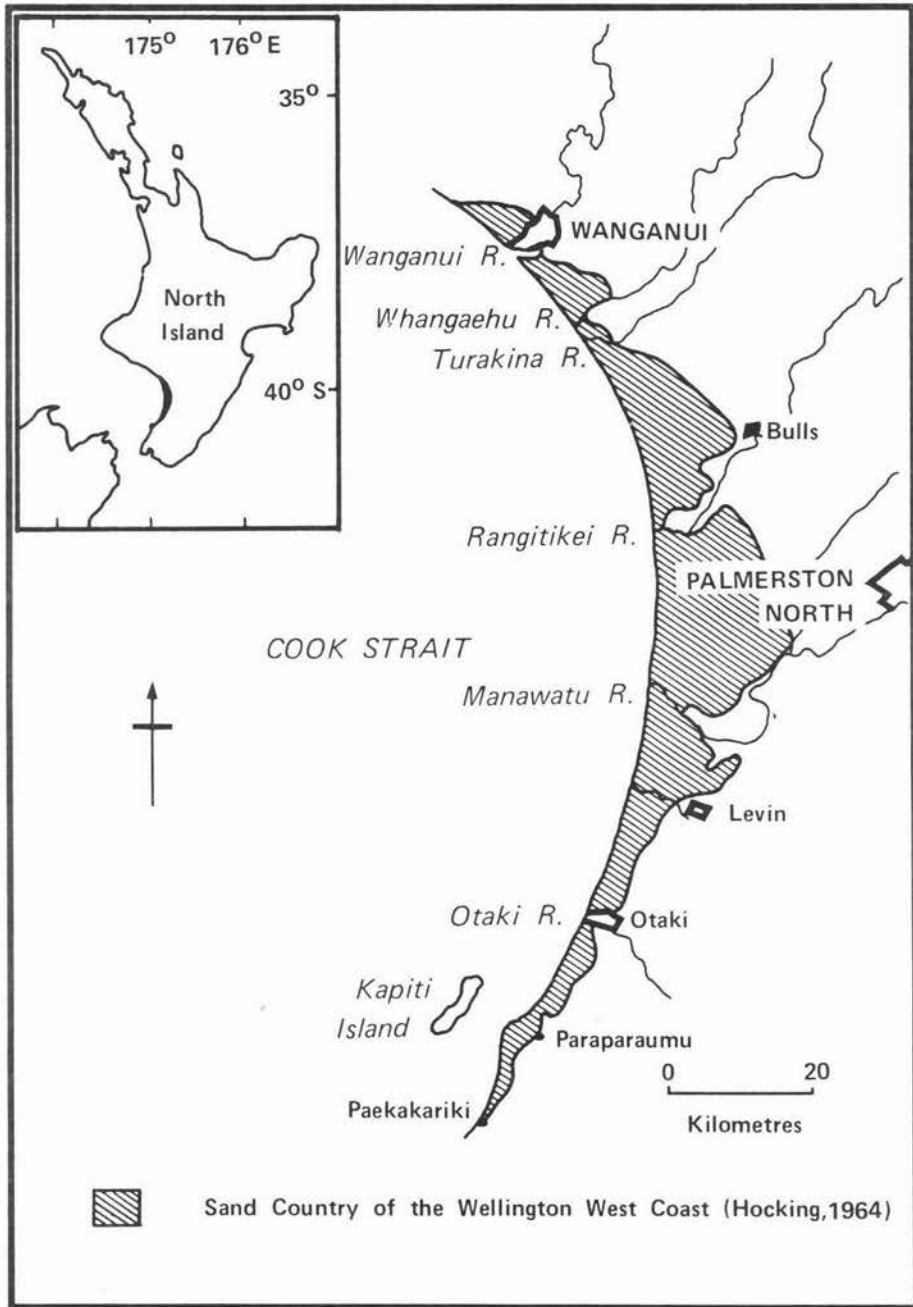


FIG. 1 LOCATION : WEST WELLINGTON COAST.

- (1) Provide a basis for future surveys involving long-term change along the coast.
- (2) Assist planners in the development of coastal recreation and protection schemes.
- (3) Enable the west Wellington coastal environment to be examined in the context of other New Zealand coastal areas, and to contribute towards a greater comprehension of the national coastal environment.

## 1.2 Thesis Format

The thesis is divided into five sections. Section One includes an introduction to the topic and a review of beach sediment literature. The various components of the material and energy sets of the environment are described in Section Two. Section Three is a discussion of field and laboratory investigation of beach sediment and beach morphology along the west Wellington coast. Section Four discusses the nature of, and the contributing factors for, recent coastline change; special reference is made to the Waikanae-Paekakariki district. Section Five contains conclusions based on the research undertaken.

## 1.3 Previous Research

The following review of New Zealand coastal literature is restricted to coastal sediment research. A more general review has recently been undertaken by Burgess (1971).

Previous research has tended to be of two major types.

- (1) Unpublished studies relating to east coast beaches, such as those of Blake (1964), Burgess (1968), Dingwall (1966), Kirk (1967), Martin (1969) and Smith (1968). Coastal change and grain size parameters have been related to littoral processes.
- (2) Mineralogical investigations of West Coast North Island beach deposits, including those of Finch (1947), Fleming (1946), Kear (1965), Gow (1967), Hutton (1945), Nicholson and Fyfe (1958) and Oliver (1948). These published reports have dealt with the location, estimation and evaluation of ironsand reserves.

With respect to the West Coast North Island beaches, other work has been carried out by Burgess (1971), Ross (1963), Summerhayes (1969) and van der Linden (1969); Sevon (1966a) has conducted research on beach sediments at Farewell Spit, northwest Nelson, whose environmental conditions are similar to those of the west Wellington beaches. Burgess examined coastline change at Wanganui and the processes contributing to such change; Ross, in his treatment of magnetite concentrations, discussed the effect of mineralogical variation on the selective sorting of foreshore deposits, and reasons for the concentration of ironsand deposits about river mouths; Sevon reported on the grain size parameters and mineralogy of the beach and dune deposits of Farewell Spit, northwest Nelson; Summerhayes interpreted the distribution of beach and offshore deposits of northern New Zealand in terms of ocean current patterns; van der Linden described sediment distribution and sedimentation processes on the northwestern shelf of the South Island, and for part of Cook Strait; and Sevon reported on the grain size parameters and mineralogy of the beach and dune deposits of Farewell Spit.



Other coastal research, involving grain size parameters, size-sorting relationships and/or environmental differentiation has been undertaken by Andrews and van der Lingen (1969), McLean (1970), McLean and Kirk (1969), Marshall (1929) and Sevon (1966b).

## 2. THE ENVIRONMENT

2.1 The Terrestrial Environment

2.2 The Marine Environment

## 2.1 THE TERRESTRIAL ENVIRONMENT

### 2.11 Introduction

The terrestrial environment is treated in terms of the geologic and geomorphic history, drainage system and climate of the region. The geological section focuses upon eustatic changes in sea level which have affected both the present coastal configuration and the supply of material to the coast. The most recent geomorphic event has been the set of dune building phases. These phases reflect an abundance of sediment available at the foreshore, and the inland migration of sand under a prevailing onshore wind system.

The catchment and flow regimes of the major rivers are described and their respective supply of beach sediment evaluated.

A brief review of the climate of the region is included. The direction of approach of the dominant wind systems and seasonal and diurnal fluctuations in wind strength are described, the association between wind strength and volumetric change across the beach profiles being treated in a later Section. Rainfall has the obvious effect of producing runoff, which as streamflow transports material to the coast, and rainfall, with temperature, affects the capacity of winds to move sand deposits inland and along the beach. The areal distribution of each of these parameters is discussed.

2.12 Geologic and Geomorphic History

Aspects of the geology and physiography of sections of western Wellington Province have been treated by Adkin (1919, 1921, 1951), Cotton (1918), Cowie (1963, 1967), Fair (1968), Fleming (1953, 1971), Fleming and Hutton (1949), Hall (1964), Hocking (1964), MacPherson (1946), Oliver (1948), Rich (1959), Saunders (1968) and Te Punga (1957).

Because of local variations in the rate and direction of eustatic movement, and the quantity and nature of sediment available from a variety of sources, the geological history for the region as a whole is difficult to coordinate. Likewise, the geomorphic history is complex. As Saunders (1968:133) has noted,

"The (Manawatu) coastal lowland itself has experienced an intriguingly complex history. Also it seems that adjacent and quite small areas have had somewhat different histories and thus difficulties have often arisen when attempts have been made to relate the sequence of events in different parts of the lowland."<sup>1</sup>

For example, when general uplift occurred in the northern part of the lowland during the Oturian Stage, downwarping took place to the south, the hinge line being south of the Otaki river (Adkin, 1919; Oliver, 1948).

The present shoreline plan is related to the development of a large sedimentary syncline trending northeast-southwest, the Wanganui Basin. This Tertiary structure is bounded to the east and southeast by the Kaimanawa and Ruahine Ranges, to the northeast by the Volcanic Plateau, and continues offshore into Cook Strait.<sup>2</sup> Much of the present physiography of the area is a direct result of deformation, including block faulting, in the greywacke basement of the syncline.

## 2.121 Development of the Wanganui Basin

The New Zealand geosyncline began to rise in the Cretaceous Period, but was submerged during the Pliocene, allowing the deposition of marine sediments on its peneplained crest. It re-emerged during the Kaikoura Orogeny to form the present axial range.<sup>3</sup> Downwarping of the adjacent land caused a deep syncline to form to the west of this axis. This syncline received large quantities of sediment, whose rate of supply varied with available relief and the level of volcanic activity in the source regions.

Marine sedimentation comprising several thousand feet of siltstone and sandstone strata continued until the end of the early Pleistocene, with block faulting commencing in the late Pleistocene. The surface expression of anticlinal folds draped over the faulted basement blocks is a prominent feature of the present landscape of the Manawatu-Rangitikei district.

## 2.122 Hawera Stage

The deposition of sediment after basement deformation was related to a shoreline parallel to the present coast. Hawera sediments rich in titaniferous magnetite and augite from the Taranaki volcanic set arrived as ash showers and beach sands to mix with hypersthene- and andesite-rich deposits transported from the Tongariro district by the major rivers.

Features developed in the higher portions of the coastal lowland during this period remain a distinctive part of

the present landscape; marine planation followed by upwarping of areas of softer rock, the consequent entrenchment of rivers in the north, and the development of marine and river terraces. A sequential development of the marine terraces is postulated by Hall (1964).<sup>4</sup>

The eustatic changes in sea level affected the composition of beach deposits. Evidence of this is to be found in the Otaki district; with stream rejuvenation a greater supply of locally derived greywacke was deposited in the littoral zone in comparison to volcanic material supplied from the north. Such a situation exists at present, the beach and dune sands having a lower proportion of ferromagnesian material than that found by Oliver (1948) in the Otaki Formation - a marine deposit assigned to the Oturian Interglacial.

#### 2.123 Post-glacial Development of the Sand Country

Sand soils cover 270,000 acres in an almost continuous coastal belt between Paekakariki and Patea (Hocking, 1964). Their maximum inland extension is twelve miles, at Rangiotu. On the premise that sand dunes are a feature of a stable or prograding coast, Fleming (1971) has established by carbon dating that most dune deposits of the Wellington west coast Sand Country date from the last interglacial sea level maximum ( $5140 \pm 90$  BP).

Material for dune development is of three basic types: (1) greywacke from the axial ranges; (2) siltstones and mudstones flanking (1); and (3) volcanic material from the Taranaki and Tongariro districts.

In general, these deposits have been mixed into a variety of mineral suites in the littoral zone, which in turn has become a second order source of dune material. An exception to this pattern has been the genesis of the Te Whaka and Koputaroa dunes, material for these having been obtained from local glacial riverbed deposits (Fleming, 1971). Mineralogical evidence for this view is the absence of micaceous minerals in these deposits, mica being well represented in volcanic materials.

Cowie (1963) has identified four major dune building phases in the Manawatu. In order of decreasing age these are as follows:

(1) Koputaroa Phase

Limited in extent, and a much older deposit (c. 10-15,000 BP) than succeeding phases. Glacial source material.

(2) Foxtton Phase

Occurs as a coastal belt two to four miles wide, abutting onto post-glacial cliffs and old river deposits (c. 1800-4,500 BP).

(3) Motuiti Phase

Carbon dating and buried Maori deposits indicate a Post-Taupo phase (150-1800 BP). Later advance possibly generated by destruction of vegetation by early human occupancy of previously stable dunes.

(4) Waitarere Phase

Appears as a belt up to two miles wide immediately east of the present foreshore, and in places where wind erosion has taken place on the previously stable Motuiti sand plains and dunes. This phase is largely a result of overgrazing and burning of original vegetation since the onset of European occupancy, and partly due to increased inland erosion providing an abundance of material at the beach.

## 2.13 Climate

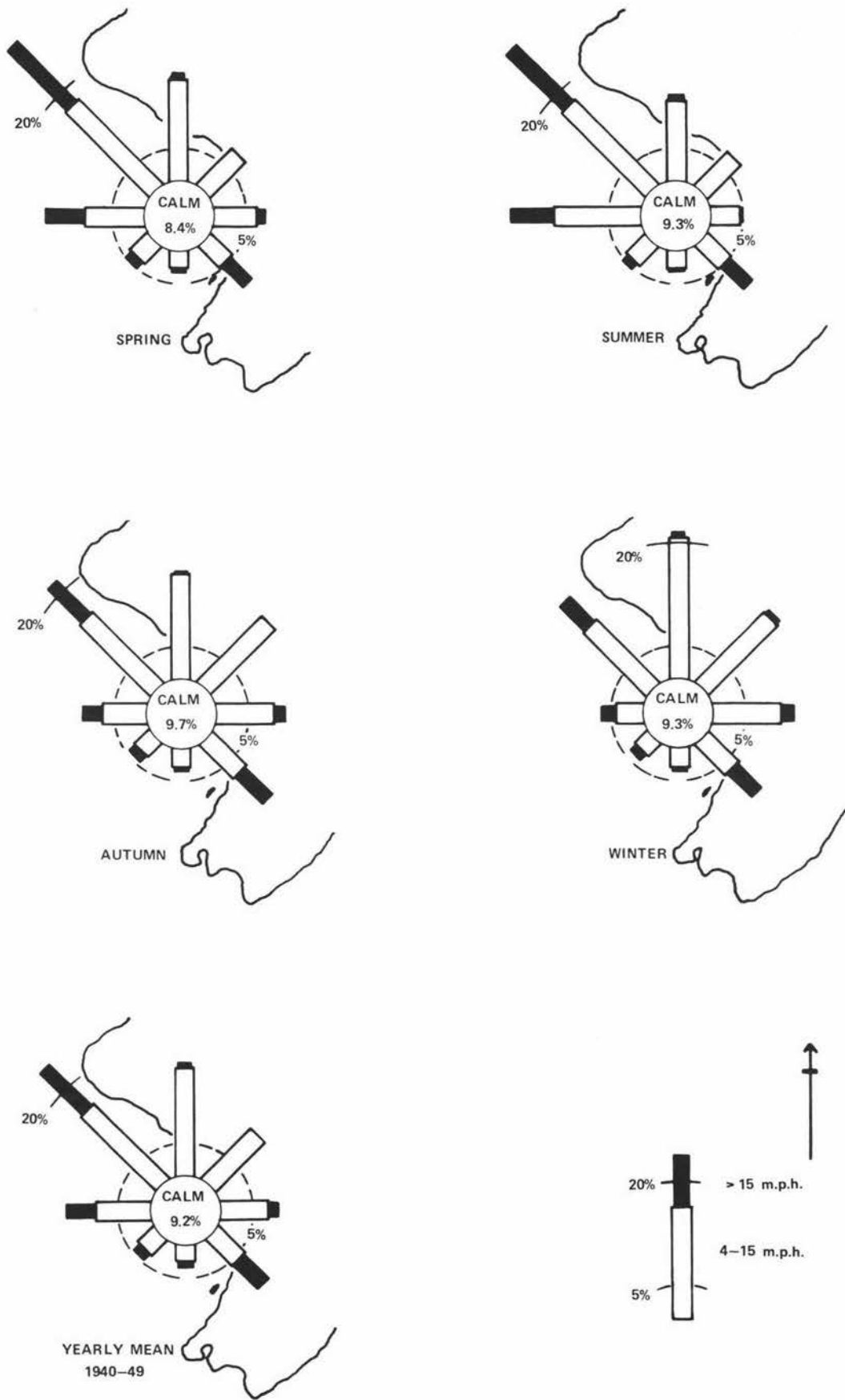
The Sand Country<sup>5</sup> lies within Robertson's D climatic district which is characterised by warm summers and mild winters, a rainfall of 35-50 inches evenly distributed throughout the year, and the prevalence of west to northwest winds with relatively frequent gales (Robertson, 1959).

### 2.131 Wind

The surface winds are influenced by the topography of central New Zealand. A westerly or southwesterly wind entering the South Taranaki Bight is deflected southwards as it is concentrated through Cook Strait, and may eventually flow along the Kaikoura coast as a northeasterly (Garnier, 1958). The orientation of the Cook Strait narrows gives gale force southerly winds direct access to the southern beaches of the study area. Further north, the strongest winds approach from the northwest.

A diurnal variation in windspeed has been noted at Ohakea, the mean hourly windspeed for the period 1960-68 ranging from less than nine miles per hour during early morning to over fourteen miles per hour in the afternoon.<sup>6</sup> Seasonal changes in wind speed and direction at Ohakea are shown in Figure 2. The strongest winds are from the west and northwest, speeds being at a maximum in spring, and a minimum through the winter months. The inland movement of dunes indicates the dominant wind pattern, the long axis of longitudinal dunes and the wings of the crescentic blowout dunes being orientated in a general WNW-ESE direction (Saunders, 1968).





Note: Data supplied by N.Z. Met. Service

FIG. 2 PERCENTAGE FREQUENCY OF SURFACE WIND SPEED AND DIRECTION AT OHAKEA, 1940-49.

## 2.132 Rainfall

The areal distribution of mean annual rainfall is shown in Figure 3. Rainfall totals range from less than thirty-five inches in the Foxton and Himatangi districts to over one hundred inches along the axial range and on Kapiti Island. There is a slight increase north of Santoft, with the increase being more rapid to the south along the narrowing coastal plain.

Rainfall is evenly distributed throughout the year, with a slight tendency towards mid-spring and early winter maxima. The mean annual variability of rainfall is only twenty per cent, although periods of drought have recently been experienced in the region.

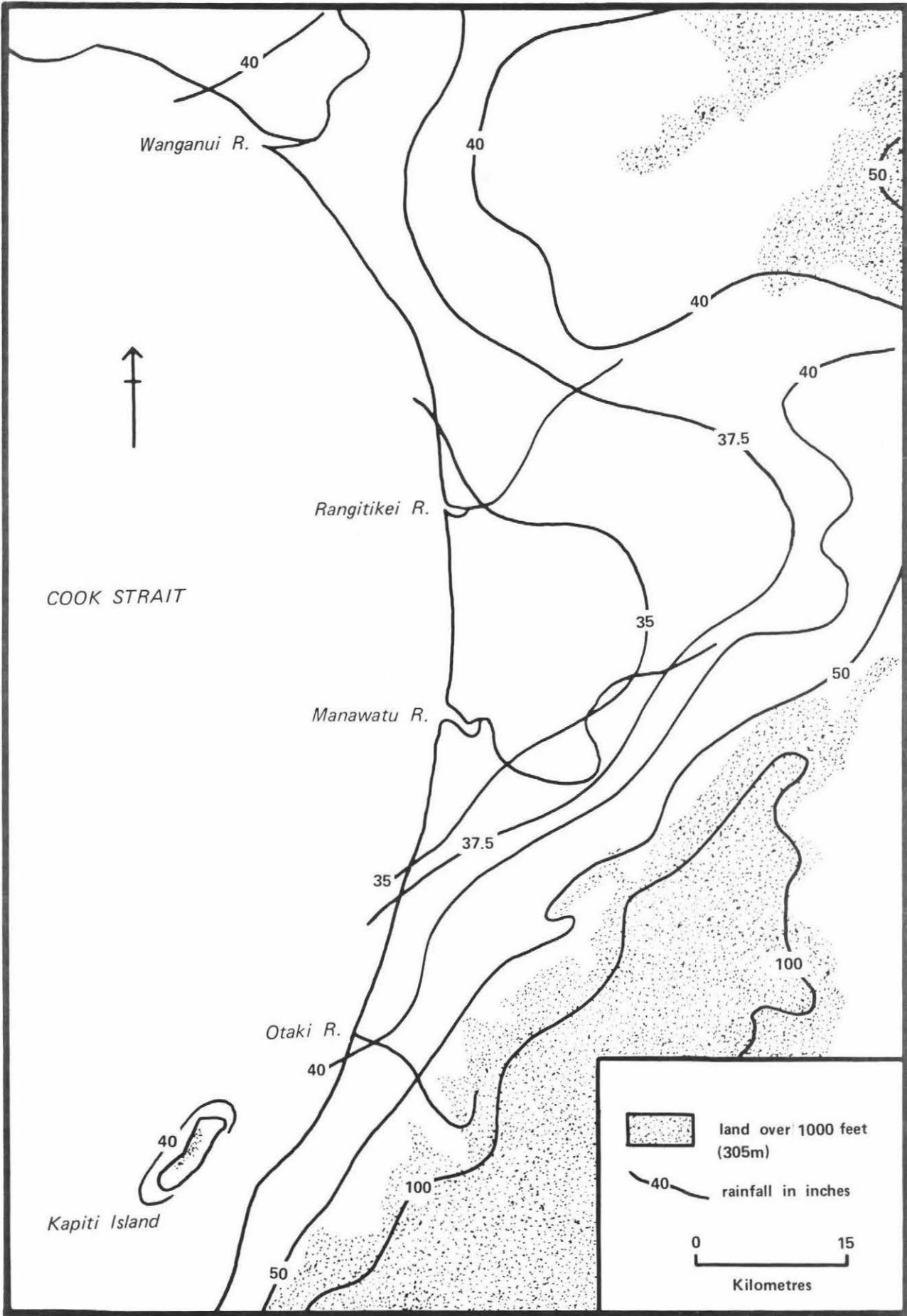
## 2.133 Temperature

Temperatures are moderate, with no seasonal extremes and only slight areal differences. The January, July and mean annual temperatures for selected district stations are shown in Table I.

