EROSION OF THE WASHDYKE-SEADOWN LOWLAND COAST
- PAST, PRESENT AND FUTURE

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ABSTRACT

This thesis examines the coastal erosion phenomenon of the Washdyke-Seadown lowland coast. The area consists of 12.25 km of mixed sand-gravel beach between Dashing Rocks and the Opihi River Mouth. The coast is backed by a low-lying hinterland of fluvial origin. Erosion and sea flooding pose a hazard and are threatening many valuable assets. These include a substantial wildlife habitat, farmland, the Seadown drain, State Highway One, the main trunk railway line, and the Washdyke Industrial Estate.

A combination of historical, field and laboratory data were used in determining the morphological process and sedimentary characteristics of the area.

The beach is dominated by pebbly, moderately-poorly to very poorly sorted greywackes. Grain size was found to have decreased by 0.8 ϕ since 1978. Coarsest sediments are associated with construction works on the beach. Most sediment has been lost from the mid section of the beach since 1977 (-247 142 m^3). In this period the southern end of the Washdyke Barrier has gained 40 194 m^3 of sediment.

The hinterland is composed of typical lowland swamp deposits. It was found to contain gravel of sufficient size to be used on the beach. However, because of the gravels' oxidised character, its long term value to the beach may be limited.

Maximum coastal retreat recorded was -440 m at the southern end of the beach. Erosion decreased towards the Opihi River Mouth. This was due to the presence of stopbanks and net northerly drift of sediment feeding that end of the beach. The highest long term erosion rate found was -3.6 m.yr . This was considerably less than previous studies have indicated. If current rates of erosion persist the Washdyke Lagoon, Seadown Drain and remaining beach sediment will be lost in about 89 years, 36 years and 51 years respectively. These predictions were considered optimistic because they were based on linear extrapolation.

It was found that the unconfined Washdyke Barrier, and the stopbank controlled Seadown coast, behaved in different ways. The Washdyke Barrier has rotated and become very broad while the Seadown Coast has retreated parallel, confining the backshore against the stopbanks.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

This thesis addresses the erosion phenomenon of the Washdyke-Seadown lowland coast; a mixed sand-gravel beach at the southern terminus of the Canterbury Plains. The field area covers the area between Dashing Rocks-Smithfield Beach in the south west, to the Opihi River mouth to the north east. The area also includes the immediate hinterland backing the beach. Figure 1.1 shows the study area in relation to its surrounds.

It has been recognised since late last century (Timaru Herald, 2.5.1879, p.1) that this beach has a severe erosion problem. This is natural in origin but has been accelerated by the Timaru Harbour breakwater construction commencing in 1879. The erosion problem is due to a lack of sediment supply. This appears to be because there is no input from littoral drift from the south, as northerly drifting sediment is trapped behind the breakwater. This has been calculated to occur at a rate of 60,000 $m^3.yr^{-1}$ (Tierney, 1969; Tierney & Kirk, 1978). Also, there are no rivers to act as a major source. Therefore sediment must come from the hinterland to balance the sediment budget (Kirk, 1986, pers. comm.). The beach is orientated towards the south east (McLean, 1967) and the prevailing waves. Hence, besides erosion saltwater overtopping also presents a hazard (Plate 1.1).