TABLE I: Temperature statistics of selected Sand Country stations.

Station	Recording Period	Temperature (°C)			
		Jan.	July	Year	Range
Flock House	1948-60	16.8	7.8	12.8	9.5
Ohakea	1940-60	17.4	8.4	13.1	8.4
Levin	1949-60	16.8	8.1	12.9	8.2
Paraparaumu	1953-60	17.1	8.0	13.0	9.1

Source: Adapted from Saunders, 1968:151.



Source: Compiled from N.Z. Met. Service Unpub. Map.

FIG. 3 MEAN ANNUAL RAINFALL DISTRIBUTION, WEST WELLINGTON PROVINCE

## 2.14 The Drainage System

Twenty-three streams discharge along the study beaches, although only a small number of these constitute major suppliers of foreshore sediment. The courses of all major rivers are in part influenced by the structure of the Wanganui Basin, and so they have relatively direct access to the coast. The meandering Manawatu river is the major exception. The prevailing southerly littoral drift has diverted the mouths of most rivers and streams southward. The present northward orientation of the Otaki river mouth may be a response to the downstream migration of its meanders; it has been known to rapidly alter its channel near the mouth.

The drainage system is discussed in three sections: the northern rivers, the southern rivers and the drainage network of the Sand Country.

### 2.141 Northern Rivers

This set includes the Wanganui, Whangaehu, Turakina, Rangitikei and Manawatu rivers. The Wanganui river is 195 miles long and rises on the western flank of the Central Volcanic Plateau. Its catchment is composed of soft, unconsolidated sandstones and mudstones. The Whangaehu river transports runoff and sediment from Mt. Ruapehu and contrasts with the Turakina river which, except in its final stages, flows entirely through Pliocene sedimentary deposits. The load carried by the Whangaehu is proportionally greater than that of either the Wanganui or Turakina

rivers due to its steeper downstream gradient. During flood conditions the Rangitikei river discharges pebbles at the coast.

For the last thirty miles of its course the Manawatu river has a gradient of only one foot per mile, and so in spite of its having a probable maximum discharge of 150,000 cusecs, its meandering nature and its silt/mudstone load suggest that it is not a major supplier of foreshore material. The course of the Manawatu river through the Sand Country does, however, restrict the inland advance of dunes, re-cycling the dune sand to the estuary area.

#### 2.142 Southern Rivers

The major rivers to the south are the Ohau, Otaki and Waikanae. These flow west and northwest. They have cut deep valleys in the Tararua foothills<sup>7</sup> and have deposited large alluvial gravel fans which form the base of the present coastal lowland.

All streams flowing out of the Tararuas transport gravels to the lowlands, although only the Otaki river is able to transport large quantities of material of grade larger than sand to the sea. Metal extraction plants annually remove approximately 20,000 and 30,000 cubic yards of material from the Ohau and Waikanae river channels, respectively. Downstream from these plants the rivers suffer a severe loss in gradient, with an associated reduction in the size grade of the bed load. The average volume of material taken annually from the Otaki river is 250,000 cubic yards, much of this being pebbles, cobbles and boulders.

2.143 Sand Country Drainage<sup>8</sup>

With the exception of the major river courses, drainage in the Sand Country is conspicuous for its lack of a developed stream network and of tributary streams. Saunders (1968) suggests that the present pattern results from water seeping either into the major channels or directly to the coast, and from the effect of dune forms impeding the flow of available surface water.

The consequent impeded drainage is seen as a sequence of lakes and swamps throughout the study area. The importance of this drainage system in supplying sediment to the foreshore is minimal, although it does have important roles in limiting the rate of dune migration inland and in the development of sand plains, as the wind cannot erode sand from below the local water table.

2.15 Summary

The geologic history of the western Wellington province has been complex, and has been marked by the development of the Wanganui Basin. The latter is responsible for the major features of the present physiography, offshore bathymetric patterns and the smooth coastal outline. The Sand Country is the most recent physiographic unit, and is the result of a series of distinctive dune building phases.

The major proportion of materials supplied to the west Wellington coast is transported by the Whangaehu, Rangitikei and Otaki rivers. None of the major streams indicate a reduction in their future supply of material to the coast.

Although the rainfall is relatively homogenous over the coastal lowland, the catchments of most rivers lie well inland in regions where high intensity rainstorms are common. The surface wind flow pattern is strongly affected by relief and coastal configuration, with the result that the northern and central beaches are subject to strong northwesterly winds and that gales flowing through the narrows of Cook Strait are experienced along the southern beaches. Aseasonal gale force winds may reach the coast at irregular intervals.

## 2.2 THE MARINE ENVIRONMENT

### 2.21 Introduction

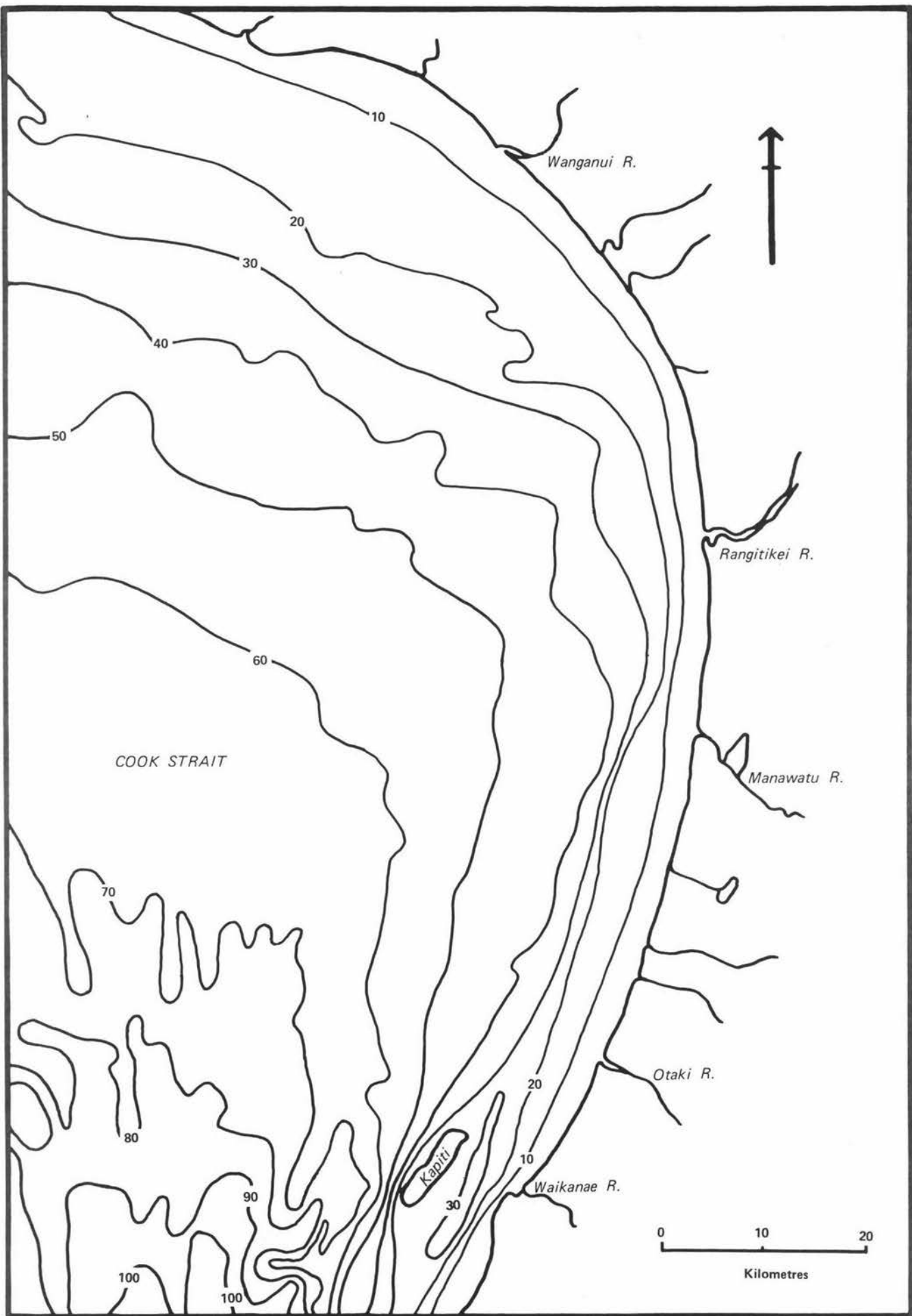
In this chapter the components of the marine environment of Cook Strait are discussed. Since the marine environment, however, is known to be a complex, interacting system, no one variable can be considered to act in isolation. The wave and current energy available to any beach is strongly influenced by the coastal configuration and offshore topography, the latter determining both the direction from which generated energy may arrive and its subsequent modification by refraction before reaching the foreshore. As the waves and currents move shoreward the bottom topography itself may be altered by the supply, redistribution and removal of offshore material. The presence or absence of offshore bars is known to have an important influence on whether accretion or erosion of foreshore deposits may take place, for a given level of supply of material from onshore sources.

The aim of this chapter is therefore to review the type of offshore sediment and wave energy which are developed in, and modified by, the marine environment of Cook Strait, and which are eventually available at the beach for the removal of sediment and the consequent development and modification of foreshore morphology.

### 2.22 Bathymetry

The bathymetric features of eastern Cook Strait are shown in Figure 4. These include an extensive shelf area





Source: Compiled from N.Z.O.I. Bathymetry Charts.

FIG. 4 OFFSHORE BATHYMETRY OF EASTERN COOK STRAIT

dissected by a deep canyon - the Northwestern Shelf - which extends into southern Cook Strait. The shelf area rarely exceeds 75 fathoms (c. 140 m) in depth, and is part of the Western Shelf of New Zealand.

The submarine contours are sub-parallel to the present shoreline and reflect the offshore continuation of the Wanganui Basin. Gradients offshore to the 50 fathom (c. 90 m) contour are given for four localities along the coast in Table II. It can be seen that gradients increase southward, especially south of the Rangitikei river.

TABLE II: Gradients normal to the coast extending to a depth of 50 fathoms.

Locality	Gradient
Wanganui	1 : 472
Otaki	1 : 140
Paekakariki	1 : 140
Paremata	1 : 56

Rapid offshore deepening occurs in the Narrows Basin southwest of Kapiti Island, culminating in a depth of 214 fathoms (c. 390 m). In this zone local relief is considerable, Fisherman's Rock extending to within a few feet of mean sea level from a local depth of approximately 1,000 feet (c. 310 m).

The bathymetry affects both the direction and strength of marine currents and causes the modification of wave trains by the process of refraction. Wave refraction occurs when the direction of travel of a wave crest changes as it encounters changes in water depths (Munk and Traylor, 1947). The construction of wave

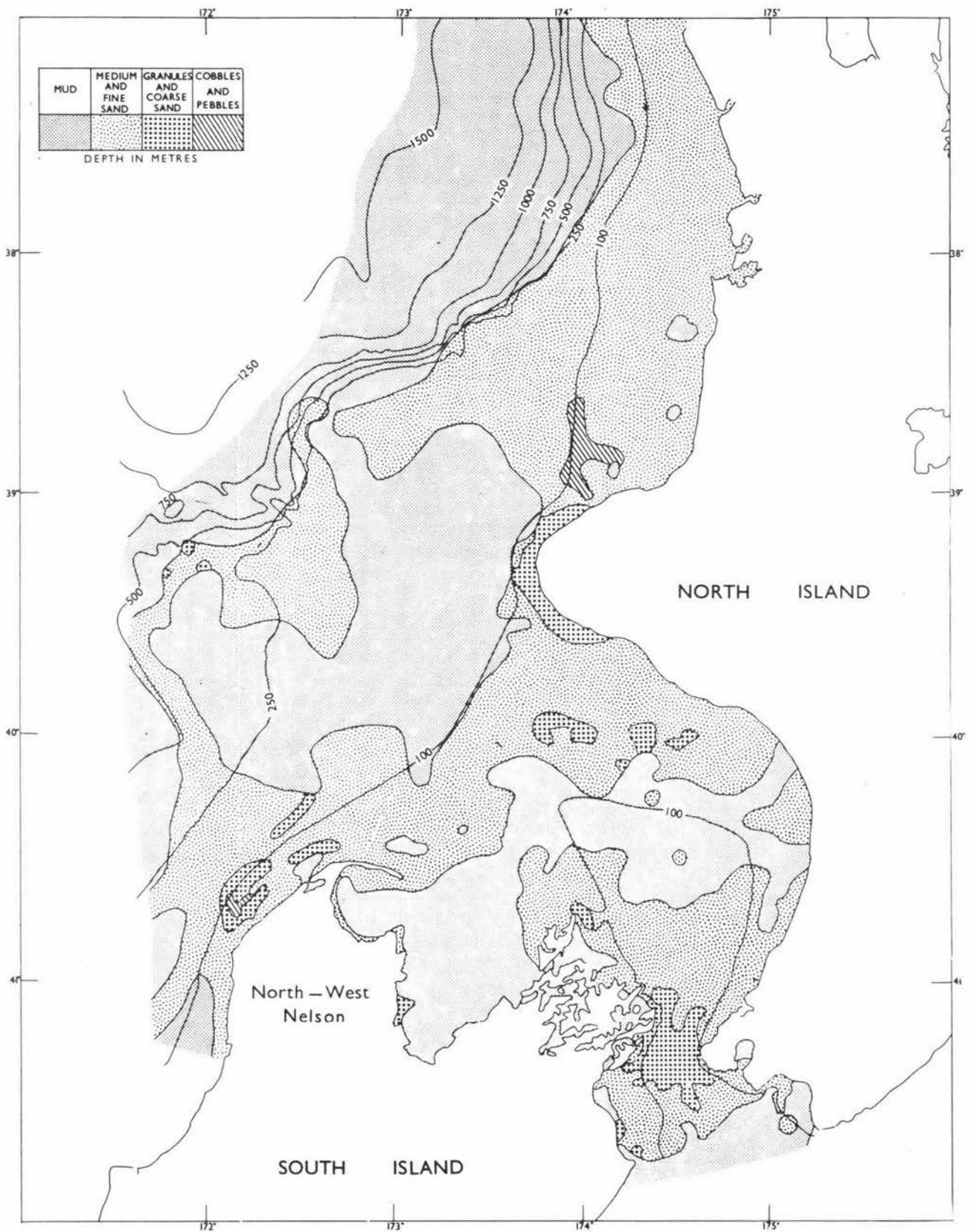
refraction diagrams based on bathymetric charts enables the angle of change and the consequent distribution of energy along the coast to be evaluated. There is also a feedback relationship between offshore topography and wave refraction, as the latter continually modifies the bottom contours by the redistribution of sediment. This aspect is of particular significance in districts such as Raumati where the removal of offshore bar deposits has been suggested as a possible cause of erosion (Donnelley, 1959).

A discussion of wave refraction in Cook Strait and its consequences for the study beaches is presented in a later section.

## 2.23 Offshore Sediments

The distribution of sediments for the western shelf of central New Zealand is shown in Figure 5. For the whole of this shelf fine and very fine sands predominate to a depth of 250 fathoms (c. 140 m), the upper edge of the continental slope. There are two extensive mud zones, however, in the environs of Cook Strait (McDougall and Brodie, 1967): (1) a mud/silt deposit to the west of Cape Egmont; and (2) a mud/silt deposit situated between  $40^{\circ} 15'S$  and  $40^{\circ} 40'S$  in an arc from northwest Nelson to lobes at both the Rangitikei and Otaki rivers.

McDougall and Brodie suggest that these mud/silt zones represent either a response to present relatively low current velocities or partly relict Quaternary sediments deposited in a former Egmont Gulf. Van der Linden (1969) considers the Cook



**FIG. 5 SEDIMENT DISTRIBUTION OVER THE CONTINENTAL SHELF WEST OF CENTRAL NEW ZEALAND**

Source: van der Linden, 1969:100-101.

Strait mud deposit of (2) above as being derived from suspension material from rivers flowing into the South Taranaki Bight and sediments from the Nelson and Westland regions.

Six to seven million cubic yards of material are estimated to enter Cook Strait annually from South Island sources, although van der Linden believes that this figure is too low by a factor of at least five. No estimate is available for the total annual supply of the North Island rivers so that it is difficult to evaluate the relative importance of onshore and offshore source areas. Deposition of the mud occurs as the current stream diverges over the widening shelf at the western entrance to Cook Strait, causing a decrease in the suspension load capacity of the D'Urville Current.

The mud zones are separated by a narrower belt of fine and very fine sands, a situation analogous to that described by McDougall and Brodie (1967) for the whole western shelf of the North Island. These findings show that Shepard's (1963) hypothesis - that sediment size decreases across a continental shelf - is not always acceptable, especially in an area where large-scale eustatic changes in sea level have taken place.

To the southeast of Cook Strait grain size increases as the shelf is progressively replaced by the Narrows Basin, with the dominant shelf fraction of fine sand being displaced by a coarse sand mode. The sediment distribution as shown in Figure 5 does not indicate the actual irregularity of the distribution caused by the varied local submarine relief of the narrows. With the relatively high current velocities on the floor of the Narrows Basin, no silts or muds are present; the gravelly sand, sandy gravel and

concretionary boulders are winnowed deposits. Conversely, the presence of marine organism growth on pebbles is cited as evidence that no marked scour is taking place at present (Reed and Leopard, 1954).

Present day deposition is thought to be confined mainly to the mud and very fine sand zones offshore, and to the nearshore zone where present wave and wave-induced current energy conditions are sufficiently strong to be able to move almost all sediment discharged into the littoral zone. As mentioned previously, it is difficult to estimate the importance of the offshore deposits in providing material at the foreshore, and for bar formation in the breaker zone vis-a-vis onshore and longshore supplies.

Variation in offshore sediments is not confined to modal size; in some areas conditions favourable for the development of shell beds have caused very high local carbonate concentrations to occur in marine deposits. Also, the distribution of magnetite in the Western Shelf sediments has been reported by McDougall and Brodie (1967). They maintain that its presence is fairly uniform proportions to a depth of at least 20 inches

"... argues for an extended history of the magnetite as a marine sediment. ... Some of the magnetite has undoubtedly been concentrated in near-beach processes at late stands of sea level, and has been rederived from these concentrations (either from high-sea-level dunes or new submerged beaches and dunes)."<sup>9</sup>

The distribution of offshore sediments, then, is affected by the complex eustatic history of the Wanganui Basin, the D'Urville Current supplying material from the west coast of the South Island as well as the present discharge of the west Wellington rivers.

## 2.24 Coastal Currents

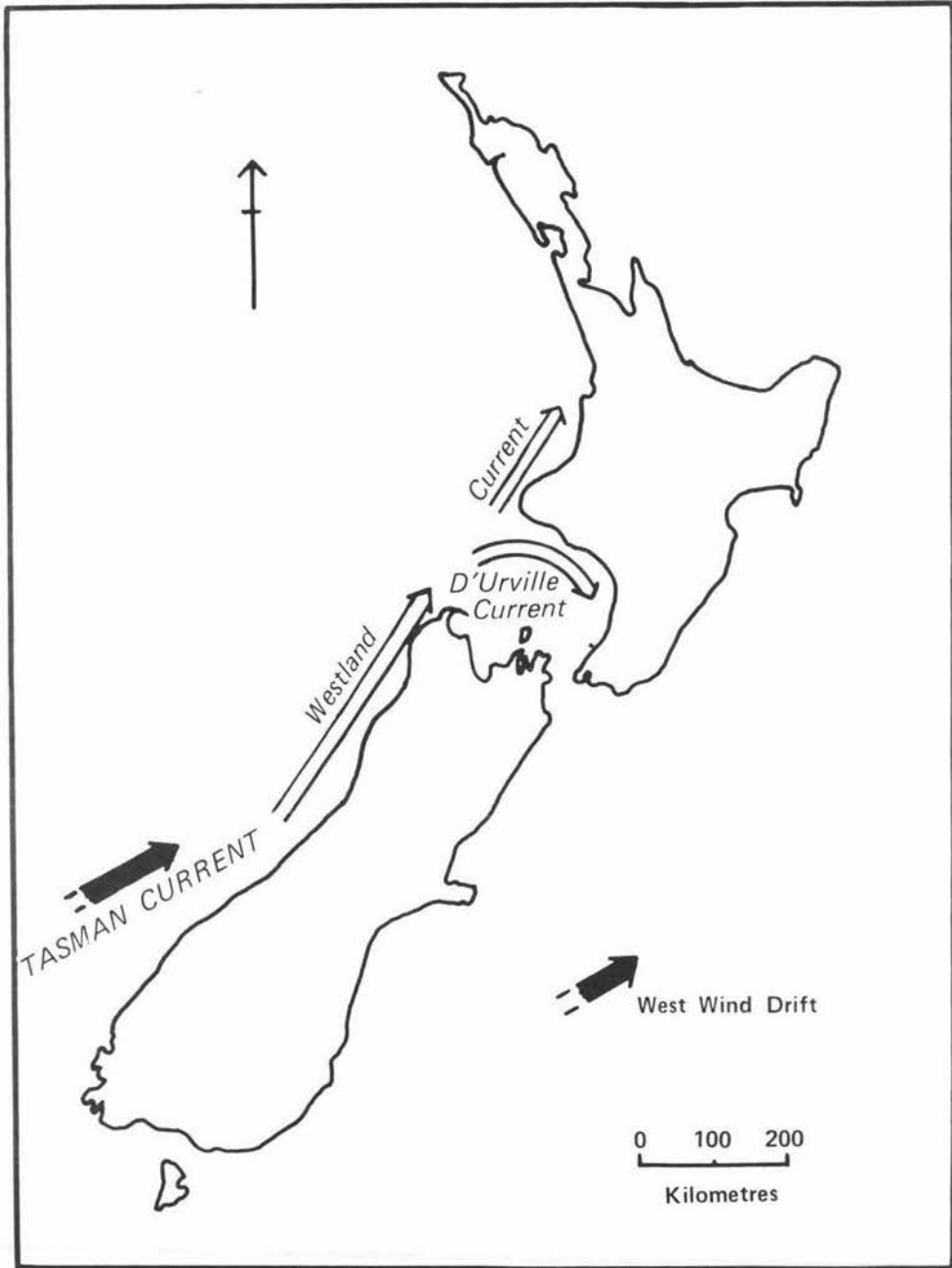
Brodie (1960) identified the surface circulation pattern for the west Wellington coast as the south-flowing D'Urville Current derived from the clockwise deflection of the north-flowing Westland Current,<sup>10</sup> itself resulting from the oceanic Tasman Current (Figure 6). The flow of the D'Urville Current is also strongly influenced by the coastal configuration of central New Zealand and the prevailing wind system.