The ongoing erosion has caused serious economic and

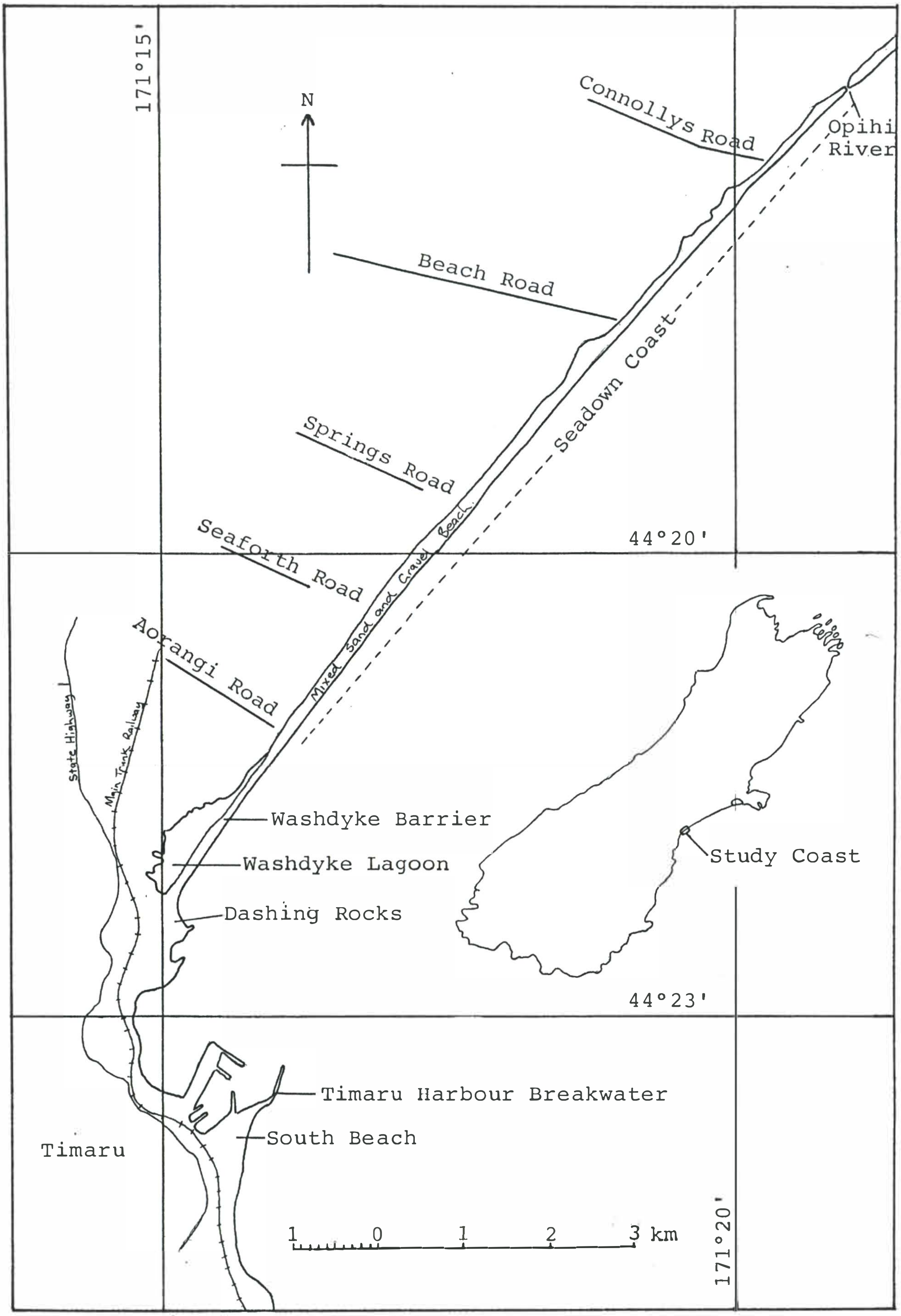


Figure 1.1 Location Map of the Study Coast

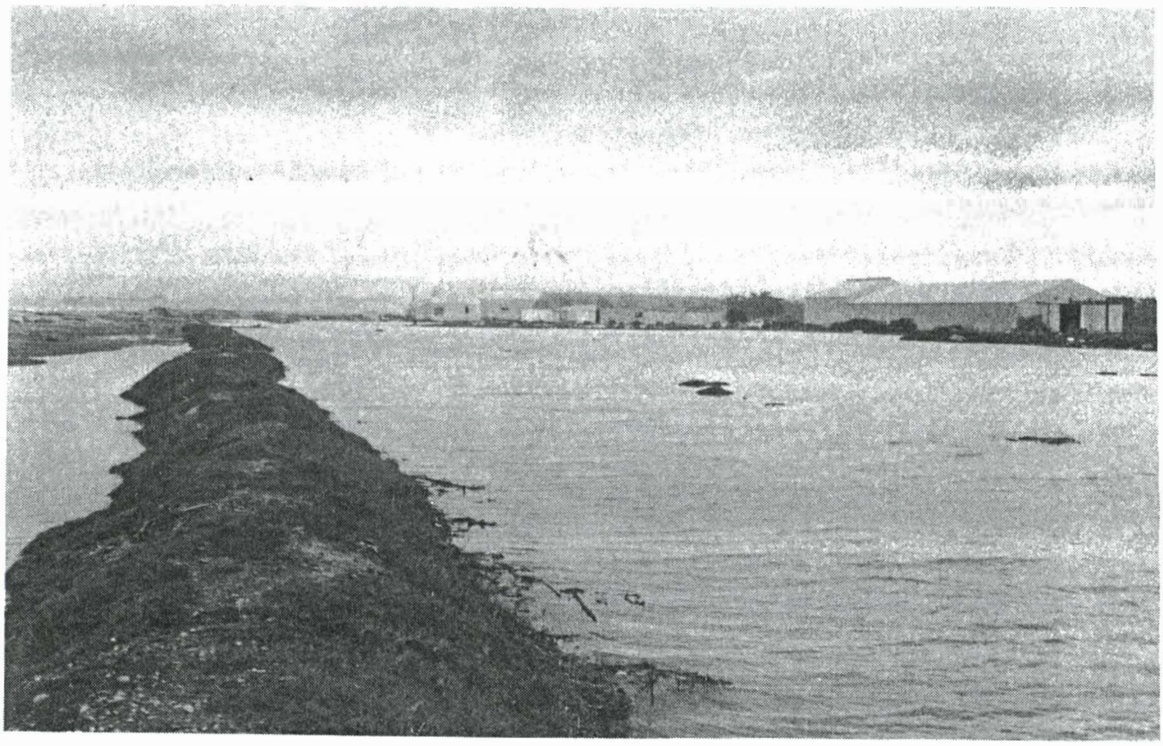


Plate 1.1 Seaflooding at Aorangi Road, 1.7.1986
(Source: D. Todd, S.C.C.B.)

social problems, as the Washdyke Lagoon - an important wildlife habitat, and many highly valuable assets are endangered. These assets include the main trunk railway, State Highway One, the Washdyke-Seadown drainage system, high class rural and industrial land, and the Washdyke industrial estate, with a 1986 capital value in excess of $23 million (South Canterbury Catchment Board, 1986, Application for G.A. 38 Grant).

Already the Timaru City sewerage outlet has had to be replaced at a cost of $20 million (Binney, 1987, pers. comm., Plate 1.2), stopbanks have had to be frequently replaced, and much high quality farmland to the north has been lost this century (McIntyre, 1958).

Actions in response to the coastal erosion are being undertaken. The South Canterbury Catchment Board has relocated its drainage system to a zone predicted to be safe for thirty years. The board has also been running an intensive survey programme of the area since 1977. Surveying is on a regular three monthly basis, and after each coastal storm the beach is resurveyed to note the severity of damage to the beach and stopbanks.

The Timaru City Council has formed an inter-agency committee governing Washdyke, installed planning restrictions around certain areas at Washdyke, experimented with beach renourishment, and has incorporated new design aspects for the city's new sewer outfall.

1.2 PREVIOUS STUDIES

In recent years much work has been done around the area between South Beach and the Washdyke Lagoon examining

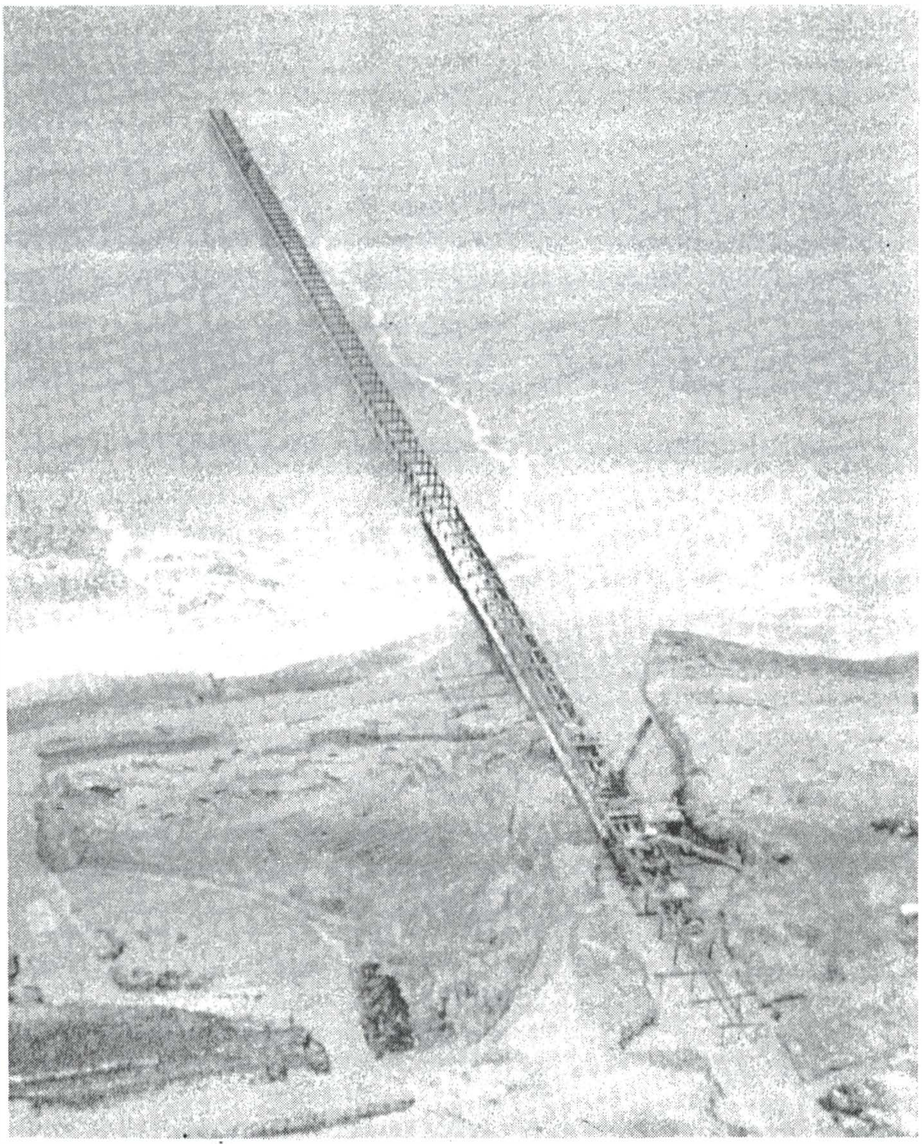


Plate 1.2 Construction of the New Sewage Outfall, Seaforth Road
(Source: D. Todd, S.C.C.B.)

coastal changes (Kirk, 1967; Hastie, 1982, 1983; Kirk 1982; Kirk & Weaver, 1985, etc.). However previous work is descriptive in nature regarding coastal changes and is orientated towards specific projects such as the new sewerage scheme and drain location.

The two most significant works regarding morphology, sediment and processes along the beach in question are those of Kirk(1967) and van Mechelen (1978). Kirk (1967) included the field area as part of a wider study, examining the whole of the Canterbury Bight. Van Mechelen (1978) concentrated his erosion study along the Smithfield-Opihi beach, hence his work can be viewed as the most detailed to date of the area.

1.3 PURPOSE OF THE INVESTIGATION

Zenkovich (1967) observed that mixed beaches, composed of sand and gravel, were relatively rare on a world scale and that they were more complex in process and form than either pure sand or pure gravel beaches. However, they are common along the east coast of the South Island (Kirk, 1980). It was also noted by Kirk (1980, p.189) that "... the literature of mixed beaches is quite small so that neither their typical morphologies nor their apparently complex dynamics are widely known". This general lack of knowledge (combined with the specific problems of the field area) provided the opportunity to carry out a geographical and scientific study of a retrograding mixed sand-gravel beach.

There are considerable deficiencies of information relating to the sediment budget for the coastal stretch concerned, as little work detailing this has been carried out. This lack of knowledge concerns facts about the thickness and distribution of the remaining beach sediments, and how long they will remain on the beach. A detailed account of sediment distribution within the hinterland is also lacking. These factors are of fundamental importance in relation to the coastal problem, as once the remaining beach sediments are removed, coastal erosion can be expected to accelerate the rates depending on the sediment structure of the hinterland.

It is apparent from previous work that erosion rates are highest along Washdyke Barrier and decrease towards the Opihi River (van Mechelen, 1978; Kirk, 1979, 1982). However, rates of erosion presented in the literature are highly variable. For example, the rates given for the Washdyke Barrier range between approximately 4.3 $m.yr^{-1}$ to over 9.0 $m.yr^{-1}$ (van Mechelen, 1978; Kirk, 1982). This variation makes prediction of coastal change difficult. Besides Kirk (1979), no attempts have been made to predict the future positions of the study beach.

It extends from a consideration of both the background and previous studies given, that the thesis aims to determine the following:

(1) to describe the characteristics of the field area, paying particular attention to

a) general morphological characteristics,

b) the volume and sediments of the beach system,

c) the characteristics of the sediments comprising the beach's hinterland,

d) past and present erosion trends of the beach.

(2) to predict likely future coastal erosion and its impact.

(3) to provide information useful for future management of the area.

(4) to add to the knowledge of mixed sand-gravel beaches.

1.4 THESIS APPROACH

In examining coastal erosion three approaches were adopted. The first was to collect and analyse readily available historical data. This included old maps, surveys, aerial photographs, newspaper articles and reports from previous investigations. This was necessary to detect what information was available and what specific areas of research had been undertaken. Unfortunately, historical records were not continuous. Large gaps in information were found. These particularly related to maps and surveys of the area between the 1865 survey and the 1934 aerial photographs. Kirk (1987) also observed a lack of storm recordings between 1929 and 1962. Adding to this problem, much of the historical information could not be used with confidence. For example, many old maps of the Timaru surrounds showed little detail of the Washdyke Lagoon area, particularly in the accurate positioning of the Washdyke Barrier. Hence some sources of information were unreliable. A knowledge of historical erosion trends is essential as this provides a sound foundation to develop a better understanding of present processes.