Further work by Heath (1969) has confirmed this surface flow pattern. While bottom flow can only be inferred from the prevailing movement of surface drift cards Heath (pers. comm.) believes that the shallow nature of the Cook Strait shelf area would prevent the development of an opposing bottom flow. The formation of Farewell Spit, and other evidence<sup>11</sup> tend to confirm the pattern inferred from drift card behaviour.

This southward-flowing stream is reinforced by the prevailing wind-induced current. Using Wanganui Harbour Board wave data for the period 1968-69 Burgess (1971) calculated the ratio between the north-to-south and south-to-north longshore wave energy components respectively as 2 : 1, at a depth approximately fifteen feet below mean sea level.

During periods of strong southerly winds, the prevailing current is northward, its greatest effect being felt south of Kapiti Island. During such conditions the southerlies minimise the in-draught into Cook Strait from the north and west, allowing the Westland Current to extend north of Cape Egmont (Brodie, 1960).

During the monthly surveys, driftwood floats were used



Source: Brodie, 1960:249.

FIG. 6 SURFACE COASTAL CURRENTS,  
CENTRAL NEW ZEALAND



to identify the general direction of littoral drift. At most stations the direction of drift coincided either with the local wind pattern - indicating that the wood was moved directly by the wind, or wind-induced littoral current - or with the wave-induced current, itself a result of wave generation by the prevailing wind system. For example, drift to the north was dominant for the May and August surveys, during which moderate southerly winds prevailed.

The currents of Cook Strait are strongly affected by tides, especially in the narrows where in most measurements strong tidal currents mask drift current effects (Gilmour, 1960). The strongest surface currents occur during the winter when strong winds are in phase with the tides. Oceanographic Services (1970) recorded a maximum surface water velocity of 1.1 knots - the average being 0.5 knots - off Waipipi Point for the period 18 February - 21 March, 1970. In contrast, strong tidal currents of three to four knots have been noted by Gilmour (1960) for the narrows of Cook Strait, where a known maximum of seven knots has been recorded. The New Zealand Pilot (1958) reports that the tidal stream along the west Wellington coast sets to the southwest with an ebb- and to the north-east with a flood-tide.

## 2.25 Waves

### 2.251 General Setting

In terms of a classification based on their mode of generation, two types of waves are incident at most coastlines.

- (1) Small, locally-produced wind waves. This type is of minor importance for the west Wellington coast.

- (2) Waves which are generated by storms and reach the coast either directly as storm waves, or, if they have moved out from under their zone of generation, as swell.

For the Southern Hemisphere Davies (1964) locates the mean latitude of the zone of maximum gale force winds as varying from  $54^{\circ}\text{S}$  in summer to  $56^{\circ}\text{S}$  in winter, so that the South Island is marginal to this storm belt. As the deep depressions of the southern oceans move eastwards below  $50^{\circ}\text{S}$ , fronts extend out from this depression belt across New Zealand, the deepening of depressions which form on these fronts sometimes continuing to the point of generating gale or hurricane force winds. Davies notes that outside the storm belt important waves are likely to move as swell, fanning out for thirty to forty degrees of latitude on either side of the direction of the generating wind and travel along great circle courses, so that

"... waves propagated in the southern storm belt by winds blowing from any direction between northwest and south all tend to take a general course from southwestward as they move away from the region of generation."<sup>12</sup>

The prevailing westerly trade wind system would cause the west Wellington coast to be subject to swell predominantly from the west-southwest quarter, but the southwest component is greatly affected by the presence of the Nelson-Marlborough landmass.

## 2.252 Environmental Factors

The height and period of wind-generated waves is a function of the velocity and duration of windflow, and the fetch, or sea distance over which the wind flows (King, 1959).

The available fetch is important in determining the type of wave, or wave spectrum, arriving at the coastline. Fetch lengths are shown in Figure 7 for various locations along the coast, and for a variety of directions of wave approach.

Because of the configuration of central New Zealand the variation in fetch along the coast is not regular, the situation being complicated by the location of Kapiti Island and the promontories of northwest Nelson and Cape Egmont. All stations have unlimited fetch to the northwest, except those in the lee of Kapiti, and the northernmost beaches. The latter have unlimited fetch to the west. For the southern beaches fetch is a maximum to the northwest, decreasing to the west and south.

While severe southerly storms often generate waves in Cook Strait, a report by Oceanographic Services (1970) maintains that the lack of fetch mitigates against the development of a high-energy southerly wave train, in comparison with that generated under unlimited fetch to the northwest. Using hindcast techniques<sup>13</sup> Oceanographic Services compared the characteristics of waves arriving at the then proposed Waipipi loading buoy during a design storm of September, 1959, with those generated by the 'Wahine' storm of April, 1968. The 1959 storm produced particularly high waves due to its persistency and to an extremely long fetch to the west. It generated three consecutive wave trains, and at one time waves from each train were arriving simultaneously to produce a deepwater wave height of forty feet. During the 'Wahine' storm wind speeds reached 145 knots at Oteranga Bay west of Wellington, but hindcast wave heights did not exceed 17.5 feet at Waipipi Point due to the fetch limitations and the short duration of the high wind speeds.

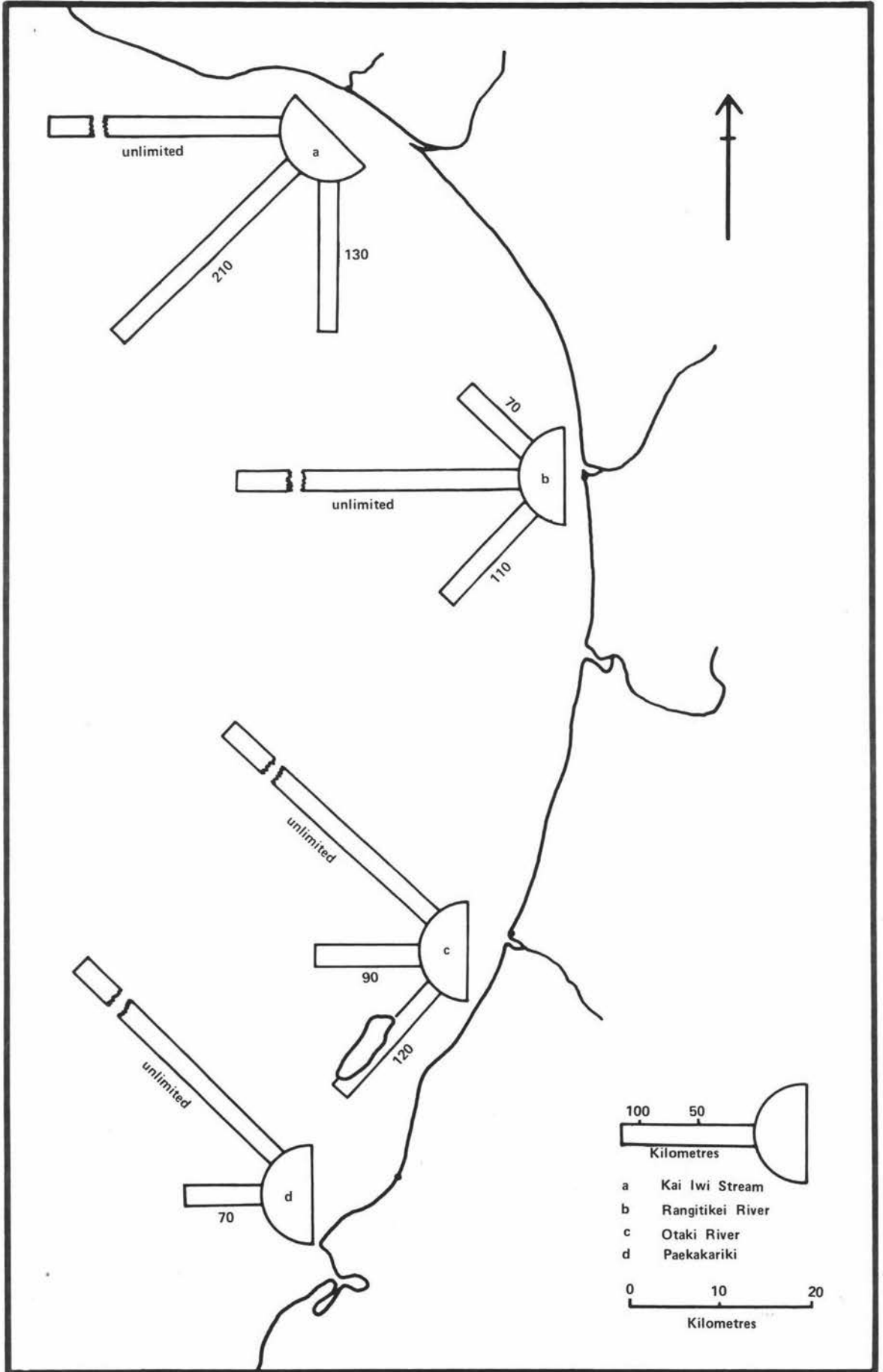


FIG. 7 LINEAR FETCH AT SELECTED SITES, WEST WELLINGTON COAST

This aspect of fetch limitations to the south will be briefly discussed in the section on wave refraction patterns.

## 2.253 Wave Climate

The following information on wave data for the coast has been obtained from the 1970 report by Oceanographic Services, and the analysis of Shell B.P. Todd and Wanganui Harbour Board data by Burgess (1971). No extensive programme of wave observation was undertaken by the writer, the wave height and period at each station being recorded only during each monthly visit.

In a description of the Wanganui wave environment Burgess (1971) notes a number of features.

- (1) The prevailing waves arrive from the west-southwest quarter.
- (2) Data collected for the period October 1968 - December 1969 at Castlecliff Beach indicate a mean breaker wave height of four feet, and that, while no clearly defined seasonal difference in wave height was apparent, significant variations occurred on a day-to-day basis. For the period of observation, Burgess suggests December - March as the time of mildest wave conditions.
- (3) Wave periods ranged from five to eighteen seconds, with the six to nine seconds group being the modal class for all months except February and May. The mean period for the year was approximately nine seconds.
- (4) In having a breaker wave height frequently exceeding four feet, the coast is described by Burgess (1971) as being one of moderate - to - high energy.
- (5) Wave refraction ensures that waves approach the shore at angles generally less than five degrees, and available longshore energy at Wanganui favours littoral movement of sediment

from north to south, although sequences of wave trains from a southern direction do occur.

The report by Oceanographic Services provides a further source of wave information, derived by the hindcast technique. Because of fetch considerations and the duration of generating winds, almost all waves greater than ten feet in height will arrive from the northwest-southwest quarter, with the greatest proportion from the west. Table III gives the distribution of heights of swell waves for the year 1959.

TABLE III: Swell wave statistics off Waipipi Point, 1959.

Height (feet)	Frequency (per cent)
0 - 4	85.2
5 - 10	8.8
11 - 14	3.0
16 - 20	2.1
over 20	0.9
over 5	14.8

Source: Environmental Study off Waipipi Point.  
Oceanographic Services,  
1970:17.

#### 2.254 Survey Data

During each survey the breaker wave height in feet was estimated at each station. The stations were then grouped into four sets, the sets being organised from north to south. The average wave height of each set, for each of the six surveys, appears in Table IV.

TABLE IV: Summary of breaker wave heights observed during surveys 1-6 incl.

Station Sets and included Stations

		A	B	C	D	Mean
		1-5 incl.	6-10 incl.	11-15 incl.	16-22 incl.	
Survey No.	1	3.8	3.1	1.4	2.0	2.6
	2	4.4	3.0	1.8	1.0	2.6
	3	3.3	2.1	2.1	0.5	2.0
	4	3.9	1.5	1.3	3.5	2.6
	5	5.1	5.0	3.0	1.7	3.6
	6	2.8	2.9	2.1	1.3	2.3
Mean		3.9	2.9	2.0	1.7	2.6

Note a breaker wave heights in feet.

b dates of each survey given in section 3.1.

c location of each station shown in Figure 12.

In spite of the low level of accuracy in measurement, and the fact that the wave height of each station was recorded only six times, a number of comments can be made on the basis of the field data.

- (1) Wave heights are greatest to the north, and decrease southward along the coast, the average height for all surveys ranging from 3.9 feet for set A to 1.7 feet for set D. Exceptions to this trend occurred during the May and August surveys, when the direction of wave approach was from the south.

Both these trends are consistent with the theoretical distribution of energy indicated by wave refraction diagrams for westerly and southerly wave trains.

- (2) The observed average wave height near Wanganui is almost identical to that found by Burgess for the Wanganui Harbour Board data.

- (3) No marked pattern of seasonal change is evident for any group of stations, although one observation cannot be regarded as a valid estimate of wave heights for the whole of each month.
- (4) The greatest variation in wave heights occur at the southern part of the coast on the extremities of the beach section protected by Kapiti Island from wave attack from the west. The beach at Kenakena Point, however, experienced consistently low wave heights, irrespective of the direction of wave arrival.

For the section of coast north of Otaki - that portion relatively unaffected by the presence of Kapiti Island - the modal wave period was twelve seconds. In contrast wave periods of up to twenty seconds were observed in the lee of Kapiti. With this exception no seasonal or longshore variation in wave period was apparent.

## 2.26 Wave Refraction

While swell waves may retain their characteristics for both long periods and distances at sea, all wave trains entering Cook Strait undergo refraction before reaching the coastline. As they move into shallower water of depths equal to half their deep-water wavelength the waves begin to 'feel' bottom (Munk and Traylor, 1947) and of their parameters only the period  $T$  remains unaltered, initially. Their height  $H$  increases and their velocity and length  $L$  decrease, thereby increasing the wave steepness ratio ( $H/L$ ).

Refraction diagrams<sup>14</sup> were constructed using the graphical method outlined in Oceanographical Engineering, Ch. 7 (Wiegel, 1964). Bathymetric contours were obtained for Cook Strait region from the



Cook Strait, Patea and Tasman Charts of the New Zealand Oceanographic Institute Coastal Series, and for the Kapiti - Rauoterangi Channel area from Chart No. 4631 published by the Hydrographic Branch of the Navy Office. Wave refraction diagrams are only models of the real processes which occur and contain a number of simplifications.

- (1) The process of diffraction, in which energy flows along the wave crests, has not been evaluated. This process may occur as waves pass into the 'shadow' of Kapiti Island. Its effect relative to that of refraction is small, however, where the bottom topography continues to slope (Shepard, 1963) - as in the case near Kapiti.
- (2) A wave train is composed of a spectrum of wave heights and periods, so that the refraction pattern for a ten-second southerly wave train, for example, does not in reality represent the behaviour of every wave in that train. Munk and Traylor have shown that refraction may begin for a long fourteen-second swell at a depth of 500 feet (c. 150 m), and for a short seven-second wind wave at 125 feet (c. 38 m). Since the consequent refraction pattern for each type of wave will be different, a short-period sea may be separated from a long-period swell by the bottom topography.
- (3) With the complex coastal configuration of central New Zealand waves from a variety of directions may arrive at a beach simultaneously; a feature predicted by Oceanographic Services and described earlier in section 2.252.

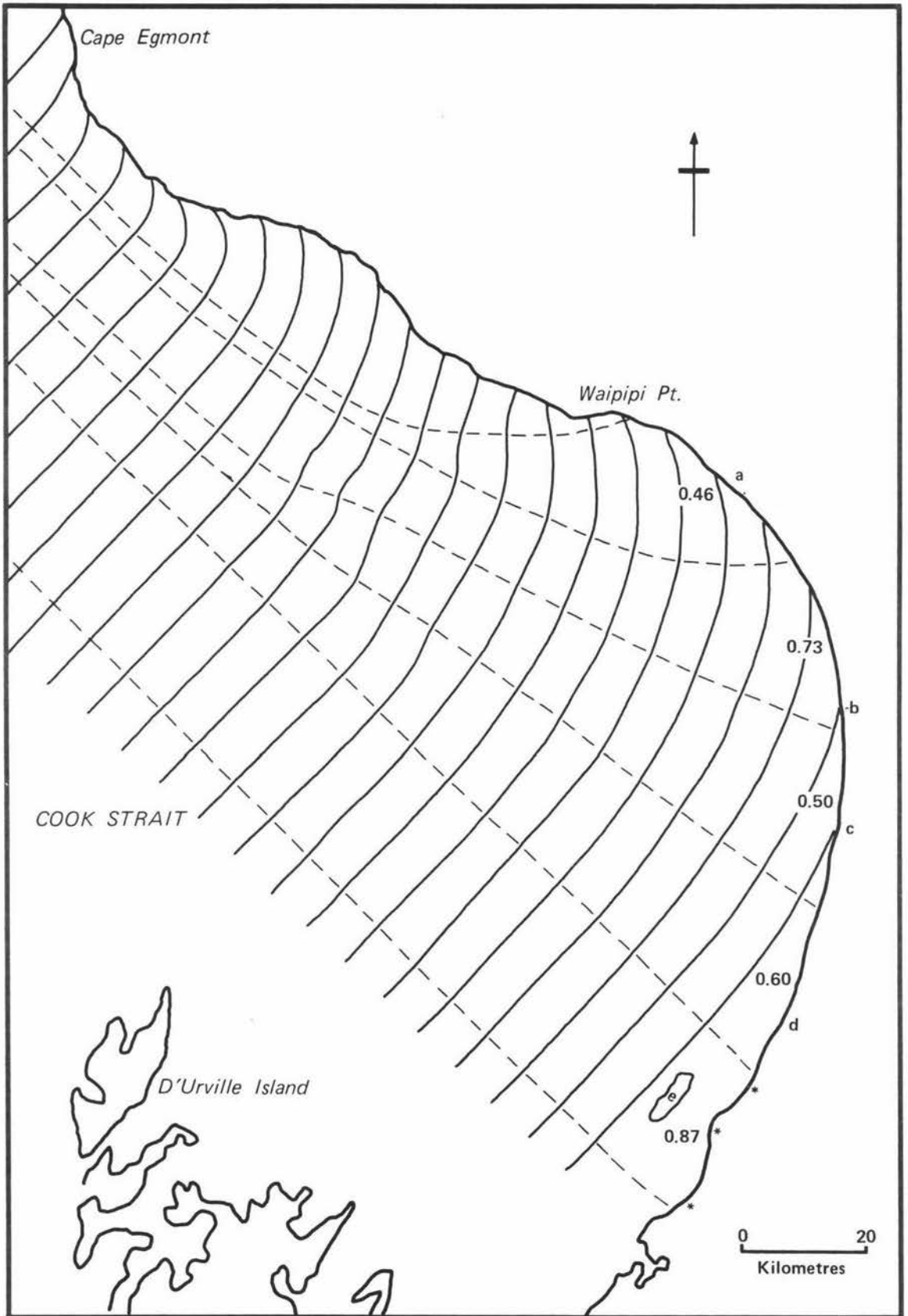
Errors in such diagrams include those resulting from the graphical method of construction, their magnitude being a function of the scale of the bathymetric charts employed.

In spite of the above considerations, wave refraction diagrams are known to give a realistic indication of the actual wave height and energy distribution along a coast. That is, wave refraction is one of the primary mechanisms controlling changes in wave height (Munk and Traylor, 1947). On this premise features of the refraction patterns are discussed below. Diagrams were

constructed for swell of period ten seconds approaching the study beaches initially from the northwest, west, southwest and south. These appear below as Figures 8, 9, 10 and 11. In order to measure the effect of refraction of the westerly wave train for beaches in the lee of Kapiti Island a wave crest was transferred from the Cook Strait Coastal Series bathymetric chart to the larger-scale Navy Office chart.<sup>15</sup> The resulting refraction pattern appears, and is discussed, in Section 4.

For a northwesterly wave train (Figure 8) the maximum refraction coefficients occur to the south, as the result of the bottom contours in this region trending approximately southeast. The refraction pattern illustrates the strong genetic relationship between this direction of wave approach and the development of Kenakena Point in the lee of Kapiti Island. In contrast, the low refraction coefficients along the northernmost beaches result from marked divergence caused by the wave crests arriving initially perpendicular to the submarine contours. Shoals west of the Wanganui river mouth prevent a simple pattern of increasing refraction coefficients southward along the coast.