Secondly, field observations and laboratory analysis contributed to the understanding of the present coastal processes. Field work included profile surveying, excavating the beach, current tracer experiments and sediment sample collection. Figure 1.2 shows specific profile localities addressed in the text. Profile names given are those used by the South Canterbury Catchment Board. The numbers for Washdyke 200 to 2302 refer to metres along the barrier from the first survey peg near Dashing Rocks. Opihi 01S000 to Smithfield 06S1225 refers to the profile number, and how many kilometres south of the Opihi Rover mouth it is located. Throughout the text, the Washdyke Profiles, the two Smithfield Profiles (06S1225, and 06S1205), and Opihi 01S000 will be named in full. This is to clarify the difference between each profile, and in the case of Opihi 01S000, to tell it apart from the Opihi River or Opihi River mouth. Other profiles will be called by their name only (e.g. Aorangi Road).

The laboratory work was primarily concerned with the analysis of sediment characteristics. The results from this analysis are then used to infer sediment transport directions along the coast.

The final approach was to combine all the data collected to present an erosional history of the coast and to predict future positions of the shoreline. Once the major trends of erosion have been addressed, a more confident approach can be made into planning and management decisions affecting the area.

1.5 THESIS FORMAT

The succeeding chapters discuss the morphology, sediments and processes of the field area. The thesis is set out

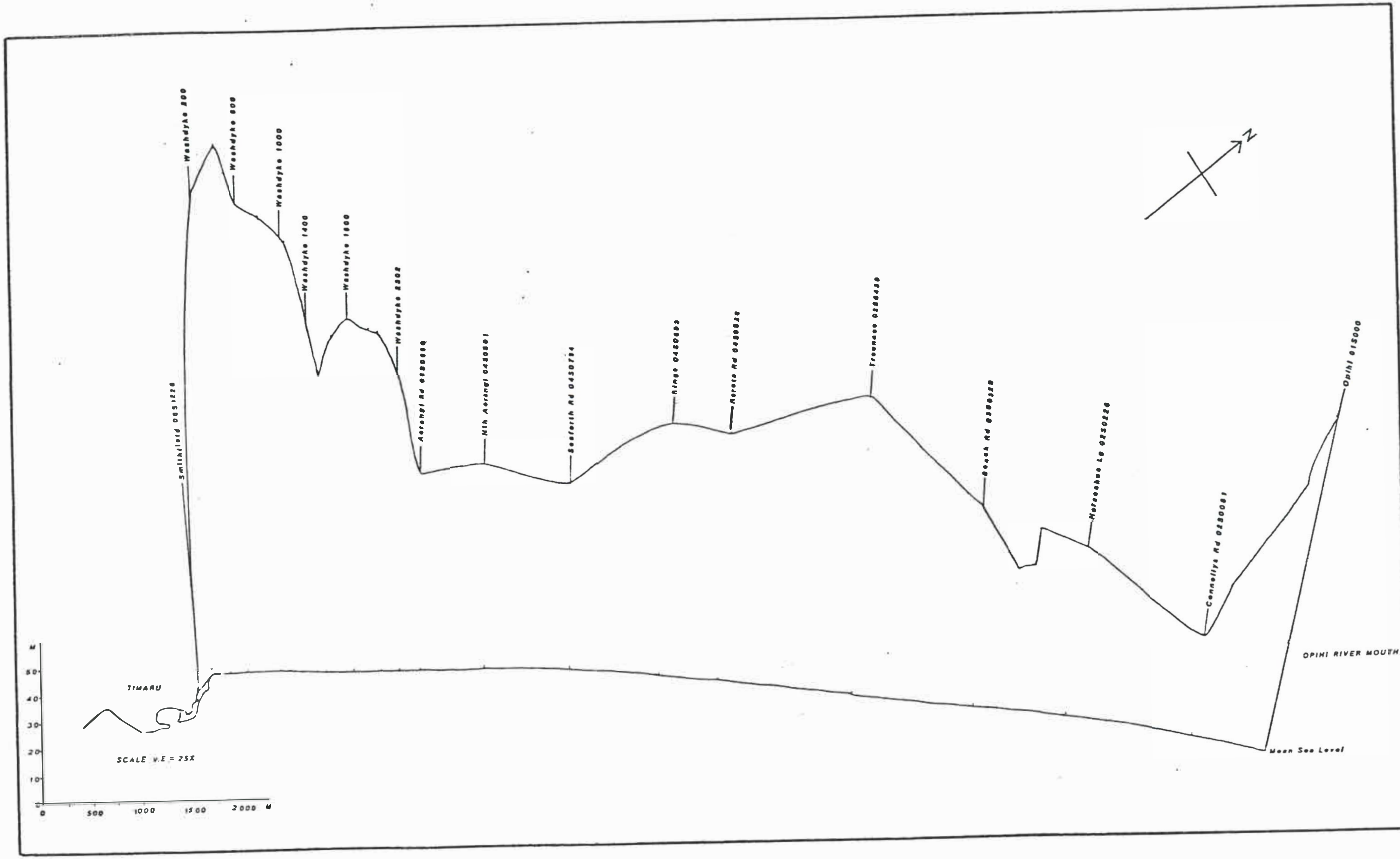


Figure 1.2 Profile Localities Named in Text

so Chapters Two to Five build a base to enable future predictions to be made in Chapter Six. Chapter Two provides a foundation for the following chapters by presenting a concise geological history of the area, a description of its major morphological features, and an examination of the present beach setting.

The next two chapters deal with present sediments on the beach. Chapter Three presents the results of a substantial sediment survey, defining the present characteristics of the beach sediment, and their spatial distribution. Processes responsible for this character are examined, as it is the local wave energy that removes and redistributes sediment along the coast. Survey data from 1977 (South Canterbury Catchment Board survey data) to 1987 are used to calculate beach sediment budgets in Chapter Four, emphasising the distribution of the sediment volume. This is primarily to determine where erosion is most likely to occur, due to a lack of sediment.

Having analysed the beach sediment characteristics and volume, the hinterland sediments are examined in Chapter Five. This is to establish what potential the hinterland has as a sediment supply for the beach in the future.

Chapter Six correlates information from the preceding chapters to detect past erosion trends, and to predict future positions of the coast. Emphasis is placed on the life span of the Washdyke Lagoon and the Seadown drainage network, as these are the two major assets that will succumb to erosion first. The final chapter presents a summary of the main findings and their implications. In addition to these, future recommendations are forwarded.

CHAPTER 2

GENERAL SETTING OF THE STUDY AREA AND ITS MORPHOLOGY

2.1 INTRODUCTION

The purpose of this chapter is to provide a background of the main features of the field site. This is to inform the reader of the major morphological features that occur throughout the text. A concise geological history of the Canterbury Plains will be given, followed by an account of general mixed sand-gravel beach morphology, found to be common along the South Island's east coast. This will lead to a broad description of the field area setting, followed by a more specific account of morphological features peculiar to the Smithfield-Opihi beach. Where applicable processes responsible for the development of these features will be discussed. It should be noted that this chapter draws largely on previous work, being supplemented by findings from the present study.

2.2 GEOLOGICAL DEVELOPMENT OF THE CANTERBURY PLAINS (PLEISTOCENE - RECENT)

The present coast of the Canterbury Bight is geologically Recent (Kirk, 1969). The oldest feature on the study coast is Dashing Rocks - the basalt being erupted during the lower Pleistocene-Upper Pliocene (N.Z.G.S., sheet 20, 1964). The Plains, whose eastern edge form the present coast, were built by a combination of tectonic uplift and successive glaciations (Hardcastle, 1908; Oram, 1941). Dominant lithology of gravels comprising the plains are argillite and greywackes (Oram, 1941; N.Z.M.S., sheet 20, 1964; Kirk, 1967; van Mechelen, 1978). Suggate (1982) noted that the plains were composed largely of water worn fluvio-glacial gravels from the last glaciation - the Otiran. Fitzharris et al. (1982), state:

> "The plains are in fact a series of giant alluvial fans, built by the major rivers - the Rangitata, Rakaia and Waimakariri - during successive glaciations, when great quantities of gravel were poured into the river systems by the glaciers that occupied the mountain valleys."

The plains originally extended up to 50 km offshore and have been eroded into their present position by Holocene sea level rises. Thus, the eroded plain formed the present broad continental shelf of the Canterbury offshore region (Hardcastle, 1908; Kirk, 1967). Sea level is generally accepted to have been at a low point approximately 18,000 years ago, rising to its present level about 5000-7000 years before present (Kirk, 1967; Suggate, 1982). The eroding gravel coastal cliffs were shown by Kirk, Owens and Kelk (1977) to be the major supplier of beach gravels on the Canterbury Bight.

2.3 MORPHOLOGY OF THE STUDY AREA

2.3.1 The present setting of the Smithfield Opihi Beach

The study beach, comprised of mixed sand and gravel, is 12.25 km long and orientated towards the south east (McLean, 1967). The beach is bound to the south by Dashing Rocks, loess cliffs and the Washdyke Lagoon. For this study, the northern terminus is the Opihi River mouth, although Kirk

(1967) suggested the whole Canterbury Bight beach could be treated as a single entity. Between these two termini the beach is backed by a low-lying hinterland composed of fluvial, swampy deposits. The beach in plan shows very gentle concavity, except at Dashing Rocks where it changes direction to face nearly due east. Hence, the southern end is sharply curved.

North of the Opihi River, the coast is backed by gravel cliffs, whilst beyond Dashing Rocks in the south, are the Benvenue Cliffs, Caroline Bay and the Timaru Harbour construction. To the seaward the beach is fronted by the gentle sloping continental shelf, dominated by fine sandy sediments (Kirk, 1977a; Tierney & Kirk, 1978; Hastie, 1982, 1983).

2.3.2 Major Morphological Features

Dashing Rocks is the northern most finger of basaltic lava flow from Mt Horrible, about 16 km east of Timaru. This lava flow forms an abrupt southern headland terminus to the study beach, disrupting the continuity of the smooth curvature of the Canterbury Bight coastline. The present reef at Dashing Rocks is a relatively modern coastal feature. This can be determined by old maps, and the 1881 survey of the Washdyke Lagoon area (Figure 2.1). This map illustrates that the Washdyke Barrier forms a nearly continuous beach with the barrier of the now defunct Waimataitai Lagoon. Dashing Rocks forms a very small seaward intrusion. This contrasts strongly with more recent photographs (Plate 2.1). Thus, the modern Dashing Rocks Reef is approximately 100 years old. As the landward migration of the beach continues, the seaward