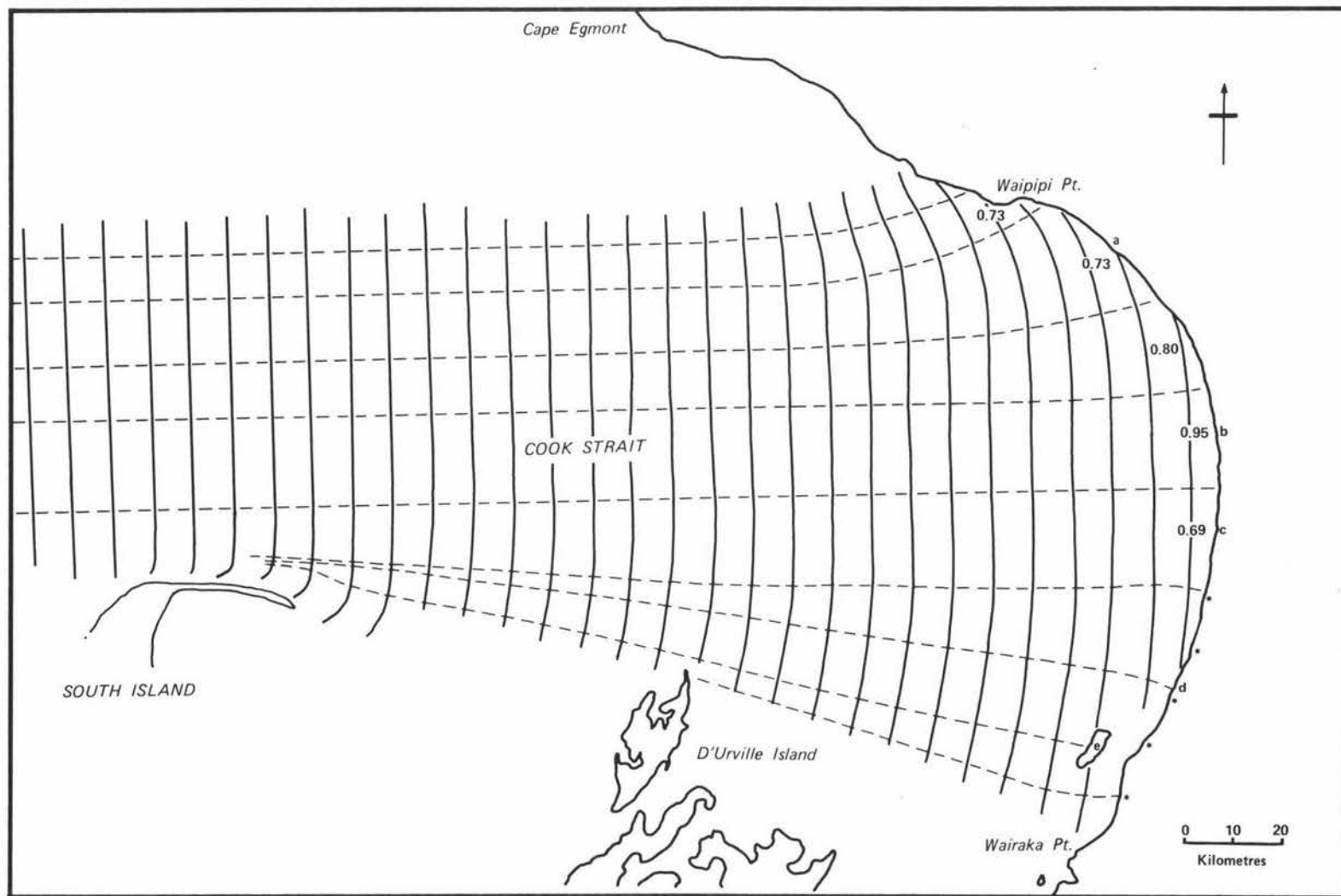
For a wave train arriving from the west the highest coefficients are to be found in the vicinity of the Rangitikei river mouth, remaining relatively high to the north. Figure 9 indicates clearly the reason for the rapid decline in wave heights south of the Manawatu river. This decline is caused by the shelter afforded to the southern beaches by Farewell Spit, and Arapawa and Kapiti Islands. Although convergence occurs near Kapiti the wave energy supplied to this district via a westerly wave train is not great. In spite of this the effect of such energy at the shore is



Notes: \* represents zone where given Kb value is the average of a wide range of values.

- a Wanganui River
- b Rangitikei River
- c Manawatu River
- d Otaki River
- e Kapiti Island

FIG. 8 REFRACTION DIAGRAM OF NORTH-WESTERLY WAVE SYSTEM : PERIOD 10 SECONDS

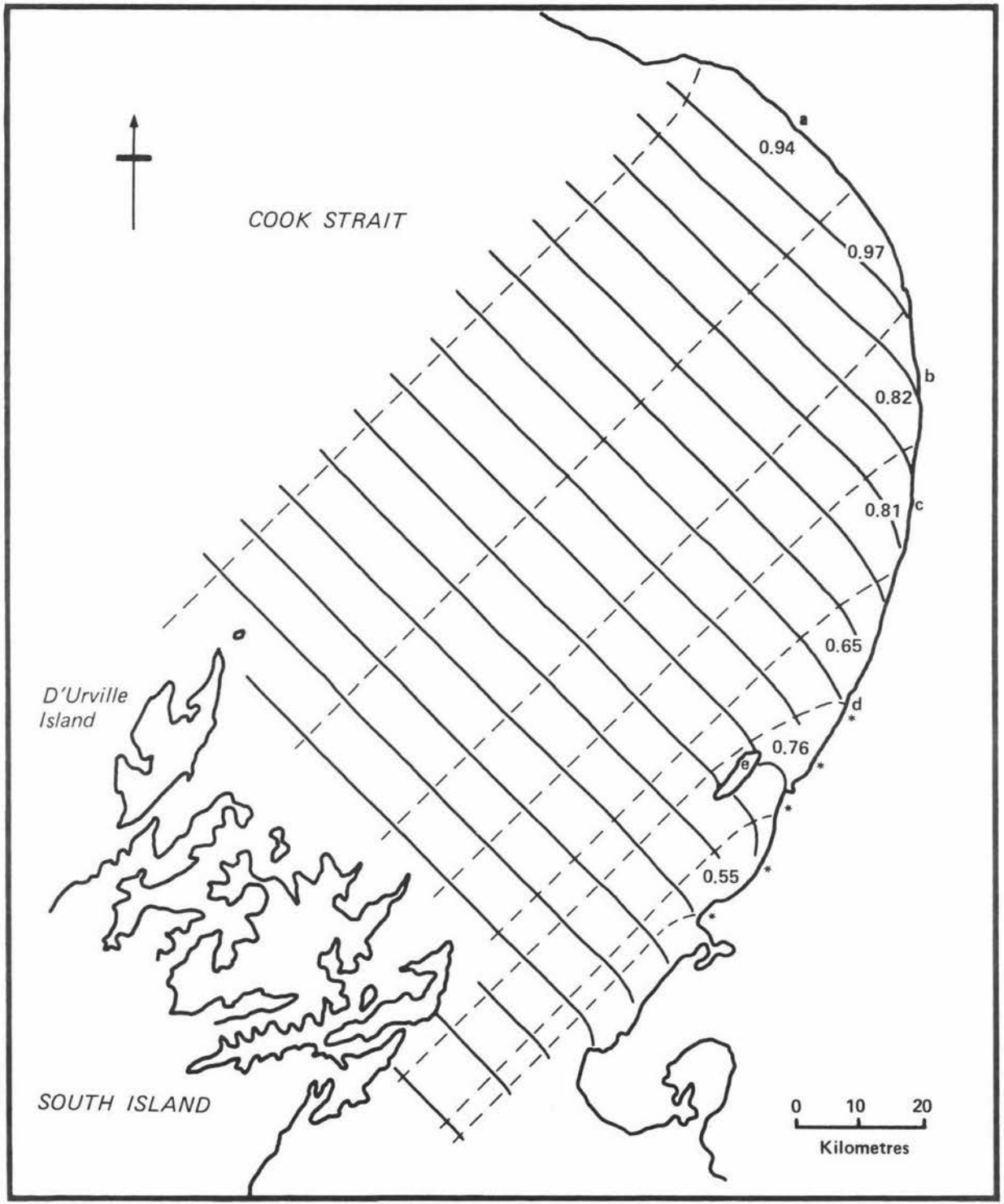


Notes: \* denotes zone of near-zero  $K_b$  values

a Wanganui River  
b Rangitikei River

c Manawatu River  
d Otaki River  
e Kapiti Island

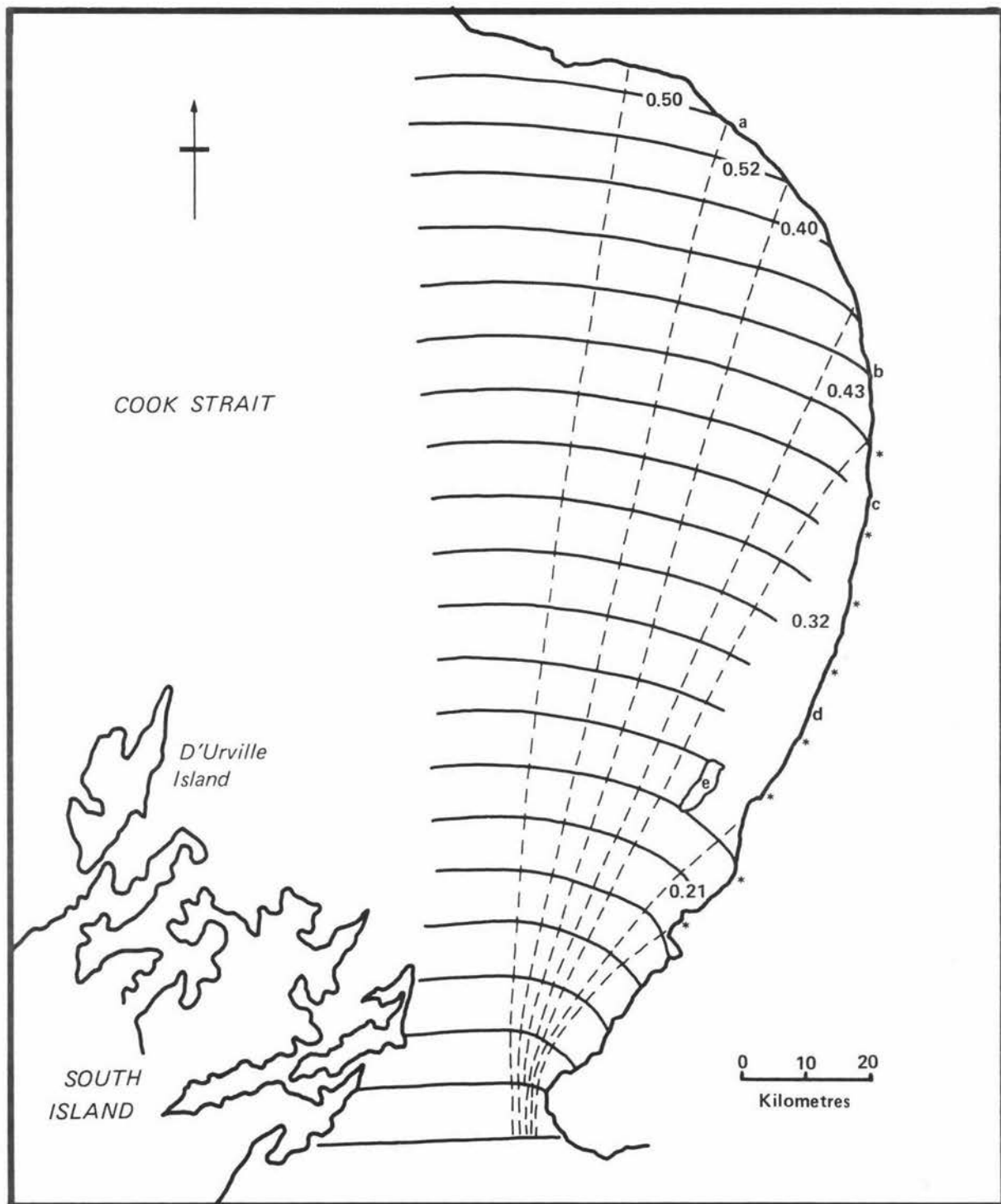
FIG. 9 REFRACTION DIAGRAM OF WESTERLY WAVE SYSTEM : PERIOD 10 SECONDS



Notes: \* represents zone where given Kb value is the average of a wide range of values.

- a Wanganui River
- b Rangitikei River
- c Manawatu River
- d Otaki River
- e Kapiti Island

FIG. 10 REFRACTION DIAGRAM OF SOUTH-WESTERLY WAVE SYSTEM : PERIOD 10 SECONDS



Notes: \* represents zone where given Kb value is the average of a wide range of values.

- a Wanganui River
- b Rangitikei River
- c Manawatu River
- d Otaki River
- e Kapiti Island

FIG. 11 REFRACTION DIAGRAM OF SOUTHERLY WAVE SYSTEM :  
PERIOD 10 SECONDS

not insignificant, owing to the local nearshore and foreshore morphology.

The refraction pattern for a southwesterly wave train is shown in Figure 10. There is a general decrease in the refraction coefficients from north to south, although comparison of the coefficients is difficult, since waves arriving at the southern beaches have been generated both over a greater fetch area and in a recognised zone of gale force winds. Wave height at the southern beaches, then, may be even greater than those incident at Wanganui, in spite of their lower refraction coefficient.

The refraction pattern for a southerly wave train, shown in Figure 11, is similar to that for the southwesterly system, with the greater refraction of the former resulting in lower coefficients at each location. All southerly waves arriving at the study beaches can be seen to derive from a narrow wave crest off southwest Wellington and so the high energy per unit length of this wave crest is distributed over a comparatively large coastal segment. Oceanographic Services suggest that the low height of southerly waves incident at Waipipi Point is a result of the lack of available fetch to the south. Since the refraction diagram of Figure 11 shows that southerly waves generated in an area of unlimited fetch may arrive at Waipipi Point it is the writer's opinion that the low wave heights in the north are more a result of the effects of refraction, rather than the limitations of fetch. The four wave refraction diagrams indicate that for the northern, central and southern coastal sections, the highest refraction coefficients occur for wave trains incident from the southwest, west and northwest respectively. The coastline appears best adjusted to a wave

approach from the west, except in the southern section where the symmetry of Kenakena Point suggests that its development is a result of a west-northwesterly direction of wave approach.

It is possible that the present coastal plan reflects the past history of the Wanganui Basin, and that the coastal plan is still being altered by the present wave regime toward a new equilibrium form. On the basis of the wave environment discussed above, however, it would seem that the prevailing west-northwesterly direction of wave approach would cause no marked changes in orientation for the coast as a whole, although local changes may occur.

#### 2.27 Summary

The shallow gradient of the western shelf area causes wave trains with a westerly component to be subject to modification over a long distance before reaching the coast. While wave trains from the south pass through the deeper Narrows Basin the poor level of alignment between their wave crests and the submarine contours further north causes these trains to undergo extreme refraction in the shallower water.

Surface drift in Cook Strait was shown to be dominated by the clockwise, south-flowing D'Urville Current. The effect of the drift current is reinforced in the northern section of the coast by that of the prevailing wave-induced current, although extended periods of northerly drift were observed in the field, during which time southerly wind and wave regimes were dominant.



Offshore sedimentation zones have developed under both past and present processes, so that the predicted decrease in grade size across the continental shelf is not apparent. Grade size does increase to the southeast where the high current velocities have winnowed the marine deposits in the narrows.

Westland is believed to be a source area for material deposited in Cook Strait as the D'Urville Current diverges and slows across the western shelf area, although no accurate estimate of the quantity of material added to the shelf via this current is available.

The wave regime for the northern beaches is described by Burgess (1971) as having a mean annual wave height of four feet with no marked seasonal variation, and with the largest, and prevailing waves approaching from the west and southwest. Data collected by the writer during the six monthly field surveys also indicated a mean wave height of four feet near Wanganui, with the heights decreasing southward along the coast. The only exceptions to this southward decrease in wave height occurred during southerly wind/wave conditions.

The greatest local variations in wave height occurred at stations on either side of Kenakena Point; a result of extremes in their degree of exposure to the various wave trains. At Kenakena Point, wave heights were consistently low, irrespective of the direction of wave approach. This same location registered waves of period up to twenty seconds, in contrast to the northern beaches whose modal period was twelve seconds.

All wave trains of period ten seconds were shown to

undergo refraction, the extent of which depended upon the initial degree of alignment between the wave crest and the offshore contours. Refraction coefficients for the various wave trains were established along the coast. The northern beaches have maximum coefficients for waves from the southwest, the southern beaches for northwesterly trains. The refraction diagrams also demonstrate that for waves of period greater than or equal to ten seconds approaching from the west, the southern half of the west Wellington coast is protected by the projection of Farewell Spit.

The refraction diagrams, together with the symmetry of Kenakena Point, suggest that the present plan of the coast is best adjusted to wave trains from a west-northwesterly direction, although the present outline may to a large degree reflect the geologic history of the area.

Finally, it is argued on the basis of the refraction diagrams drawn for a ten-second southerly wave train that direct fetch distances do not necessarily indicate the level of wave energy that may be incident along a coast. A southerly wave train of unlimited fetch has been shown to be incident along the west Wellington coast, due to the process of refraction.

Notes

- 1 As treated here the coastal lowland is defined as that coastal belt of dissected marine, deltaic fluvial terraces extending the length of the study area. It includes the Sand Country, the most recently created section.
- 2 The term Cook Strait is used throughout the thesis in its fullest maritime, and not in its popular geographical sense. The Cook Strait region includes the offshore areas of the Cook Strait and Tasman Coastal Series charts of the N.Z. Oceanographic Institute. The term therefore approximates to the regional waters east of a line segment between Cape Egmont and Cape Farewell which separate the North and South Islands of New Zealand.
- 3 Fleming considers that the elevation of Kapiti Island and the Tararua Ranges may have been concurrent, producing a minor syncline between the two greywacke blocks. MacPherson (1946) described this syncline as a southern extension of the Pohangina syncline to the northeast. During the Otiran Stage the coast is assumed to have been south of the Kapiti Strait, which was a deep depression receiving gravels from the Waikanae district. (Fleming, 1971:145)
- 4 Hall, 1964:19.
- 5 A variety of microclimates exist in the Sand Country within the sand plain-dune complex, in response to local variations in relief, soil type and the water table. These factors influence the nature and density of the vegetation cover, which in turn affects the rate at which sand movement can take place.
- 6 Town and Country Planning Division, Ministry of Works, 1971:25.
- 7 Parts of the headwaters of the Otaki and Waikanae rivers are orientated along fault valleys in the Tararua Ranges.
- 8 This section is based on Saunder's 1968 article: The physical environment of the Manawatu Sand Country.
- 9 McDougall and Brodie, 1967:44.

- 10 The northern limit of the Westland Current is variable, for although the inshore section tends to round Farewell Spit into Cook Strait, Brodie notes that, at times, the waters off the western entrance to Cook Strait are moving northwards to influence the North Island west coast north of Cape Egmont.
- 11 Accretion to the north, erosion and nil nourishment to the south of the Wanganui river mouth on construction of the harbour moles; distribution of gravel and pebbles on the Otaki foreshore skewed to the south of the Otaki river mouth; bodies from drowning tragedies at Otaki beach are often recovered on Te Horo and Waikanae foreshores.
- 12 Davies, 1964:132.
- 13 The hindcasting technique involves the use of daily meteorological surface charts and the wave generation theories of Sverdrup, Munk and Bretschneider (SMB), and of Pierson, Neumann and James (PNJ). 1959 was selected as the worst year in the past twenty-five year period. Consecutive six-hourly wave statistics were generated for the location  $39^{\circ} 51' 12''$  S,  $174^{\circ} 36' 30''$  E.
- 14 The major assumption in the application of wave refraction theory is that for a given wave crest there is no lateral flow of energy i.e. the transmitted energy of the wave crest remains constant between the wave orthogonals - lines everywhere perpendicular to the wave crest - as the wave moves over changing bottom topography (Neiheisel, 1954). The concentration of energy per unit length of wave crest is determined by the distance  $s$  between the wave orthogonals. When the orthogonals converge the energy per unit length  $E$  increases, and the breaker wave height  $H_b$  increases, since

$$E \propto H_b^{\frac{1}{3}} \quad (\text{Shepard, p. 73})$$

Conversely, divergence of the orthogonals represents a decrease in breaker wave height and energy per unit length available between the orthogonals.

The change in breaker wave height caused by refraction is inversely proportional to the cube root of the ratio of the distance between the orthogonals in deep water,  $s_d$ , and that between the orthogonals in the breaker zone,  $s_b$ . Near the breaker zone, therefore, the refraction coefficient  $K_b$  for the change in wave height due to refraction is:

$$K_b = \left( \frac{s_d}{s_b} \right)^{\frac{1}{3}} \quad (\text{Shepard, p. 73})$$

- 15 In the wave refraction diagrams in section 2.26 the refraction coefficients for the southern beach segment have been calculated without reference to the 'shadow' effect of Kapiti Island. They therefore represent averages only of values which are shown in the larger-scale refraction diagram (Figure 21) to vary considerably over a short coastal section.

3. FIELD AND LABORATORY INVESTIGATION  
OF BEACH SEDIMENT AND BEACH  
MORPHOLOGY

3.1 Field and Laboratory Procedures

3.2 Beach Sediments

3.3 Beach Morphology

### 3.1 FIELD AND LABORATORY PROCEDURES

#### 3.11 Field Procedures

Twenty-two profile stations were established along the seventy-five mile (120 Km) section of coast, which extended from the Wanganui river south to the Whareroa stream. The location of the stations, shown in Figure 12, depended on accessibility and the rate of change in beach process and materials along the coast, and their distribution is therefore biased towards the southern portion. While more stations would have been desirable, the above number allowed the whole coast to be surveyed within periods during which similar offshore wave conditions operated.

A series of parallel profiles were obtained at two stations near the Otaki river, where large beach cusps and berms dominated the beach.

Six monthly surveys were made between May and November, 1971, on the following dates; May 19, 20, 21, 24; June 17, 18, 19, 21; July 16, 17, 19, 20; August 16, 17, 19, 20; September 13, 14, 15, 16; November 15, 17, 18, 19. Profiles were surveyed across the beach from reference pegs using a theodolite, survey staff and a fibre-glass metric tape.

To evaluate volumetric change, cross-sectional areas were calculated for each profile over a fixed distance and converted into volumetric terms by considering a one metre wide strip along the profile. In previous research volumetric change has been based on a one foot wide strip across the beach, and reported in terms of cubic feet of cut or fill. It can be shown that a change of one

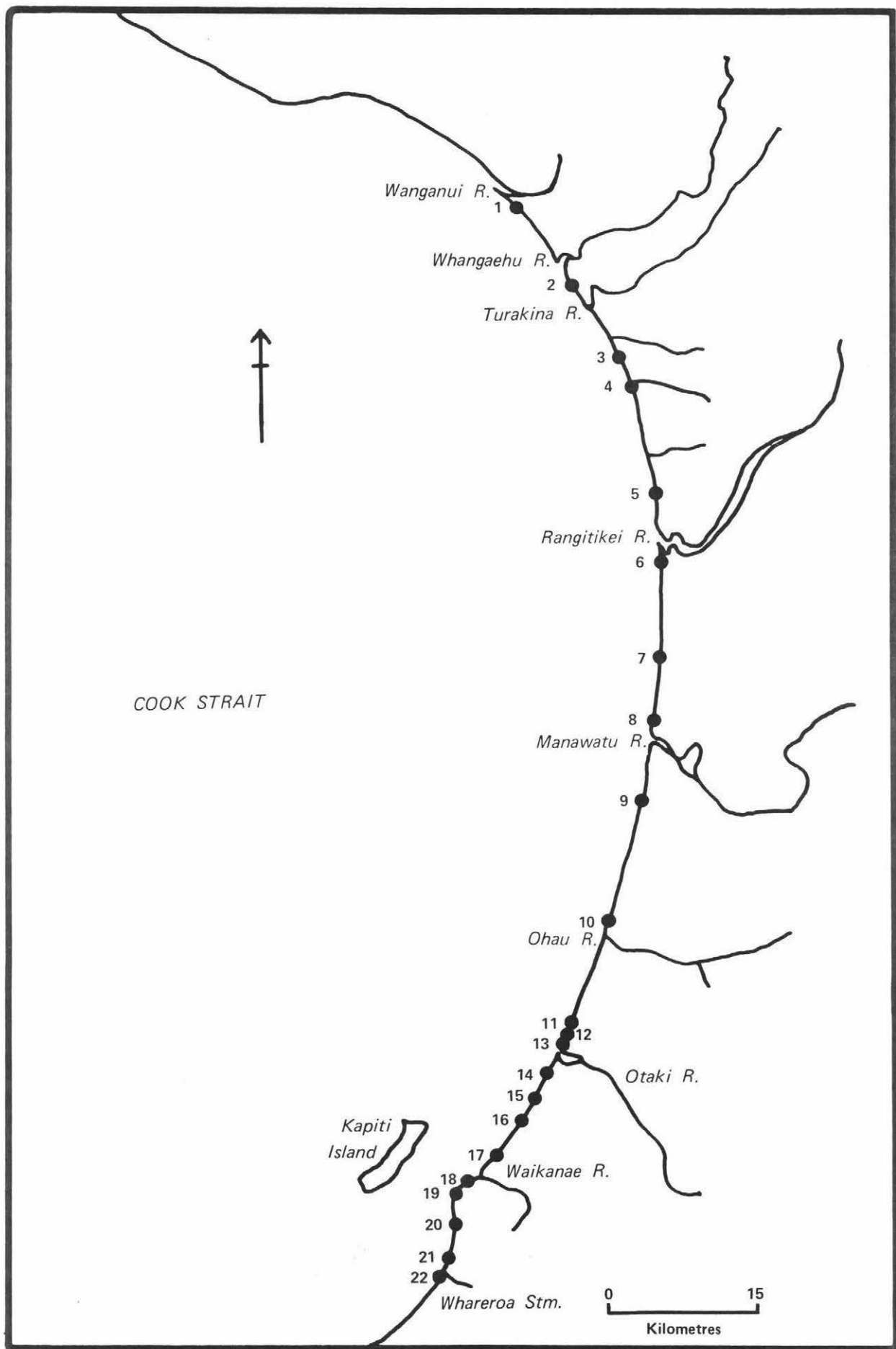


FIG. 12 LOCATION OF SAMPLING STATIONS



cubic metre in the present study is equivalent to one of 10.76 cubic feet occurring in previous research.

At most stations five sediment samples were obtained along the profile; single samples were taken from the dune crest and backshore areas, and three random samples from a ten metre segment at mid tide. All samples on sandy profiles were collected in half pint plastic cartons which penetrated to a depth of approximately four centimetres. Where coarser fractions were present a 1-1.5 Kg sample was taken.

On the basis of field conditions encountered during the six surveys, surveys 1 and 5 were selected as representing the periods of lowest and highest wave energy conditions, respectively. Sediment samples for each of these surveys were then analysed in the laboratory.

### 3.12 Laboratory Procedures

All samples were bench dried. Samples, where necessary, were separated into two parts: (1) that retained on a 2 mm sieve (No. 8 mesh B.S.); and (2) that passing a 2 mm sieve. The latter was split by repeated quartering down to a sub-sample of 40 to 60 gm, which was re-dried and sieved for ten minutes on a Dura Lab sieve shaker.

The particle size distribution, by weight, was then obtained by combining the data of (1) and (2) after applying a correcting factor to the former. Data from the sieve analysis were plotted as a cumulative frequency curve on log-frequency graph paper,

as grain size distributions are either approximately log-normal (Krumbein and Pettijohn, 1938) or represent a mixture of log-normally distributed sediment populations. Percentiles were read from the graph and the grain size parameters of Folk and Ward (1957) calculated. Formulae for these parameters are given in Appendix A.

All calculations were carried out on a Canola 164 P calculator.

## 3.2 BEACH SEDIMENTS

### 3.21 Introduction

The particle size parameters (mean grain size, size-sorting, skewness, kurtosis, shape, roundness) of beach deposits closely reflect the characteristics of the source area (Folk, 1965), and to a lesser extent the components of the energy environment of the deposit in situ (McLean and Kirk, 1969).

In the majority of New Zealand coastal studies, workers have been able to consider the mineralogy of materials supplied to the beach as being relatively homogenous, with separate sources providing similar types of material to the coastal system. Changes in size parameters have accordingly been interpreted as real responses to the beach processes operating either on a spatial, or temporal, basis.

Where each of a number of sources introduce material of distinct mineralogy, however, any attempt to interpret process on the basis of the results of sieve analysis may be invalid.

In this section the various sources and types of material supplied to the beaches of the South Taranaki Bight are described, and the ramifications of differences in mineralogy discussed in terms of the principle of hydraulic equivalence. An attempt is made to justify the use of the results of sieve analysis, which are then used to indicate longshore and seasonal variations in the mean grain size of foreshore samples. Finally, the degree to which the Folk parameters of size, degree of sorting, skewness and kurtosis

differentiate between the various depositional environments is evaluated.

### 3.22 Mineral Composition and Source Areas

A schematic diagram of the source areas of the various mineral suites is shown in Figure 13. The terrigenous deposits, those derived from a land base, represent the greatest proportion of material and are derived from a number of sources.

- (1) Volcanic deposits rich in ferromagnesian minerals derived from the Taranaki region and relict deposits.
- (2) Andesitic minerals from the Volcanic Plateau.
- (3) Greywackes rich in feldspar and quartz derived from the Tararua Ranges.

Biogenous deposits such as shell and shell fragments are common along the coast, particularly in the southern section in the vicinity of Rauoterangi Channel.

The proportion of ironsand content in beach deposits declines southwards (Finch, 1947; Oliver, 1948; Willett (in Burgess, 1971)) as a result of increasing distance from the primary source and the large input of contaminating materials by rivers to the south. It is suggested by Willett that hypersthene is carried to the coast by the Wanganui river, contributing to the low ironsand concentration on the southern spit of that river. In the vicinity of other river mouths both Finch (1947) and Ross (1963) have noted very high local ironsand concentrations which interrupt the general longshore trend. Magnetite levels are greater in beach than dune

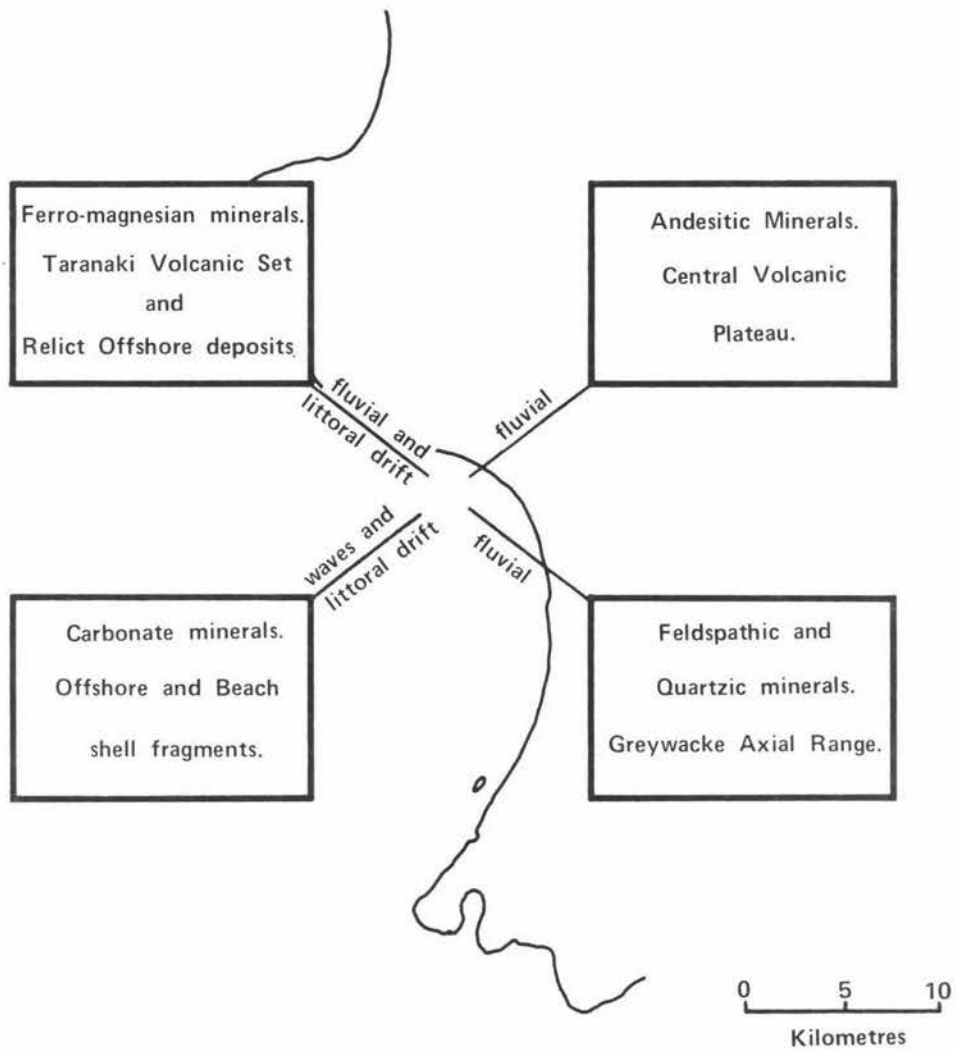


FIG. 13 SOURCE AREAS OF MINERAL SUITES SUPPLIED TO THE WEST WELLINGTON COAST

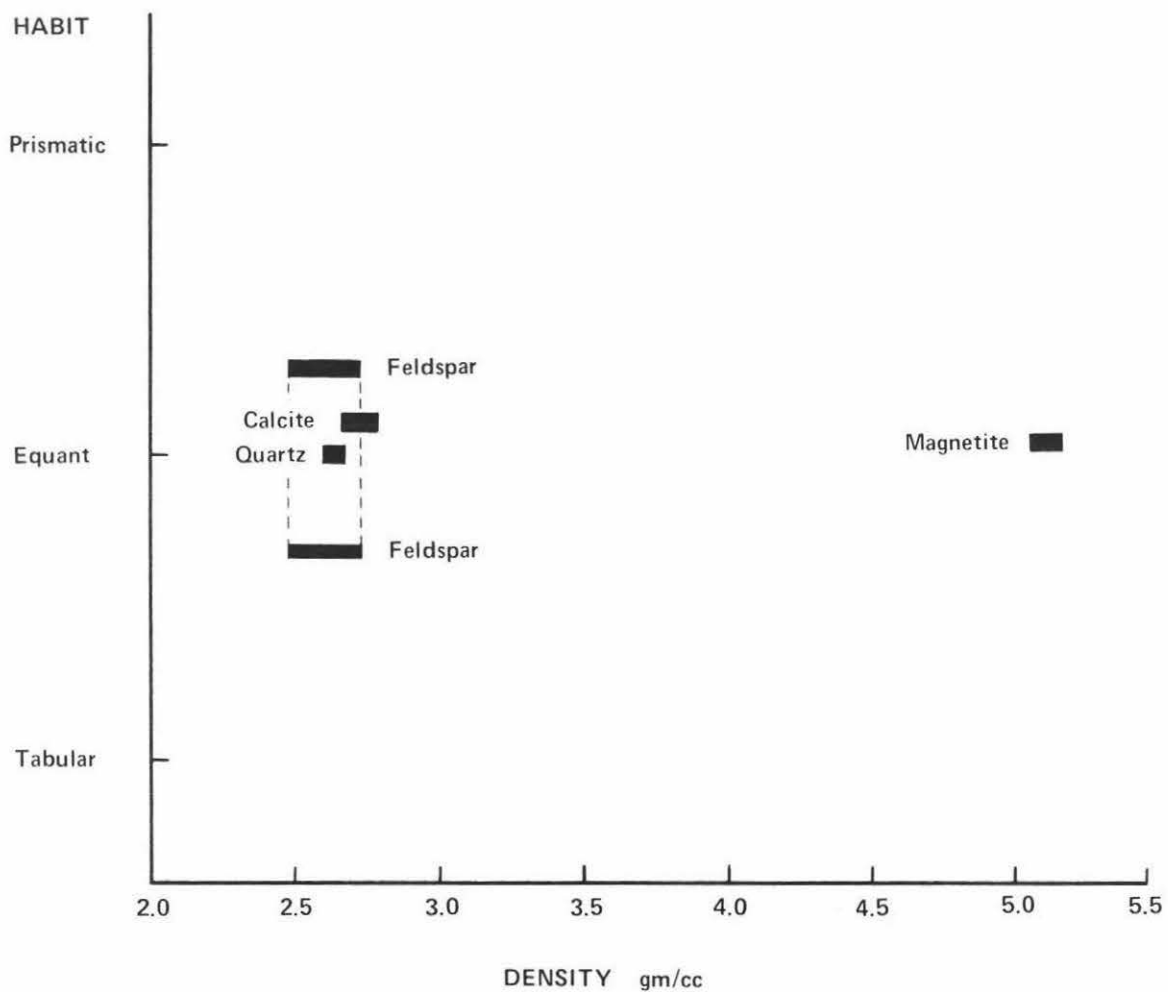
deposits, increasing across the foreshore from low- to high-tide levels to reach a maximum in the backshore. Field observations by the writer confirm the existence of this trend as far south as Tangimoana.

### 3.23 Hydraulic Equivalence

The hydraulic equivalence of a particle is largely a function of its size, shape and density. Griffiths (1967) describes the selective sorting of particles on the basis of size, shape and effective density as being an extremely efficient process, and so particles whose parameters are similar will congregate in a given sedimentation unit, their aggregation representing their similar response to a given set of hydraulic conditions. Sieve analysis of samples obtained from such units would provide satisfactory data to allow the description and comparison of various beach environments.

Where grains of different mineralogy occur together in a deposit, however, due to mixing in the littoral zone, it is possible that grain size parameters determined by sieving may give a misleading indication of the depositional environment, as such a procedure may separate particles which in fact responded to the processes operating in an identical manner.

Figure 14 indicates the level of hydraulic equivalence of some minerals in the study area. Although the habits and densities of feldspar, quartz and calcite are similar, carbonate shell fragments may behave quite differently to quartz and



Source: Griffiths, 1967:217.

FIG. 14 LEVELS OF HYDRAULIC EQUIVALENCE OF SELECTED HEAVY MINERALS ON WEST WELLINGTON FORESHORE

feldspathic sediment according to its size, shape and effective density. The diagram also indicates the higher density of magnetite.

Ross (1963) has compared the density, mean size and shape of titano-magnetite with that of the residual beach deposit north of Wanganui. The results are shown in Table V.

TABLE V: A comparison of properties of titano-magnetite and the residual deposit.

	Density gm./cc.	Mean size		Shape
		$\phi$	mm.	
titano-magnetite	4.74	2.7	.15	spherical
sample residue	2.99	2.0	.25	angular

Source: Ross, 1963:206.

The magnetite was found to be denser, smaller and more spherical.

### 3.24 Justification of Sieve Analysis

It has been shown that deposits of varying mineralogy occur in the study area and that such variation is reflected in size and shape, as well as density. The statistical degree of sorting, in terms of particle size data alone, may lead, therefore, to a distorted view of the degree of hydraulic sorting.

It is believed, however, that the use of grain size data, as a measure of hydraulic sorting, may be justified on a number of grounds.



- (1) Except for the high local concentrations around river mouths, relatively low concentrations of ironsands occur south of Wanganui, the level rapidly decreasing over a short section of the coast. The validity of comparing samples on the basis of mean size would therefore be most suspect when samples near Whangaehu are compared with those of Paraparaumu and Paekakariki. The testing of significant variation between adjacent beach stations should not be greatly affected, especially when stations are not separated by a major river mouth.
- (2) Where shell and shell fragments appeared as surficial deposits, they were scraped away and not included in the sample prepared for sieving. Samples were obtained where shell fragments were predominant, but these were not collected during surveys 1 or 5, and so were not sieved.
- (3) If grain size distributions were appreciably affected by mineralogy, this source of variation might be expected to 'confound' any meaning in raw grain size statistics, in so far as these are used as indicators of selective sorting. The distinctive colour and size characteristics of ironsand and shell deposits, however, allowed the presence of these minerals to be detected in both field and laboratory work, and appropriate cautionary measures to be exercised.

### 3.25 Mean Grain Size Variation

The variation in mean grain size of beach deposits with respect to time and/or place may be the result of a number of factors:

(1) littoral drift; (2) the location, number and type of material sources; and (3) changing exposure and wave energy conditions along the coast.

Samples from a given location may be compared on the basis of varying energy conditions obtaining during different sampling periods.

In the ideal case, grain size decreases away from the

point of initial deposition in the direction of littoral drift, and the greater the wave energy available at the foreshore the coarser the beach deposit. With the large number of sources of material of various grades available to the study beach, however, the idealised patterns are unlikely to occur. The extent to which the actual distribution departs from the general pattern is investigated below.

### 3.251 Longshore Variation

A scatter diagram of grain size variation with distance along the coast for surveys 1 and 5 is shown in Figure 15. Plots represent the mean of the three mid-tide samples. Surveys 1 and 5 are considered by the writer as being respectively the periods of least and greatest wave energy encountered during the six surveys.

For neither survey is there a simple trend in size gradation along the coast. A number of reasons can be given in partial explanation of the observed pattern.

- (1) The numerous streams and rivers that discharge a variety of sediment into the beach system.
- (2) The rate of discharge of the major rivers such as the Rangitikei, Whangaehu, Ohau and Otaki determines the grade of material discharged at any given time. The situation is further complicated by the unknown rate of migration of flood deposits along the coast.
- (3) The rivers present a partial - at times total - barrier to the longshore movement of sediment, this barrier often extending to moderate offshore depths.

Survey data indicate that fine sands ( $2\phi$  to  $3\phi$ ) dominate the foreshore of the west Wellington coast. The limited

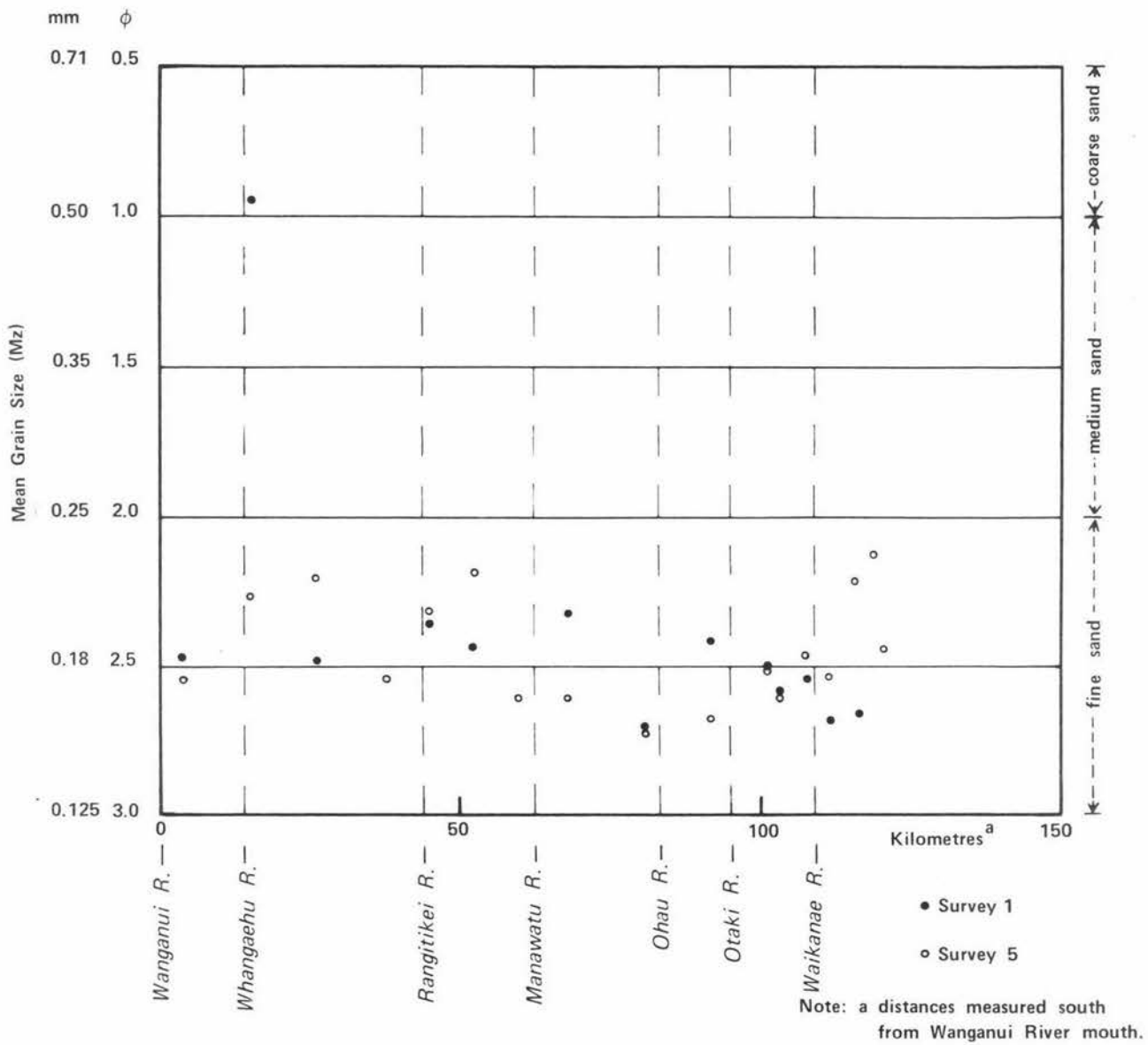


FIG. 15 LONGSHORE MEAN GRAIN SIZE VARIATION OF FORESHORE SAMPLES

sections of coarser grades occur near the Otaki<sup>1</sup> and Whangaehu river mouths, and at the southernmost station (Station 22). The variable nature of the Whangaehu deposit is demonstrated by the fact that coarse sand (1 $\phi$  to 2 $\phi$ ) in the first survey had been displaced by fine sands by survey 5.

The relative absence of fractions less than 2 $\phi$  in the samples is a consequence of the sampling method employed, and does not imply that coarse material cannot be moved by waves and wave-induced currents far from its point of entry into the beach system. Gravel and pebble stringers were found many miles from their inferred source, and laminae of coarser material were sometimes located under a surface deposit of finer material, but were not included in the sample. These coarser layers were concentrated to the south of the rivers transporting them to the sea, that is, in the direction of the prevailing littoral drift.