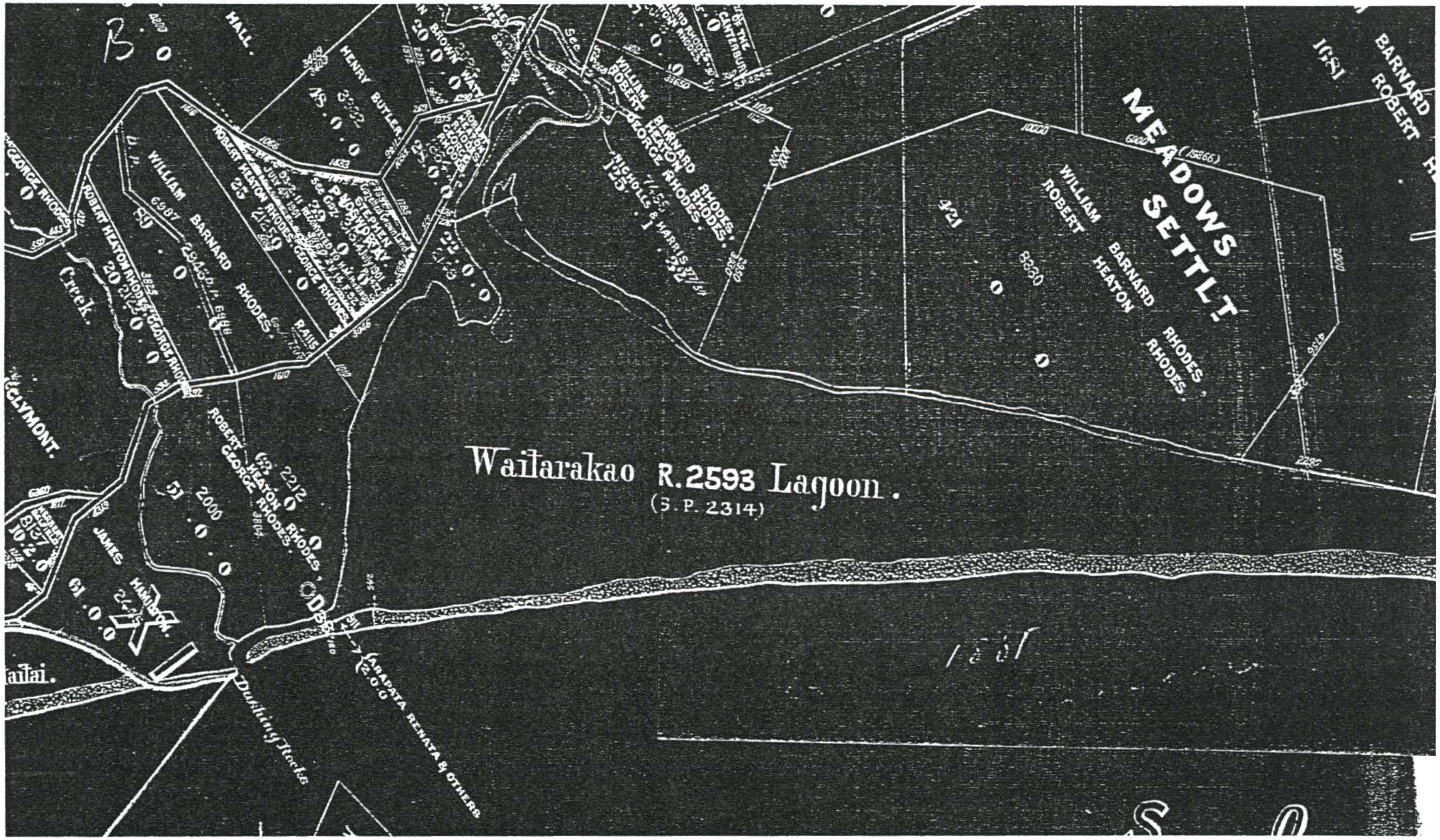


Figure 2.1 1881 Survey of Washdyke (Waitarakao) Lagoon.
Note Dashing Rocks to the Left

Plate 2.1 Dashing Rocks, looking South, March 1987.
Note: Timaru Harbour Breakwater is the line on the horizon

projection of the reef increases correspondingly.

The present surface of the reef is nearly horizontal, averaging 0.5 m above mean sea level (South Canterbury Catchment Board survey data). The surface is dominated by columnar jointing spaced approximately one metre apart. McIntyre (1958) suggested the basalt was approximately 4.0 ft (1.22 m) thick at the coast.

The exposure of Dashing Rocks in recent times has become a recreational asset for the Timaru area. During field work, the author noted numerous people fishing and collecting mussels. Several school parties were also observed examining rock pool life for nature and biology courses.

At present the water covered area of the Washdyke Lagoon covers approximately 36 ha. The lagoon is confined to the landward by a lowlying hinterland and to the seaward by a barrier beach. Sediments of the lagoon floor are typical of this type of environment, being composed of muds, silts and peats (Reineck & Singh, 1975). Interfingered with these fine sediments are gravels and coarse sand from washover lobes entering the lagoon. The Washdyke Lagoon is sub triangular in shape with an indentation at the top corner, formed by the Washdyke Creek delta.

The importance of the lagoon is two-fold. Firstly, along with its barrier beach, it provides a transition zone between intense wave energy and the lowlying hinterland. Secondly, it is one of the few remaining coastal wetlands in the vicinity and is recognised as an important wildlife sanctuary, by organisations such as the Department of Conservation, Department of the Environment and the Royal Forest and Bird Protection Society.

A unique morphological feature of the study coast is the remnants of a buried forest (Plate 2.2). The forest was seen to penetrate the beach surface between Connolly's Road and Aorangi Road, during field research. It is possibly an extension of forest remnants found inland at Arowhenua (Burrows, 1987, pers. comm.). Because of their uniformly upright aspect, strongly rooted nature and association with a soil rich substratum, the stumps are assumed to be in situ.

The forest was buried by fluvial sediments and has consequently been exposed by sea water inundation. If the exposed forest on the coast is the same as the inland Arowhenua forest, then its age is no older than 1000 years (Burrows, 1987, pers. comm.).

The species found on the beach are typical of present day lowland swamp forest. These include Totara, Kahikatea and Matai (Molloy, 1987, pers. comm.).

Todd (1983) identified the following features of the Opihi River mouth. Most of the lagoon is located on the northern side of the river, although some ponding occurs to the south (i.e. within the study area). Todd considered this pond to be a response of stopbanks blocking an old southerly channel. The area of the lagoon is decreasing due to coastal retreat, its present area being approximately 60 ha. Sediments on the lagoon floor are similar to those of the Washdyke Lagoon, being mainly sands and silts. Pebbles dominate the main channels. The river mouth is usually a single channel, running obliquely to the barrier beach. Its position can change rapidly or remain static for a long period, depending on the river flow conditions.

Plate 2.2 Buried Forest exposed at low tide, just south of Trounces, May 1987

The Milford Lagoon serves an important function as a recreational facility, primarily as one of New Zealand's major salmon fishing rivers. Many huts on the northern side are subjected to frequent flooding by the lagoon.

2.4 THE MIXED SAND-GRAVEL BEACH SYSTEM

2.4.1 Natural Features

The dynamics and morphologies of these mixed sand-gravel beaches have been documented by McLean (1970) and more comprehensively by Kirk (1980). McLean (1970, p.142) noted that all the major South Island, east coast mixed sand-gravel beaches have the following features in common:

"(1) They contain a wide range of sediment sizes (sand to boulders);

(2) They are derived from the same dominant rock type (greywacke);

(3) They are backed by Pleistocene and Holocene alluvial plains and fans often crossed by major rivers; and

(4) They are exposed to the high energy waves of an East Coast Swell Environment (Davis, 1964)."