In studies of grain size distribution a t-test procedure has often been employed to ascertain whether or not statistically significant differences exist between samples, or sets of samples, from adjacent stations. A problem in such multiple-comparison tests, however, is that

"... for experiments where many comparisons are to be made, we are almost certain to declare some differences to be significant, even when the means are a homogenous set."

Steel and Torrie, 1960:109.

In order to avoid this situation the Tukey w-procedure<sup>2</sup> was used to determine whether statistically significant changes in grain size were present within groups of stations between the major rivers. Significant decreases, at the five per cent level, occurred for

survey 1 between stations 7 and 8, and between stations 9 and 10, the latter station having the lowest mean grain size (2.7 $\phi$ ) of all stations. Decreases also occurred away from the Otaki river mouth. South of the Waikanae river the mean size decreased away from station 19, the most sheltered of all stations. The change in grain size, then, is not always a direct reflection of energy conditions, and, in the latter case may be related more to the type of sediment available for deposition at each location.

The results show that, while no general decrease in mean grain size occurs along the coast, on the largest sections of beach between major rivers a decrease has been identified in the direction of the prevailing littoral drift.

### 3.252 Seasonal Variation

An increase in wave energy may cause an increase in the mean grain size of foreshore sediment. A t-test was applied to paired observations of the means of the three mid-tide samples from surveys 1 and 5 to test the hypothesis that no differences in mean grain size occur on the profiles for the two sampling periods. At a significance level of 5 per cent, eight of sixteen stations tested showed a significant change, seven of these reaching the 1 per cent probability level. Only five of the eight stations (nos. 4, 7, 12, 18 and 20), however, registered an increase in grain size. The three remaining stations (nos. 2, 9 and 11) experienced a decrease in grain size. Neither set shows any marked longshore grouping.

The data, then, do not suggest any general change in surficial foreshore deposits in response to a change in wave energy conditions for surveys 1 and 5. It must be noted, however, that sampling was restricted to the surface layers, and, as was stated in section 3.251, coarser material was often present as lower laminae.

### 3.26 Environmental Differentiation

Research on recent sedimentary deposits has provided evidence both for and against the hypothesis that grain size characteristics differentiate between various sedimentary environments. For example, Mason and Folk (1958) conclude that skewness distinguished beach from dune deposits, but this has been contested by Shepard and Young (1961).

In a New Zealand context work has been carried out by Andrews and van der Lingen (1969) and Sevon (1966a, 1966b). Sevon's study of Farewell Spit demonstrated that statistically significant differences in mean, sorting and skewness occurred between foreshore deposits on the one hand and backshore and dune deposits on the other. When data from samples drawn from more than one coastal compartment were compared by the same author, it was found that no single parameter remained sufficiently consistent to be used in ascribing a sediment to a particular sedimentary environment. In research which involved the sampling of various coastal compartments, Andrews and van der Lingen (1969) showed that unimodal samples exhibited greater variation between compartments than between the foreshore, backshore and dune

environments of a given compartment, and found no support for the hypothesis that the distributions of beach sands were negatively skewed, that is, skewed towards the coarser fractions.

The ability of grain size parameters to discriminate between foreshore, backshore and dune environments would therefore seem to be greatest within a given coastal compartment, where material and energy inputs are likely to be more homogenous. 'Student's'  $t$ -test was applied to data from samples obtained from the mid-tide (M), backshore (B) and dune (D) environments to determine whether their grain size parameters did in fact discriminate between the three environments. The results are summarised in Table VI.

With the exception of kurtosis, all grain size parameters revealed statistically significant differences at the 5 per cent level. In contrast, no apparent parameter difference occurred between the backshore and dune environments. The latter result suggests that the backshore and dune areas are closely related in terms of their development, and that they derive their grain size characteristics from aeolian processes, in contrast to the dominating influence of swash and backwash activity on foreshore development.

The results of the analysis are identical to those of Sevon for Farewell Spit, although Sevon's tests reached higher probability levels. This would suggest that environmental conditions operating in each area are similar, especially in relation to the role of aeolian activity.

The mean size of the mid-tide deposits is larger than that of the backshore and dune, a result in agreement with that of

TABLE VI: Results of t-test applied to grain size parameters for the mid-tide (M), backshore (B) and dune (D) environments.

Parameter	Inter-relationship	t	Probability level
Mean	M x B	2.12	*
	M x D	1.86	*
	B x D	0.29	NS
Sorting	M x B	2.21	*
	M x D	1.83	*
	B x D	0.51	NS
Skewness	M x B	1.90	*
	M x D	1.72	*
	B x D	0.43	NS
Kurtosis	M x B	0.22	NS
	M x D	0.47	NS
	B x D	0.85	NS

$$t_{0.05} (28) = 1.70$$

\* significant at 5% level

NS not significant.

Notes Survey 5 data, used in this test, appears in Appendix B

Mean values of the mean, sorting, skewness and kurtosis parameters, for each of the three environments are

Mid-tide (2.43, 0.44, -0.16, 1.13)  
 Backshore (2.59, 0.32, 0.03, 1.15)  
 Dune (2.57, 0.34, -0.01, 1.09)  
 respectively.



Burgess (1971) for coastal sediments in the vicinity of Wanganui, in spite of the different sampling procedures employed. This reflects the greater ability of the swash to move and concentrate the coarser material, in comparison with that of the onshore winds to move material up the backshore and dune faces. The better sorting of the backshore and dune deposits is considered to be due to the mixing of material on the foreshore and to the winnowing of these deposits by the wind. All but one mid-tide sample exhibited a negative skewness and so, as suggested by Folk (1962), and demonstrated by Sevon (1966a), it may be indicative of a particular sedimentary environment.

### 3.27 Summary

No simple pattern of longshore variation in mean grain size has been determined, although fine sand dominates the major sections of the west Wellington foreshore. The coarsest deposits were found in the vicinity of the Otaki river mouth, with secondary maxima near Whangaehu and Paekakariki. The minimum grain size occurs only nine miles north of Otaki, indicating that drift to the north along this section of beach is not reflected in grain size variation.

Coarser materials were often found under a veneer of fine sands, particularly to the south of the river mouths. A southern decrease in grain size in the central section of the coast was identified over four consecutive stations lying between the major river sources.

A test for seasonal variation in mean grain size between surveys 1 and 5 revealed that the null hypothesis - that no difference occurred between the surveys - could not be rejected for the majority of stations. The changes which did occur showed no general trend towards coarser deposits with greater wave energy conditions.

The mean, sorting and skewness parameters were each found to differentiate between the mid-tide, and the backshore and dune environments. No parameter could be used to distinguish between the backshore and dune environments, suggesting the dominating influence of aeolian activity in each of these zones.

### 3.3 BEACH MORPHOLOGY

#### 3.31 Introduction

Changes in profile configuration are known to be related to variations of wave energy and the supply of material available to the foreshore over a given period of time. Short-term variations - tidal, daily, weekly and monthly - correlate strongly with wave energy changes;<sup>3</sup> in this case the removal of material may be sub-permanent, with material being stored offshore during periods of high wave energy and returned to the foreshore as low long period waves become predominant (Shepard, 1950).

Long-term changes, in the order of years, of the coastline usually involve a continued imbalance of material supplied to and removed from the beach, and may represent a series of continued losses or gains occurring over short intervals of time.

It should be realised that sand and gravel beaches adjust rapidly to variations in beach processes, and so data from monthly surveys do not necessarily reflect processes operating for the previous month. Also, it has been noted (Burgess, 1968; Kirk, 1967) that the magnitude of change over periods within the month may be greater than the net change for that month, due to the continual regression of the profile towards an equilibrium form.<sup>4</sup>

In this Section the various profile forms are discussed, and their monthly and seasonal changes are treated in relation to the general theories of beach equilibrium. A brief attempt is made to evaluate the degree of correlation between wind patterns

and volumetric change along the coast. Finally, the relationships between foreshore slope, and size and size-sorting parameters are discussed; and the equilibrium status for the coastal foreshore is described.

### 3.32 Beach Profiles

As a result of the non-periodic changes in sediment size, and beach orientation and degree of exposure, there is no simple longshore gradation in profile types along the coast. The range of profiles can, however, be classified into five typical forms, which are shown in Figure 16.

The profiles of type A occur in the central portion of the study area. They represent the widest beaches, have the gentlest gradients and are backed by foredunes which show no evidence of cliffing at their bases. It is suggested that this section of the coast is undergoing accretion as the plan of the coast moves toward an equilibrium form.

The profiles of type B are located north and south of the above zone, and in the lee of Kapiti Island. They have a steeper gradient and narrower backshore, and cliffing has occurred at the base of the foredunes. The profiles to the southern end of Kapiti Island - where erosion has been observed over the past few decades - have almost no backshore zone and dune-cliffs of considerable height are maintained.

In the northern sections, profiles of type C occur as a result of specific exposure conditions, and are repeated in coarser

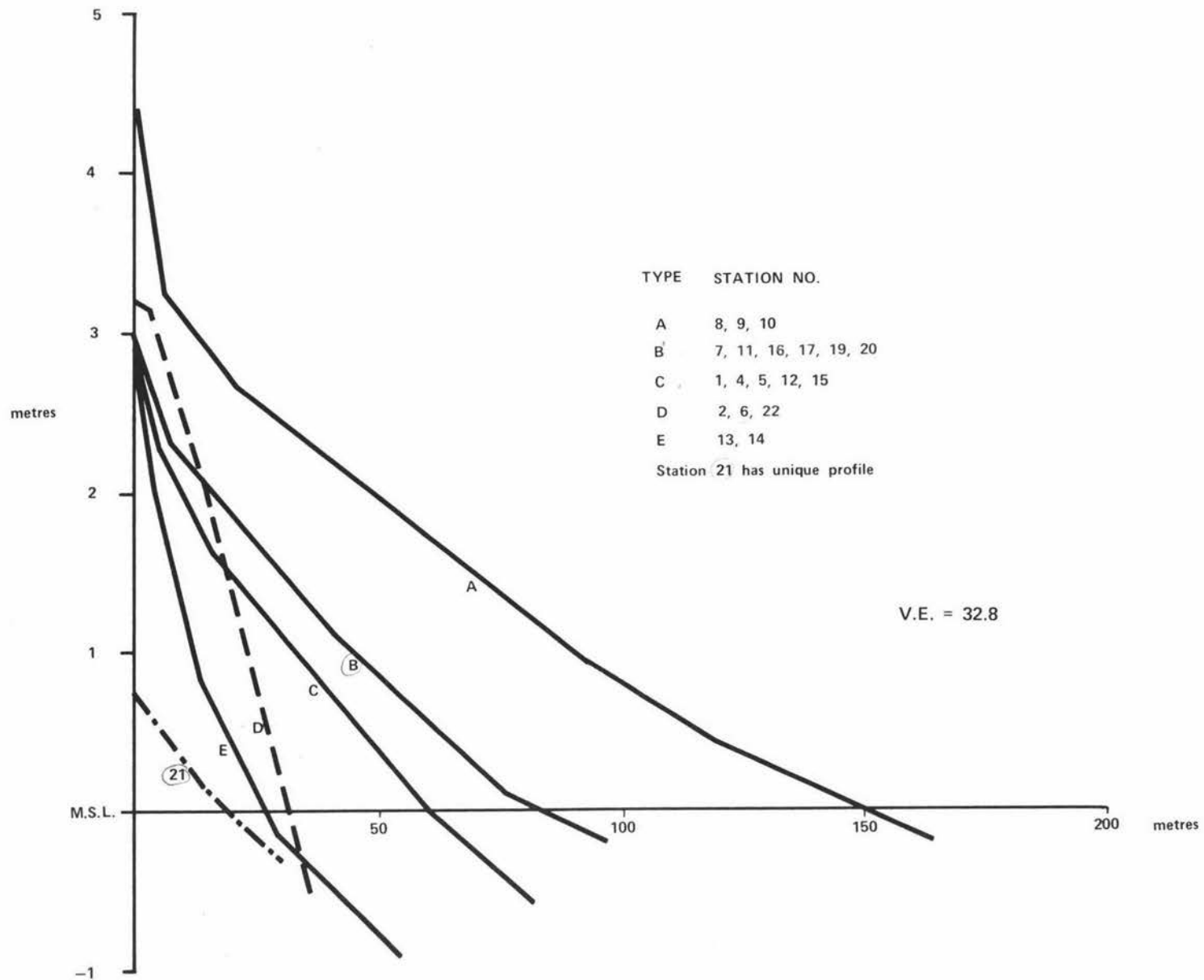


FIG. 16 IDEALISED PROFILE TYPES

sediments further south; similar profiles can therefore develop under sets of differing beach conditions.

The steepest profiles, type E, are located near the Otaki river mouth, which supplies sediment ranging in grade from sand to cobbles. This section is marked by the presence of a storm ridge more than three metres above mean sea level. Beach cusps up to one metre in depth are formed in the foreshore and backshore deposits and remain as a stable feature until altered by a major change in sea conditions. Intermediate berms can also be identified in Plate 1.

The profiles of type D occur near the mouth of the Whangachu and Rangitikei rivers, and at the southernmost station. The steepness of this type is a result of the presence of coarser material on the foreshore.

### 3.321 Monthly and Seasonal Variation

Coastal research has shown that beach profiles increase in height, width and local irregularity during periods of low swell waves, and are eroded by short-period storm waves. In the latter case the profile is 'combed', with finer material removed either off- or along-shore with coarser grades often being deposited in the form of a storm ridge high above the level of normal wave activity (Plate 1).

Where variation in wave energy along a shoreline has a seasonal aspect, the cycle of summer swell and winter storm waves will be reflected in summer fill and winter cut of the profiles,



Plate 1: View of foreshore berms and beach cusp development, south of Otaki River.

respectively. The restricted period of survey of the study beaches meant that only the winter and spring seasons could be considered, and so no quantitative estimate of profile change during summer can be offered.

The average inter-survey volumetric change for all stations is given in Figure 17. It can be seen that winter was a period of continued net accretion although losses occurred on some beaches during the period. In contrast, the period August - November was one in which net erosion of the profiles occurred, although some accretion took place. It is the writer's opinion that the erosion in spring was related to stronger onshore winds occurring during this period; this will be discussed below. The net accretion during winter may not be typical of the usual coastal pattern and could be simply a reflection of the very mild winter conditions of 1971.

The maximum deposition in a monthly period was 67 cubic metres, at Himatangi (profile 7), which also experienced the greatest erosion in a month (52 cubic metres). In comparison with figures given by Kirk (1969) for mixed sand-shingle beaches of the Canterbury Bight, the beaches in the study area are seen to be much more mobile, suggesting that, on the basis of the period surveyed, the study beaches experience a greater range of wave energy conditions. This, however, is not supported by field observation of wave conditions during survey periods.

It is demonstrated in Table VII that the greater volumetric change is not simply a function of the length of profile, as the set of beaches experiencing greatest volumetric change also



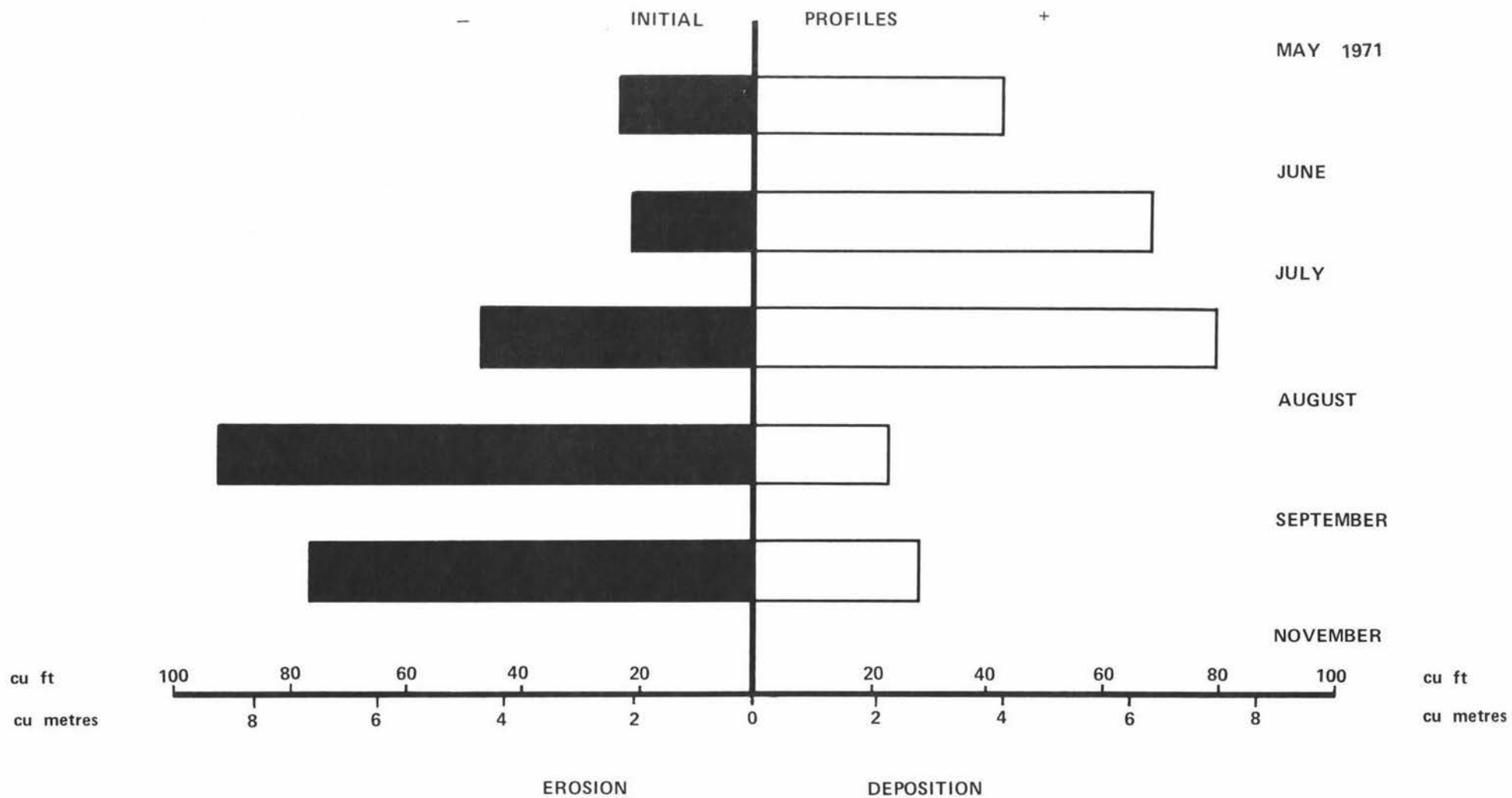


FIG. 17 AVERAGE INTER-SURVEY VOLUMETRIC CHANGE ACROSS EACH PROFILE

had the greatest average depth change per unit length of profile. The longer backshore areas of such profiles, however, may be a convenient place of storage for wind-blown sands, which would affect total volume changes.

To determine whether location of beach profiles affected the magnitude and type of volumetric change, the stations were grouped into four sets, according to their distance from Wanganui. A summary of the average seasonal changes for each group is shown in Figure 18. Because of the great differences in profile length, the average change in depth per unit length of the profile for each set is given in Table VII.

TABLE VII: Average depth added to (+) or lost from (-) profiles/unit length of profile on the basis of station sets.

Set	May-Aug.	Aug.-Sept.
W	+ 18	- 25
X	+ 17	- 15
Y	+ 14	- 17
Z	+ 3	+ 3

Depths in centimetres.

Only set Z departs from the general trend. The small changes in depth and volume for each of the seven profiles in this set (almost within the range of field measurement error) is an indication of their erosional equilibrium status. The location of Kapiti Island causes marked differences in the pattern of exposure to various wave trains for these southern stations and

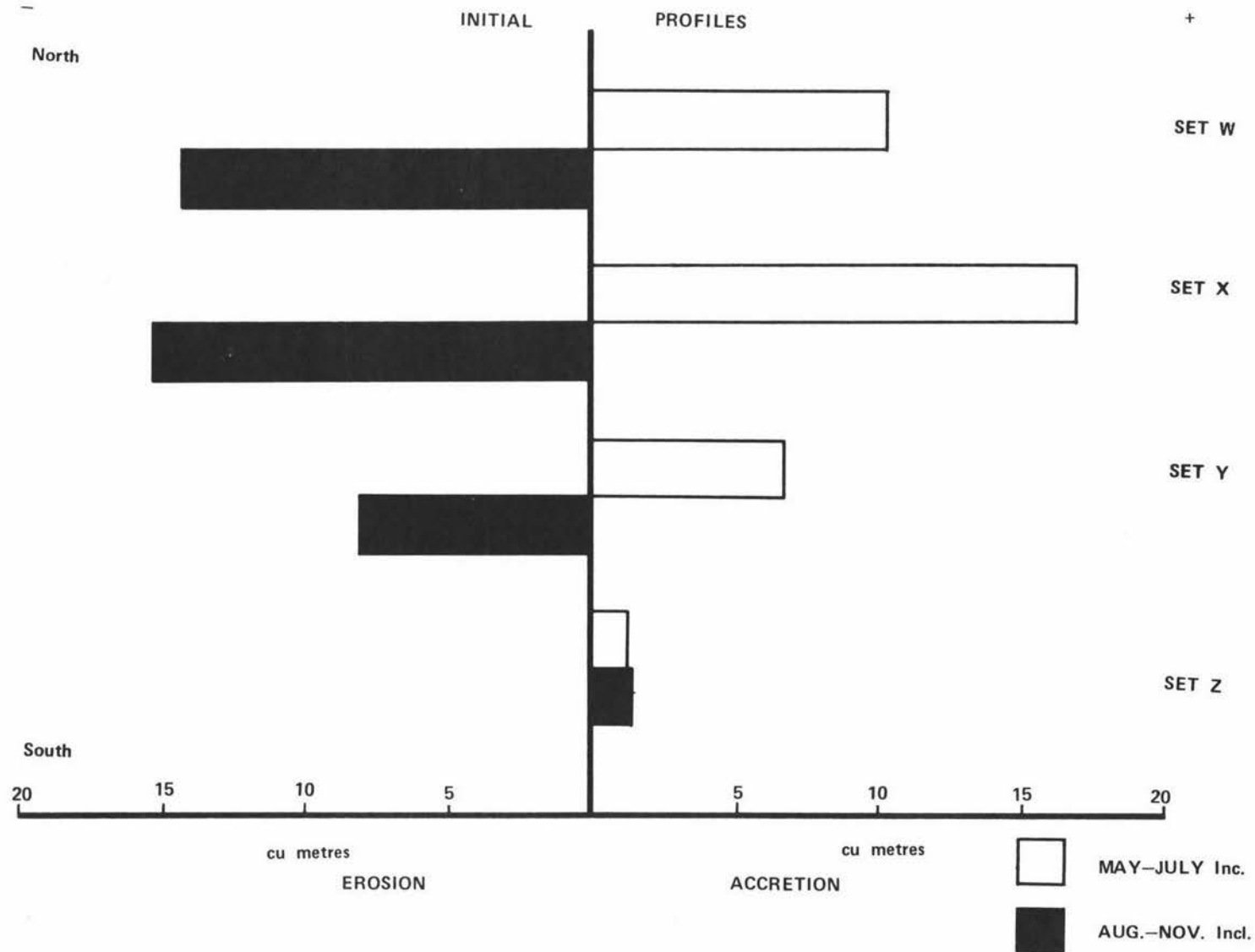


FIG. 18 NET VOLUMETRIC CHANGE PER / PROFILE ON BASIS OF STATION SETS

this is reflected in the pattern of volumetric change; the three southernmost profiles experienced winter erosion and spring accretion, while the response of the four northern profiles was consistent with that for the coast as a whole.

This pattern of seasonal change may be a result of a corresponding change in the dominant direction of wave approach, from the south in winter, and from the west and northwest in the spring. Unfortunately, suitable wave information is not available to investigate this further.

### 3.322 Wind Patterns and Volumetric Change

The frequency and intensity of onshore winds may be an important factor in the beach regime. Inman and Filloux (1960) identified a fortnightly cycle of erosion and deposition related to the combined effect of tides and waves generated by the daily sea breeze. Winds may cause currents in the inshore zone, and affect the wave parameters; King (1953) found that waves accompanied by a strong offshore wind tend to be steeper, and more destructive than those opposed by an offshore wind system.

Not all material removed from the foreshore and backshore is shifted seaward, as wind-blown sand feeds and sustains the growth of dune formations.

Wind data for the periods of general beach accretion and erosion were inspected to ascertain whether or not differences occurred in the respective wind regimes that might correlate with

the sequence of volumetric change. A summary of the data appears in Table VIII.

TABLE VIII: Wind regimes and volumetric change, May-July, August-October incl., 1971.

Wind speed (m.p.h.)	May-July	Aug.-Oct.
less than 12	79.1	48.9
12-38	20.9	49.0
over 38 (gales)	-	2.1
Volum. Change	+318	-229

- Notes: a wind speed as recorded daily at Ohakea, 9 a.m.  
 b volumetric change, in cubic metres, is the total net change for all stations.

It can be seen that the period of foreshore erosion contains a higher percentage of strong west and northwest (onshore) winds. Gale force winds, which are most effective in developing and maintaining storm profiles, also occurred in this period.

The data therefore suggest that wind patterns do have an influence on beach profile changes along the coast, although their indirect effect upon wave energy reaching the coast has not been evaluated. Wind strength at Wanganui is at a maximum for spring, and so wind patterns for the survey period are consistent with those of previous years.

A more intensive research programme on beach profile change and surface wind speeds may provide a more accurate indication of the relationship between these two variables, as it is possible that the greater part of the total volumetric change, especially the erosion, may have occurred during a short period of time within each month.

### 3.33 Foreshore Slope, Grain Size and Sorting

The steepness of the foreshore slope is a function of the ratio of energy supplied in the swash runup to that available in the backwash, this ratio being affected by the type of wave arriving at the beach, and the permeability of the beach deposit (Shepard, 1963). Permeability is in turn dependent on the size distribution characteristics of the beach deposit, as well as the level of the water table (Duncan, 1964).

The relationship between foreshore slope and grain-size parameters is considered here. Other environmental factors, such as the degree of exposure of each beach, and whether accretion or erosion is occurring, are also important. Although not considered in the statistical analysis the latter factors contribute to the variability of data about the mean regression line; with accretion the development of a foreshore berm causes a steeper foreshore slope in comparison with that of the low 'combed' profile formed during high wave energy conditions, and erosion.

It is well known that foreshore slope generally increases with mean grain size, and also with the degree of sorting

of the foreshore deposit. Folk (1965), and McLean and Kirk (1969) have studied these relationships for mixed sand-shingle beaches, employing polynomial curves of various orders to establish curves of best fit for their data.

For the restricted range of size grades present on most of the study beaches, a linear regression model is considered to be sufficient to identify any relationships (Shepard, 1963). The mean foreshore slope (Y), measured across mid-tide, is treated as a function of mean grain size (X), and the fitted linear regression lines for surveys 1 and 5 appear in Figure 19. A summary of the statistics, tests of hypotheses and population parameters is shown in Table IX. The equations are similar, and indicate that foreshore slope increases with grain size. The sample correlation coefficient (r) for survey 1 data (-0.64) is greater than that for survey 5 (-0.26), however, suggesting that under conditions of higher wave energy other factors mentioned previously may become more important. It can be seen in Table IX, though, that the confidence limits for the estimate of B are similar for each survey, and so there is no evidence that different relationships exist for the different energy conditions obtaining during each survey. The standard error<sup>6</sup> of each set of data is also almost identical.

A correlation procedure was employed to test the relationship between foreshore slope and the degree of sorting; the resultant very low correlation coefficients for each survey indicate that sorting does not seem to be a major factor in determining foreshore slope, at least not for the study beaches composed of fine sands.<sup>7</sup>

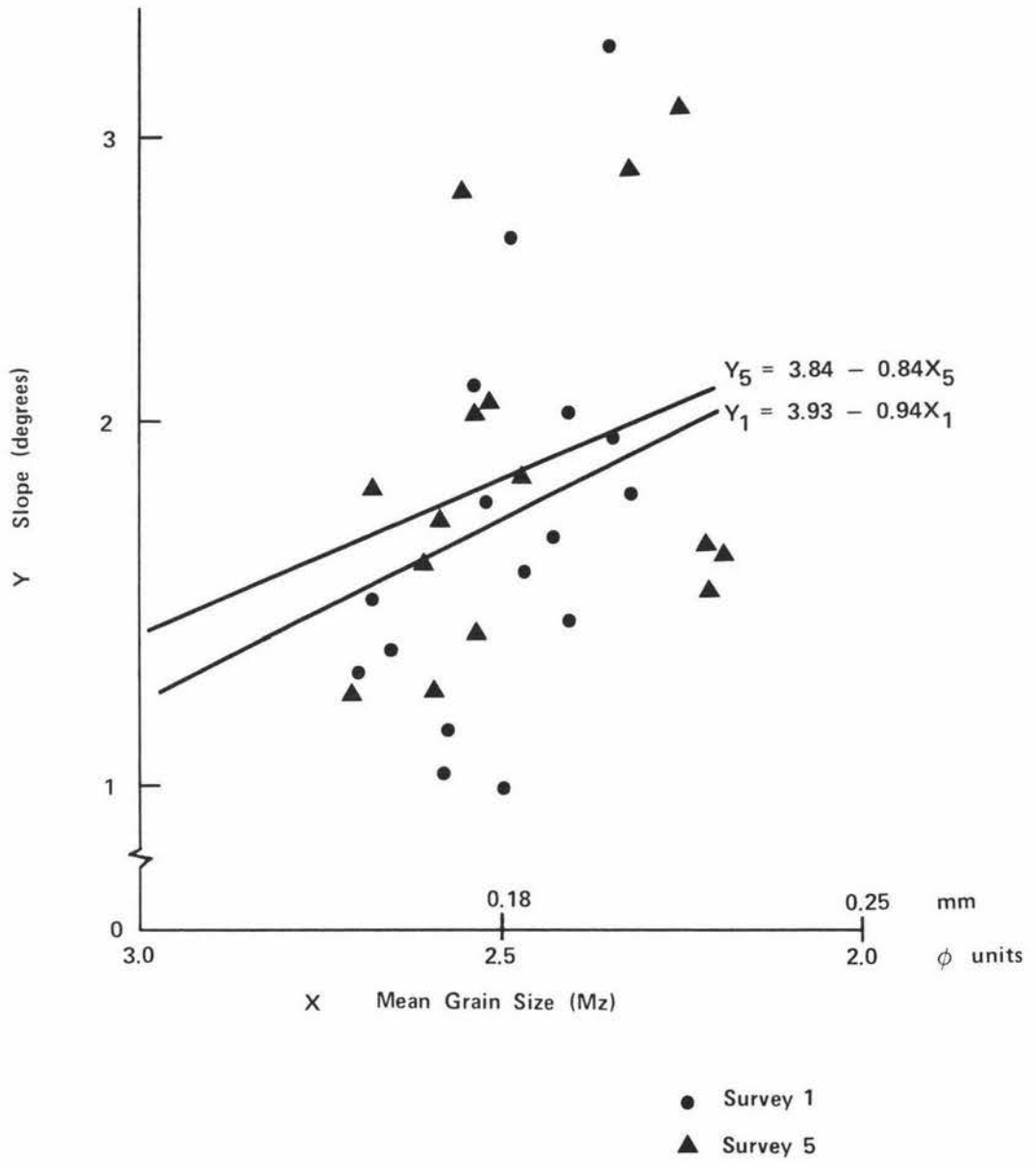


FIG. 19 THE RELATIONSHIP BETWEEN MEAN GRAIN SIZE (Mz) AND BEACH FORESHORE SLOPE



TABLE IX: Statistics, tests of hypotheses and estimates of population parameters for slope and grain size regression analysis.<sup>8</sup>

	N	$\bar{X}$	$\bar{Y}$	SSX <sup>2</sup>	SSY <sup>2</sup>	SSXY	a	b
Survey 1	17	2.40	1.67	2.77	5.92	-2.60	-0.58	-0.94
Survey 5	15	2.47	1.76	0.44	3.62	-0.37	-0.32	-0.84

	r	$\hat{\sigma}_{Y.X}$	B 95% limits	B 99% limits	Ho:B=0 Decis.
Survey 1	-0.64	0.23	-1.56 to -0.32	-1.79 to -0.09	RR
Survey 5	-0.26	0.26	-1.40 to -0.28	-1.62 to -0.06	RR

RR = reject at 1% level  
 $\hat{\sigma}_{Y.X}^2$  = standard error of the mean

Other symbols and formulae defined in Krumbein and Graybill, 1965, Chapter 10, esp. p. 230.

Relative to the average trend between foreshore slope and mean grain size identified by Shepard (1963), the study beaches are of a more gentle slope. The beaches of the South Canterbury Bight were shown by Kirk (1967) to exhibit the same characteristic. This feature is thought to be a result of the study beaches being in equilibrium with a moderate-to-high wave energy environment, which exhibits no major seasonal variations. This hypothesis is in part confirmed by a t-test performed on the change in foreshore slope, measured in degrees, occurring at each station for surveys 1 and 5. The hypothesis that no change in foreshore slope occurred at each station for the two survey periods was not rejected, at the five per cent level of significance.

3.34 Summary

There is a great variety of beach morphology along the coast, and no simple gradation in profile type exists. The widest profiles occur in the central section of the coast, and it is suggested that this reflects the continued seaward extension of the beach and growth of dune formations. The steepest profiles are located in the vicinity of the Otaki river mouth and contain the coarsest material. Rapid longshore change in profile form occurs in the vicinity of Kapiti Island due to the island regulating the level of wave activity in its lee.

With respect to volumetric change, most sections of the coast experienced winter accretion and spring erosion. This pattern was reversed only at the four southernmost stations, which suggests that a more detailed study in this district might prove fruitful. The greatest volumetric changes, both in magnitude and depth per unit length of profile, occurred at the central section of the coast. The seasonal change from winter accretion to spring erosion was found to be related in part to an increase in stronger onshore winds from the west and northwest during spring.

The relationship between foreshore slope, mean grain size and the degree of sorting for the sand beaches indicated that foreshore slopes increased with mean grain size, but that the degree of sorting correlated poorly with the former.<sup>8</sup> The higher correlation between slope and grain size for survey 1 was considered to be a result of the greater variation in beach conditions operating along the coast during survey 5, although the mean

standard error of the Y-variable was similar for each regression line.

The low foreshore gradient for a given grain size, added to the fact that the foreshore slopes showed no statistically significant changes between the two surveys, suggests that the majority of profiles are in equilibrium with a moderate-to-high wave energy environment which exhibits no marked seasonal variation, but which may vary within the respective calendar seasons.

Notes

- 1 On either side of the Otaki river mouth material - including boulders and cobbles - has been built into a storm ridge three metres above mean sea level.
- 2 The Tukey w-procedure was preferred here because of the large number of comparisons that were to be made. Torrie and Steel (p. 110) state that in this procedure the total experiment is the unit used in stating the number of errors of the type where an observed error is falsely declared to be significant. A 5 per cent test, then, is one where 5 per cent of a large number of repeated experiments will give one or more falsely significant differences when the means are a homogenous set. A disadvantage of this procedure would seem to be the increased likelihood of a Type II error occurring. In this case, significant differences which actually occur may not be identified by the procedure.  
The t-test is applied later in section 3.26 where only a small number of comparisons - usually two - are to be made.
- 3 Beach profiles generally respond quickly to changes in the process elements. Harrison and Krumbein (1964) showed in an analysis of beach process variables that their influence was greatest after a time lag of eight to twelve hours.
- 4 King (1970) suggests that the short-term changes of beach profiles in response to variations in wave dimensions tend toward an equilibrium condition by means of negative feedback relationships.
- 5 The volumes given in cubic feet represent changes made on a one foot-wide strip across the profile. The scale is included to facilitate comparison of changes identified in previous beach research with those of this study. It can be shown that, on this basis, a change of one cubic metre is equivalent to a change of 10.76 cubic feet.
- 6 The standard error of the mean is the mean square deviation of sample points from the estimated regression line. The correlation coefficient indicates the proportionate importance of the variable in determining foreshore slope, while the standard error indicates the accuracy of the estimate of the independent variable. The lower the standard error, the more accurate is the estimate of the independent variable (Ezekiel and Fox, 1959:149-50).
- 7 Sample correlation coefficient was 0.01, to two decimal places.

- 8 The negative correlation coefficient does in fact represent an increase in slope with increasing mean grain size. This results from the definition of the Phi (  $\phi$  ) scale:

$$\phi = -\text{Log}_2 (D)$$

where D is the mean diameter  
in millimeters.

An increase in grain size therefore corresponds to a decrease in the  $\phi$  value.

4. RECENT COASTAL CHANGE

#### 4.1 Introduction

The west Wellington coast is often described as having experienced widespread progradation for an extended period as a result of an abundant supply of sediment from both onshore and offshore sources. Studies by Burgess (1971), Donnelley (1959), Finch (1947) and Fleming (1953), however, contain specific references to local retrogression, serious erosion having been reported by Donnelley for the Raumati district. A number of beaches have also been subject to erosion following a period of known accretion.

A review of both the nature and rate of coastal change between Nukumaru and Paekakariki is presented with particular mention being made of the southern beaches. The effects of erosion in the Raumati district are outlined and possible factors contributing to the problem are discussed and, where possible, evaluated.

#### 4.2 Coastal Change

Burgess describes the coastline between Nukumaru and the Wanganui river as being characterised by high cliffs of often unconsolidated Nukumaruan siltstones and sandstones, whose resistance increases to the north. He notes that in some areas debris slopes at the base of the cliffs, augmented by wind-blown sand, protect the cliffs from being undermined during periods of storm wave activity. Rapid cliff erosion has been caused by the

Okehu stream flowing parallel to the cliff-line and removing this buffer zone. A similar situation has been observed by the writer at the mouth of the Kotiata stream.

South of the Wanganui river sandbanks and low foredunes support a narrow beach where little marked change has taken place. Between the Whangaehu and Rangitikei rivers the beach has prograded - approximately 200 feet in the eighty years previous to 1948 near the Fusilier wreck at Santoft (Adkin, 1948). From local conditions Adkin also infers that the Waitarere beach has advanced for the past 600-800 years.<sup>1</sup>

It is possible that progradation has continued throughout this period of time as the plan of the coast moves outward towards an equilibrium form (Hoyle and King, 1958). The profiles along this section have been shown to be wide, and of a gentle gradient. Such profiles offer the best resistance to erosion, and are indicative of a prograding coastline (King, 1959).

In a study of the section of beach extending from Otaki to Paekakariki Donnelley established that change from a period of general beach accretion to one of pronounced local erosion had taken place. The following data are reproduced from Donnelley's report.

Survey plans indicate three chains of accretion between 1897 and 1937 at Otaki Beach. To the south at Kenakena Point, a series of survey plans reveals a total of eight chains of accretion for the same period, at an average rate of eight feet per annum. The scale of accretion decreases south of Kenakena



Point to be nil at Kapiti for the period 1870-1930.

During the period 1930-1957 up to three chains of erosion occurred along a two and a half mile front between Paraparaumu and Raumati. In the decade prior to 1957, erosion spread northwards to north of the Waikanae river and southwards to Paekakariki - a coastal strip ten miles in length.

Since Donnelley's report erosion has been restricted to south of Paraparaumu, and is now most serious on a local scale south of the Wharemauku stream (S. Ellen, pers. comm.).<sup>2</sup>

#### 4.3 Effects of Erosion near Raumati

Coastal erosion in the Raumati and Paekakariki districts has caused a severe loss in beach frontage and necessitated the removal of houses from some sections. In the past (1971-72) financial year expenditure on coastal protection work by the Hutt County Council amounted to \$6,300, while that for the private sector would be much greater (S. Ellen, pers. comm.).

Coddington (1972) considers that erosion along these beaches is possibly connected with shoaling within Porirua Harbour. In addition, long-term development of 'The Golden Coast'<sup>3</sup> may involve the construction of a marina for aquatic recreational purposes. Such a construction, or the placement of groynes across the foreshore, may severely inhibit the longshore movement of sediment which nourishes the southernmost beaches. The present form of the cusped foreland may already be interrupting this

necessary southward movement of material. For these and other reasons an understanding of the factors involved in initiating and/or maintaining erosion in this district is required.

#### 4.4 Erosion Factors

Figure 20 indicates the nature of interaction between the major elements of a general erosion model for the southern beaches. Some sediment source and sink areas may actually lie outside the Waikanae-Paekakariki district; for example the supply of material from the Otaki and other rivers further north via littoral drift, and the role of Porirua Harbour as a sediment sink.

The elements are discussed under the following headings: sub-aerial beach conditions; offshore conditions; energy factors; and sediment supply, deposition and removal.

##### 4.41 Sub-aerial Beach

A typical view of beach conditions near Raumati South is shown in Plate 2. For large sections of this beach there is a lack of debris at the base of the cliffed dunes, the backshore being almost entirely absent. The beach profile is narrow and gentle in gradient so that it lacks height above mean low water level. During high tides the upper swash limit often reaches the base of the unconsolidated dunes; the high foreshore water table causes swash and backwash energy to be maximised at the cliff base which in turn is undermined, causing caving.

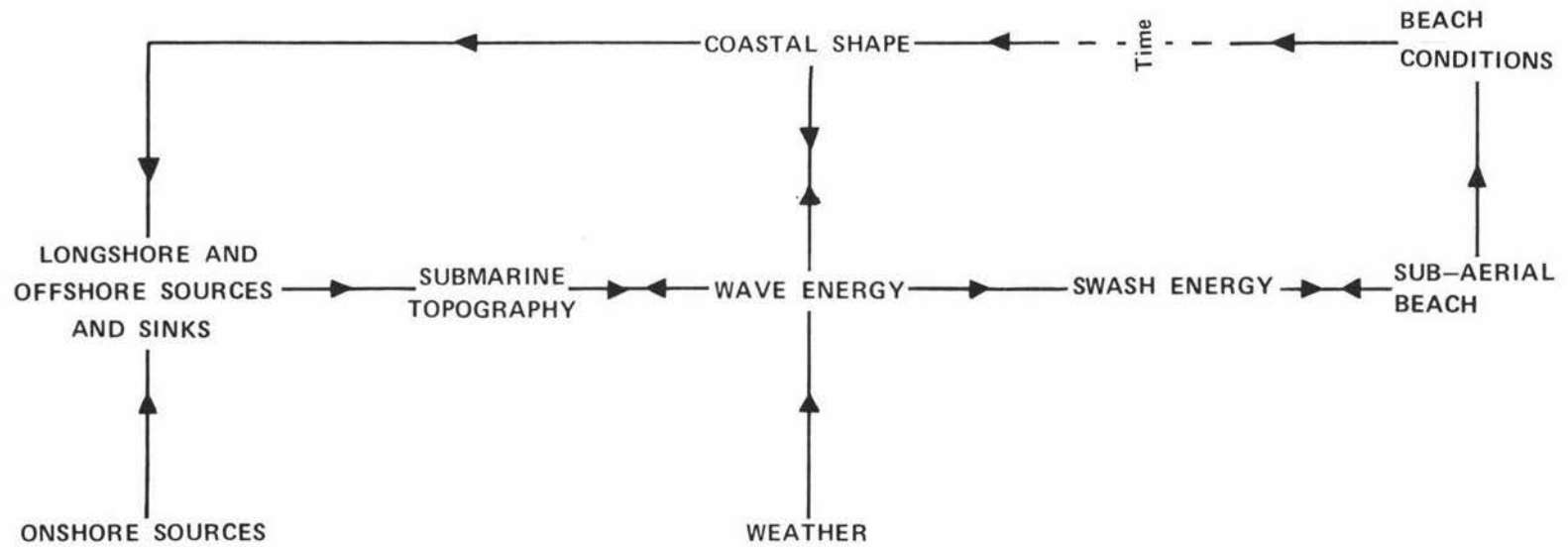


FIG. 20 NATURE OF INTERACTION BETWEEN MAJOR ELEMENTS OF A BEACH-EROSION MODEL



Plate 2: View of beach conditions, Raumati South.

Optimal conditions for erosion occur when strong onshore westerly winds and high energy wave trains coincide with spring tides.

#### 4.42 Offshore Conditions

Changes in submarine contours may be cyclic, sub-permanent or permanent. Cyclic or seasonal change has been discussed previously in section 3.31. The offshore bar acts as a reservoir for material removed from the beach during high energy conditions, from which material is returned to the beach by the action of constructive swell waves. Offshore shoals can also filter out particular waves, causing them to over-steepen and break prematurely (Oceanographic Services, 1970).