To this, Kirk (1980) added that all of the east coast has a semi-diurnal tide and is meso-tidal, the spring tide range reaches a maximum of 2.5 metres. Figure 2.2 shows the typical morphology and zonation of mixed sand-gravel beach profiles, as illustrated by Kirk (1980, p.193). The main features displayed in this diagram are the steep near-shore face, the break point step and the sharp contrast between the mixed sand-gravel beach system and the fine sand nearshore bed. Also, Kirk (1980) suggested the Canterbury

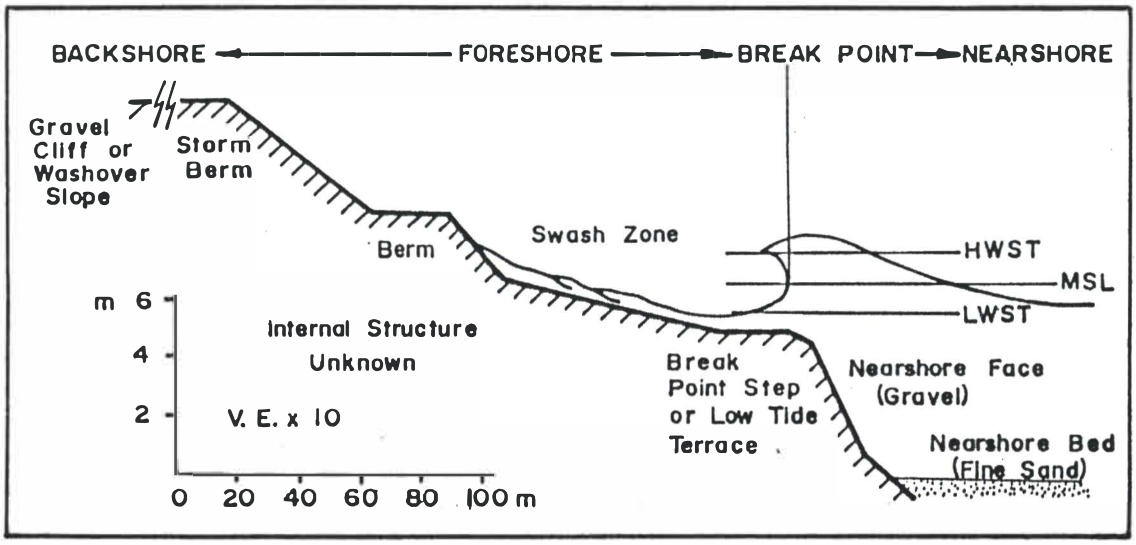


Figure 2.2 Typical Morphology and Zonation of Mixed Sand and Gravel Beach Profiles (source; Kirk 1980)

beaches were commonly between 100-200 m wide, with steep foreshore slopes ranging between 5°-12°. At cliff sites, storm berms were usually absent, with the foreshore being generally planar.

All of these features were found on the study beach. The average cross sectional width was approximately 120 m, with foreshore slopes ranging between 3.4° and 8.4°. Natural crest heights ranged between 3.66 m and 4.52 m. Artificial raising of the crest at the renourishment site, increased its height to over 6.0 m. On parts of the beach where stopbanks were acting like eroding cliffs, berms were usually, but not always absent.

Washover lobes are particularly common along the Washdyke Barrier and at Milford Lagoon (Opihi River Mouth). They also occur at intervening areas where stopbanks have been breached. The largest washover lobes are along the Washdyke Barrier. These washover lobes are steadily infilling the Washdyke Lagoon. During times of heavy seas when run up passes over the crest, sediment is eroded from the upper regions of the beach and deposited down the backshore slope. Washover commonly enters the lagoon (South Canterbury Catchment Board survey data).

Although washover lobes at Milford Lagoon have the potential to move across the low lagoon bed, they are generally smaller than those found at Washdyke Lagoon. This is because the landward tongues are regularly truncated by the migrating river mouth channels.

A notable difference found to the 'typical' morphology was that at three locations, the nearshore step appeared to be absent (Figure 2.3). Two possibilities could explain this.