Donnelley identified a shoal half a mile offshore extending from Raumati to Paekakariki which had been progressively depleted during the years up to 1959. The migration of such an offshore deposit may be related to erosion at the foreshore, since the location of the belt of erosion has itself shifted over the past few decades. Without regular and accurate surveys of the changing bathymetry, however, it is difficult to evaluate the relationship between offshore changes and the incidence of erosion in this locality, although such a relationship has been suggested by Scott (1955) in an attempt to explain erosion at Sumner, near Christchurch.

## 4.43 Energy Considerations

In section 2.26 it was suggested that the symmetry of the cusped foreland in the lee of Kapiti Island was a consequence of the action of a prevailing west-northwesterly wave train. Because of the boundary limitations of Navy Office Chart No. 4631 it was not possible to construct a large-scale refraction diagram for such a wave train. A similar diagram could, however, be developed for a westerly wave train; the refraction pattern for this is shown in Figure 21. It can be seen that the greatest breaker heights, and energy per unit length of crest, occur to the south of Kapiti Island, where very little divergence of the orthogonals takes place. Ellen believes the greatest erosion is caused by waves arriving from this direction (pers. comm.).

The symmetry of the foreland also encourages the view that no one longshore current could act in isolation to create the present coastal plan. It is more likely that the littoral drift from the north has supplied material - rather than energy - for the development of the foreland, although it is possible that opposing currents meeting in the lee of Kapiti could contribute to its development. Convergence of longshore drift near Kapiti was observed during most of the field surveys.

A shift in the direction of approach of the dominant wave train, that is from northwest to west, could be responsible for the initiation of erosion to the south of Kapiti, but no evidence for the actual occurrence of such a change is available. The same effect could be caused by an increase in either the

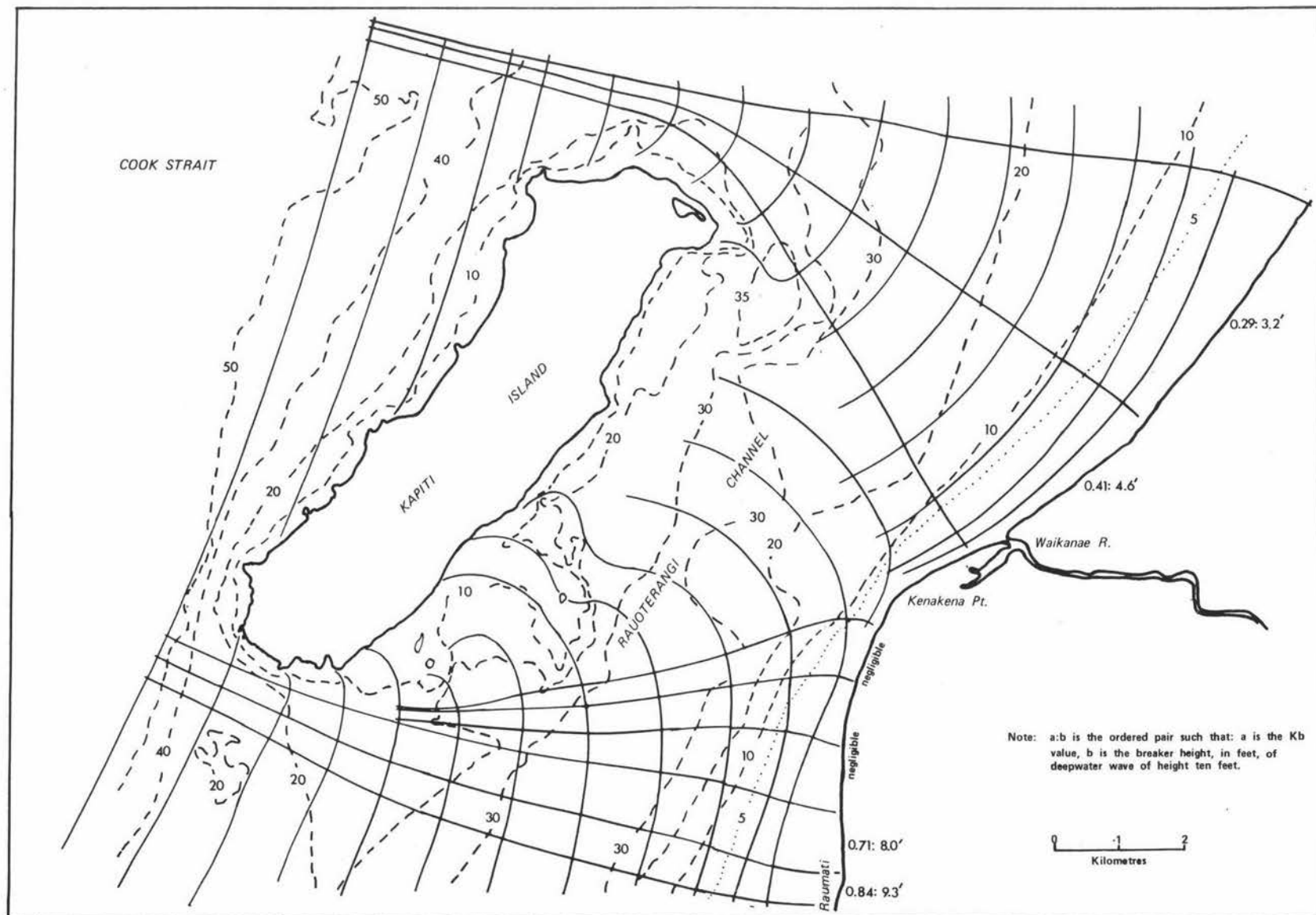


FIG. 21 REFRACTION OF WESTERLY WAVE TRAIN AROUND KAPITI ISLAND : PERIOD 10 SECONDS

frequency or intensity of destructive wave conditions, although again no relevant data have been collected in the area.

#### 4.44 Sediment Supply, Deposition and Depletion

The differential movement of sediment relative to a fixed set of coordinates determines the location of phases of accretion and erosion along a coastline. Changes on the beach itself may in time give rise to coastline change. The possible source (+) and sink (-) areas for sediment on the Waikanae-Paekakariki foreshore are shown in Figure 22.

The major input of material is that from littoral drift, especially that derived from the catchment of the Otaki river. Material is also discharged directly into the foreshore zone by the Waikanae river, along with that from the dunes and offshore sources.

Grant (1948) identified a positive relationship between the width of beaches along a mountainous coast in Southern California and the preceding winter rainfall. Although no detailed check of beach width is available, for recent years the local erosion has coincided with a reduction in the bed material of the Waikanae river and reduced runoff in the Tararua Ranges.<sup>4</sup>

The comparison of samples obtained from the foreshore and dune deposits suggests that the latter is not a major supplier of material retained on the foreshore. The finer dune deposits, however, may be a significant source for offshore sedimentation.



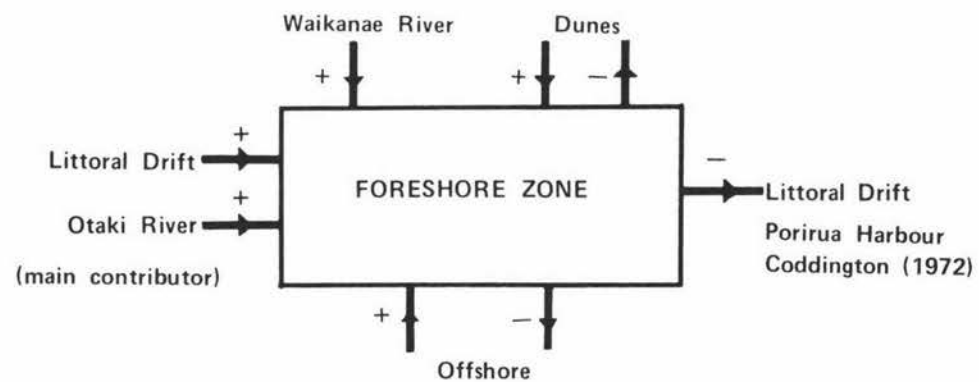


FIG. 22 SEDIMENT SOURCE-AND-SINK AREAS, WAIKANAЕ-PAEKAKARIKI  
FORESHORE ZONE

The re-cycling of sediment between the foreshore and dune areas has been previously referred to. The poor development of the backshore and foreshore berms south of Raumati indicates that little landward movement of materials is taking place, the only possible exception being to the north on the cusped foreland itself. The offshore zone is considered by the writer to be a sink, rather than a source, area for foreshore sediment. If no marked southerly drift occurs south of Paekakariki the long-term result of this trend would be an eventual recovery of the southern beaches.

It is possible that strong wave-induced currents from the south are depositing sediment, which has been removed from the southern beaches, on the cusped foreland. The rate of build-up of the cusped foreland is in the order of two to three feet in five years, or 750,000 cubic yards per year in volumetric terms (Coddington, 1972).

The possibility of a connection existing between erosion at Raumati and Paekakariki and shoaling in Porirua Harbour, as proposed by Coddington, is open to question - much depends upon the ability of current and wave energy to move sediment around Wairaka Point, west of Pukerua Bay. Refraction diagrams indicate that even waves from the northwest might oppose this flow of sediment. Its by-passing of Wairaka Point would therefore seem to rely on either a weak northerly wave train or drift or tidal currents, the latter being known to increase in strength near the narrows of Cook Strait.

Little data at present exist on the movement of sediment. It is suggested by the writer that the present incidence of erosion is associated with the continued seaward extension of the cusped foreland; it is proposed that the northern arc of the foreland has inhibited the direct movement of sediment onto the southern beaches. The foreland may be diverting the sand offshore, where it is remaining rather than being restored to the foreshores further south. The reasons for erosion at Raumati may be similar to those discussed by Scott (1955) for the Sumner Beach. Scott related the erosion at Sumner to an interaction between the growth of a spit and the migration of its associated submarine bar.

#### 4.5 Summary

It has been shown that the west Wellington coastline has undergone erosion at its extremities. While erosion to the north has occurred for at least the duration of human settlement, it is only since 1930 that erosion has been noted along the southern beaches. The concept of a continually prograding coastline is therefore valid for the central section only.

The problems caused by erosion near Kapiti Island have been accentuated by property development and the erection of houses on the foredunes. This has prevented natural fluctuation of the coastline about an equilibrium position.

A number of environmental factors have been discussed in terms of their possible relationship to the onset and maintenance of an erosion phase.

- (1) The absence of a well-developed profile, in terms of both length and height, allows the waves direct access to the poorly consolidated sand dunes. Undermining at the toe of the cliff causes it to collapse. Fallen debris which would otherwise protect the cliff from further collapse is rapidly removed from the foreshore.
- (2) Most damage appears to be caused by westerly wind and wave conditions, especially when these are augmented by spring tides. Longshore currents are responsible for introducing sediment into the area, but not for its redistribution within the area. The latter is thought to be a function of the currents induced by the refraction of waves around Kapiti Island.
- (3) The major source area for sediment is to the north, especially the catchment of the Otaki river. The writer considers that sediment is also moved by southerly wave trains towards Kenakena Point.

Coddington has proposed that material eroded from the Raumati beaches is being deposited in Porirua Harbour. If this is occurring, the boundaries of the west Wellington coastal system need to be extended. It has been shown, however, that sediment may be prevented from by-passing Wairaka Point.

It is suggested that the seaward extension of the cusped foreland may be instrumental in causing the southern beaches to remain 'under-nourished'. If so, the southern beaches may eventually recover as offshore sedimentation continues, but this is known to be a very slow process (Shepard, 1963).

The interaction of the energy and material variables has been shown to be complex, with large variations in conditions and processes over a restricted coastal area. An understanding of the present processes - especially those offshore - is handicapped by the absence of basic data, so that any attempted explanation is therefore tentative.

Without further basic research<sup>5</sup> it would seem premature to place any permanent obstruction to sediment movement along the coast, for the consequences are at present difficult to predict. The placement of groynes at the Paekakariki foreshore may also cause damage between Paekakariki and Kenakena Point, as sand is possibly moving northward from Paekakariki.

The present state of knowledge of the beach system between Paekakariki and Waikanae could perhaps best be increased by an intensive study of sand migration, in a manner similar to that outlined by Ingle (1966).

Notes

- 1 In a later (1951) article, however, Adkin states that no actual figures for the rate of advance are available. The provisional (1948) assumption of an annual rate of advance of two feet was adopted only as a 'conjectural approximation'.
- 2 Mr Ellen is the Paraparaumu Area Engineer for the Hutt County Council.
- 3 'The Golden Coast' is the popular name for the coastal region between Waikanae and Raumati.
- 4 "Because there has been substantially less rain in the Tararuas over the past three years the amount of river spoil has been reduced to the extent that the pillars ... of the ... rail bridge are now openly exposed."

Golden Coast News Shopper,  
1971, Sept. 15.

- 5 In a report to the Paraparaumu County Town Committee Mr Donnelley, the Hutt County Engineer, stated that erosion of the beach front at Raumati South had undermined the road and collapsed the stormwater outfall pipes. A Mr Parker suggested that an experimental wall be placed in the sea just south of Raumati South, using a method which had been successful in Britain.

Report of Paraparaumu County  
Town Committee Meeting.  
Golden Coast News Shopper,  
1972, April 19.

## 5. CONCLUSIONS

The specific findings of each major section have been discussed in summary sub-sections. This section is therefore confined to an assessment of the relative success of the research in fulfilling the aims set out in the Introduction, and in applying coastal research techniques.

The investigation has aimed at providing a suitable basis upon which further research along the west Wellington coastline may be based. Because of the previous lack of research south of the area treated by Burgess (1971) some of the results have consequently been of a descriptive, rather than explanatory, nature. The lack of recent local wave data was a major handicap, as the wave climate off Waipipi Point and Wanganui Harbour is not necessarily that operating near Kapiti Island. The problem was not overcome in any real sense by the monthly survey observations, and remains as a major handicap to long-term research.

An intensive study of the relationship between the wind regime and foreshore volumetric change may to some extent overcome this problem.

General trends in mean grain size variation, mineralogy, and foreshore volumetric change were identified, although for logistic reasons, and the need to maintain homogenous beach conditions during a given sampling, the sampling network was at times too coarse to be able to identify the rate of change in process or its effects. This was especially so in the vicinity of the Whangaehu and Otaki rivers due to the rapid change in the great variety of sediment size available and the presence of large



cusps, and in the vicinity of Kapiti Island, where rapid change in coastal process occurred. Both of these features warrant research on a more intensive, local scale.

Because erosion in the Waikanae-Paekakariki district has been shown to be related to energy and sedimentological factors which have their origins outside that district, it is believed that this thesis provides a necessary context in which to view the problem.

Finally, the west Wellington coast itself has been discussed in the light of both New Zealand and overseas coastal literature. Notwithstanding its smooth outline in plan, the west Wellington coast is supplied from a number of source areas, each of which contribute a variety of sediment, in terms of both size and mineralogy. The consequent longshore pattern of beach sediment and morphology is by no means simple, and is further compounded by the variety of energy environments obtaining along the coast.

In recent years the coastline has registered accretion along the central segment only. Erosion remains a major problem in the Raumati district. These facts are contrary to the generally held view of a prograding west Wellington coastline.

APPENDICES

APPENDIX A

Formulae for the Computation of Grain Size Parameters

Graphic Mean ( $M_z$ ) :

$$M_z = \frac{16\phi + 50\phi + 84\phi}{3}$$

Inclusive Graphic Standard Deviation ( $\sigma_I$ ) :

$$\sigma_I = \frac{84\phi - 16\phi}{4} + \frac{95\phi - 5\phi}{6.6}$$

under 0.35 $\phi$ ,	very well sorted
0.35 $\phi$ to 0.5 $\phi$ ,	well sorted
0.51 $\phi$ to 0.7 $\phi$ ,	moderately well sorted
0.71 $\phi$ to 1.0 $\phi$ ,	moderately sorted
1.1 $\phi$ to 2.0 $\phi$ ,	poorly sorted
2.1 $\phi$ to 4.0 $\phi$ ,	very poorly sorted
over 4.0 $\phi$ ,	extremely poorly sorted

Inclusive Graphic Skewness ( $SK_I$ ) :

$$SK_I = \frac{16\phi + 84\phi - 2(50\phi)}{2(84\phi - 16\phi)} + \frac{5\phi + 95\phi - 2(50\phi)}{2(95\phi - 5\phi)}$$

from 1.0 to 0.30,	strongly fine skewed
0.29 to 0.10,	fine skewed
0.09 to -0.10,	near symmetrical
-0.11 to -0.29,	coarse skewed
-0.30 to -1.00,	strongly coarse skewed

Graphic Kurtosis ( $K_G$ ) :

$$K_G = \frac{95\phi - 5\phi}{2.44 (75\phi - 25\phi)}$$

under 0.67,	very platykurtic
0.67 to 0.90,	platykurtic
0.91 to 1.00,	mesokurtic
1.01 to 1.50,	leptokurtic
1.51 to 3.00,	very leptokurtic
over 3.00,	extremely leptokurtic.

APPENDIX B

Grain-Size Parameters

Numbers refer to sampling station, letters A, B, C refer to mid-tide, backshore and dune environments respectively. Letters U, L, denote surface and lower samples respectively.

Sample No.	$M_z$	$\sigma_I$	$SK_I$	$K_G$
SURVEY 1				
1A	2.47	0.39	-0.03	1.36
1B	2.61	0.39	0.04	1.02
2A	0.85	1.07	0.08	0.69
2B	2.21	0.56	-0.25	0.93
3A	1.85	0.50	0.21	1.01
3B	2.43	0.41	-0.22	1.26
4A	2.49	0.31	-0.16	1.11
4B	2.33	0.49	-0.08	1.21
5A	2.54	0.30	-0.11	1.04
5B	2.69	0.31	0.18	1.03
6A	2.35	0.40	-0.23	1.20
6B	2.41	0.39	-0.12	1.44
7A	2.43	0.38	0.07	1.34
7B	2.57	0.27	-0.17	1.69
8A	2.58	0.43	-0.19	1.00
8B	2.66	0.30	0.07	1.43
9A	2.32	0.47	-0.17	1.24
9B	2.74	0.24	0.31	1.24
10A	2.70	0.38	-0.09	1.39
10B	2.84	0.27	0.16	1.01
11A	2.41	0.53	-0.25	1.13
11B	2.82	0.30	0.07	0.92
12A	2.35	0.56	-0.41	1.08
12B	1.83	-0.53	0.05	1.15
13A	-1.06	2.63	0.22	0.72
13B	1.57	0.54	0.05	1.14
14A	-1.72	2.40	0.32	0.99
14B	1.62	0.37	0.04	1.19
15A	2.50	0.42	-0.10	1.29
15B	2.49	0.35	-0.14	0.95
16A	2.58	0.34	-0.10	1.10
16B	2.63	0.28	-0.32	0.87
17A	2.53	0.38	-0.31	1.38
17B	2.66	0.27	-0.04	1.01
18A	2.68	0.27	-0.11	1.12
18B	2.65	0.28	-0.08	1.05
19A	2.41	0.52	-0.33	1.35
19B	2.69	0.23	0.01	1.00
20A	2.66	0.42	-0.19	1.52
20B	2.80	0.24	-0.07	1.00

Sample No.	$M_z$	$\sigma_I$	$SK_I$	$K_G$
SURVEY 5				
1A	2.56	0.29	-0.01	1.10
1B	2.65	0.28	0.14	1.23
1C	2.36	0.51	-0.20	1.30
2A	2.26	0.47	-0.21	0.98
2B	2.17	0.55	-0.25	1.00
2C	2.38	0.46	-0.21	1.08
3C	2.17	0.60	-0.17	0.84
4A	2.20	0.51	-0.19	0.95
4B	2.42	0.44	-0.28	1.05
4C	2.14	0.53	-0.15	0.94
5A	2.54	0.28	-0.02	1.07
5B	2.66	0.28	-0.05	1.27
5C	2.62	0.30	0.02	0.94
6A	2.32	0.44	-0.21	1.10
6B	2.29	0.42	-0.20	1.33
6C	2.36	0.51	-0.05	1.04
7A	2.22	0.61	-0.38	1.12
7B	2.54	0.29	0.18	1.24
7C	2.47	0.35	-0.18	1.09
8A	2.60	0.29	-0.06	1.08
8B	2.77	0.27	0.10	0.85
8C	2.72	0.23	0.20	1.00
9A	2.61	0.27	-0.03	1.00
9B	2.72	0.24	0.19	1.11
9C	2.74	0.24	0.25	0.94
10A	2.71	0.26	0.19	1.12
10B	2.78	0.29	0.22	0.95
10C	2.81	0.27	0.22	1.11
11A	2.68	0.31	-0.08	1.43
11B	2.77	0.25	0.09	1.27
11C	2.75	0.27	0.09	1.23
12B	2.01	0.54	-0.10	0.96
12C	1.86	0.59	0.02	0.80
13AU	1.25	0.59	-0.08	1.10
13AL	0.11	0.91	0.11	1.09
13B	1.25	0.58	-0.16	1.28
13C	1.63	0.60	0.07	0.90
14AU	1.62	0.53	0.20	1.11
14AL	-0.24	1.82	-0.33	0.66
14B	1.37	0.34	0.21	1.25
14C	1.42	0.36	-0.02	0.97
15A	2.52	0.35	-0.02	1.12
15B	2.48	0.30	0.11	1.29
15C	2.65	0.27	-0.10	1.09
16A	2.59	0.27	0.03	1.05
16B	2.75	0.22	0.05	1.29
16C	2.76	0.29	0.13	1.17
17A	2.47	0.42	-0.27	1.32
17B	2.71	0.20	-0.09	1.12
17C	2.71	0.22	0.08	1.18
18A	2.54	0.47	-0.40	1.61
18B	2.69	0.24	-0.01	1.18
18C	2.55	0.31	-0.09	1.02

Sample No.	$M_z$	$\sigma_I$	$SK_I$	$K_G$
19B	2.67	0.26	-0.09	1.36
19C	2.59	0.29	-0.05	1.06
20A	2.22	0.77	-0.43	1.04
20B	2.79	0.23	0.11	1.32
20C	2.73	0.28	-0.02	1.21
21A	2.16	0.80	-0.42	0.87
22A	1.94	0.84	-0.31	0.84
22B	2.45	0.50	-0.42	1.08
22C	2.56	0.34	-0.11	1.23

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