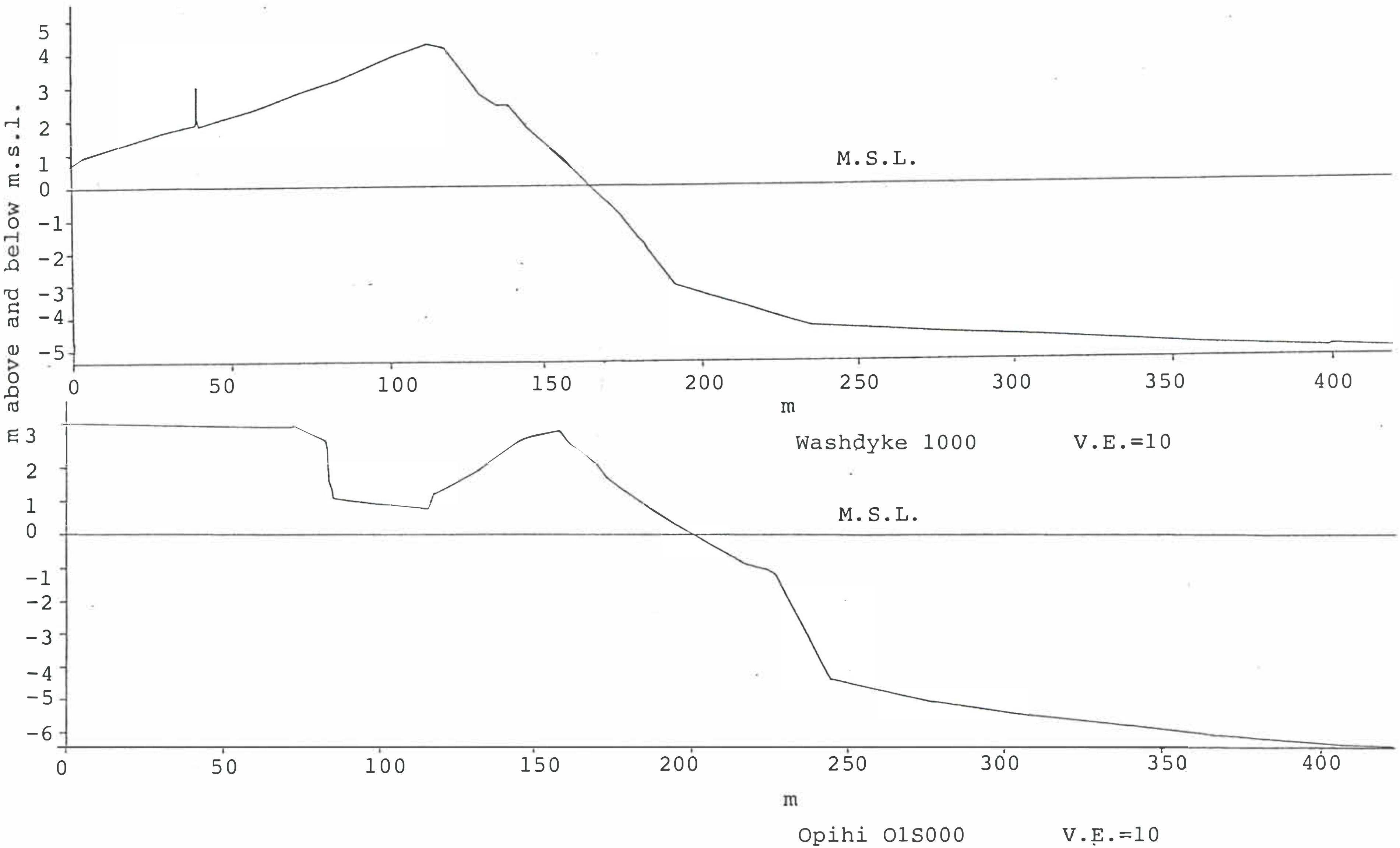


Figure 2.3 Comparison of Profiles With and Without the Nearshore Step

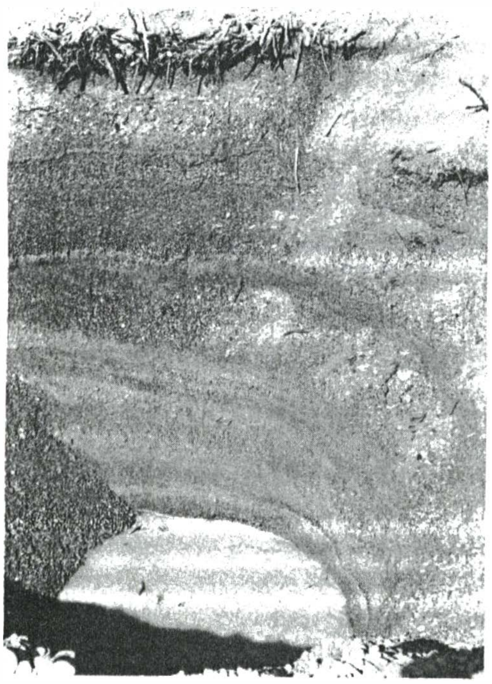
First, a real absence may occur. Alternatively, the nearshore step may have been present but not detected by the survey method used. Beach transects were taken as far seaward as possible at low tide, using an Electronic Distance Meter (E.D.M.). The Timaru Habour Board Divers held a prism attached to a six metre long pole and came landwards as far as possible. A survey gap ranging between approximately three and 50 metres was produced. Hence, the nearshore step may have been present within this gap. It was of interest that these profiles only occurred along the Washdyke Barrier, and were the only ones to contain gravels, derived from the beach on the sea floor. At the Washdyke 200 profile, distinctly lagoon type sediments were found on the seabed. Hence, if the nearshore step is absent, offshore transport may be encouraged at these sites.

The internal structure of coarse grained beaches is not widely known. Bluck (1967), Zenkovich (1967) and Humbert (1968) showed that sub horizontal bedding occurred. It was observed in the field area that the vertical structure of the beach varied with sediment thickness. It will be shown in Chapter Five that sediment thickness is influenced by the elevation of the substratum.

Four types of internal structure were found. In places of thin sediment cover, only gravel or sand was found. It has been noted by numerous writers (Marshall, 1929; Folk, 1965; Zenkovich, 1967), that fine material moves alongshore faster than coarse material. Thus, the coarse material was left as a lag deposit. This winnowing of fines is thought to occur commonly in places of thin sediment cover (Plate 2.3a). Because of the small distance between the


a


b


c


d

Plate 2.3 Internal Structure of the Beach

a) Thin cover of gravel, Seaforth Road (Source: D. Todd, S.C.C.B.)

b) Gravel concentrated on the surface, and sand below Opihi 01S000 backshore

c) Beds of sand and gravel, Washdyke 200 upper foreshore

d) Beds of sand and gravel, Opihi 01S000 foreshore beach surface and the impermeable substratum, the beach is readily saturated by swash-backwash. Hence fines are easily washed away, and deposited down drift. It was common to find adjacent patches of pure gravel and pure sand alongshore.

Thicker sediments are characterised by laminations of gravel and sand (Plate 2.3b-d). Elutriation and cusp migration are thought to develop these beds. Bluck (1967, p.132) observed:

> "The backwash of waves breaking on the porous frame travels through the gravel, rather than on the gravel surface and in its passage combs finer material seaward the size and shape of which depend upon the size and geometry of the gravel pore space: the gravel in this upper part of the beach therefore acts as a sieve on the infiltering particles."

Thus, elutriation is most likely to develop the structure shown in Plate 2.3b, where gravel is concentrated within the top few centimetres, underlain by sand.

Cusp migration is thought to produce the beds shown in Plate 2.3c,d. Mii (1958) demonstrated that cusps contained coarser material on the horns than in the bays. On the study beach, gravel was concentrated on the horns, and sand in the bays. It would be expected that as a cusp migrates down drift (Dolan, 1971), the depressed bays would become infilled with gravel from the horns. The result of this would be vertical alternation of gravel and sand beds caused by horizontal movement. This process is shown in Figure 2.4, and has been described in detail by Lauder (1987).

In the diagram it is suggested ... form alternating layers ... continuity ... is this the case?

2.4.2 Artificial Features

A review of stopbank and drain construction is given by Todd (1987). The main features of note are that stopbanking commenced in 1939 between the northern end of

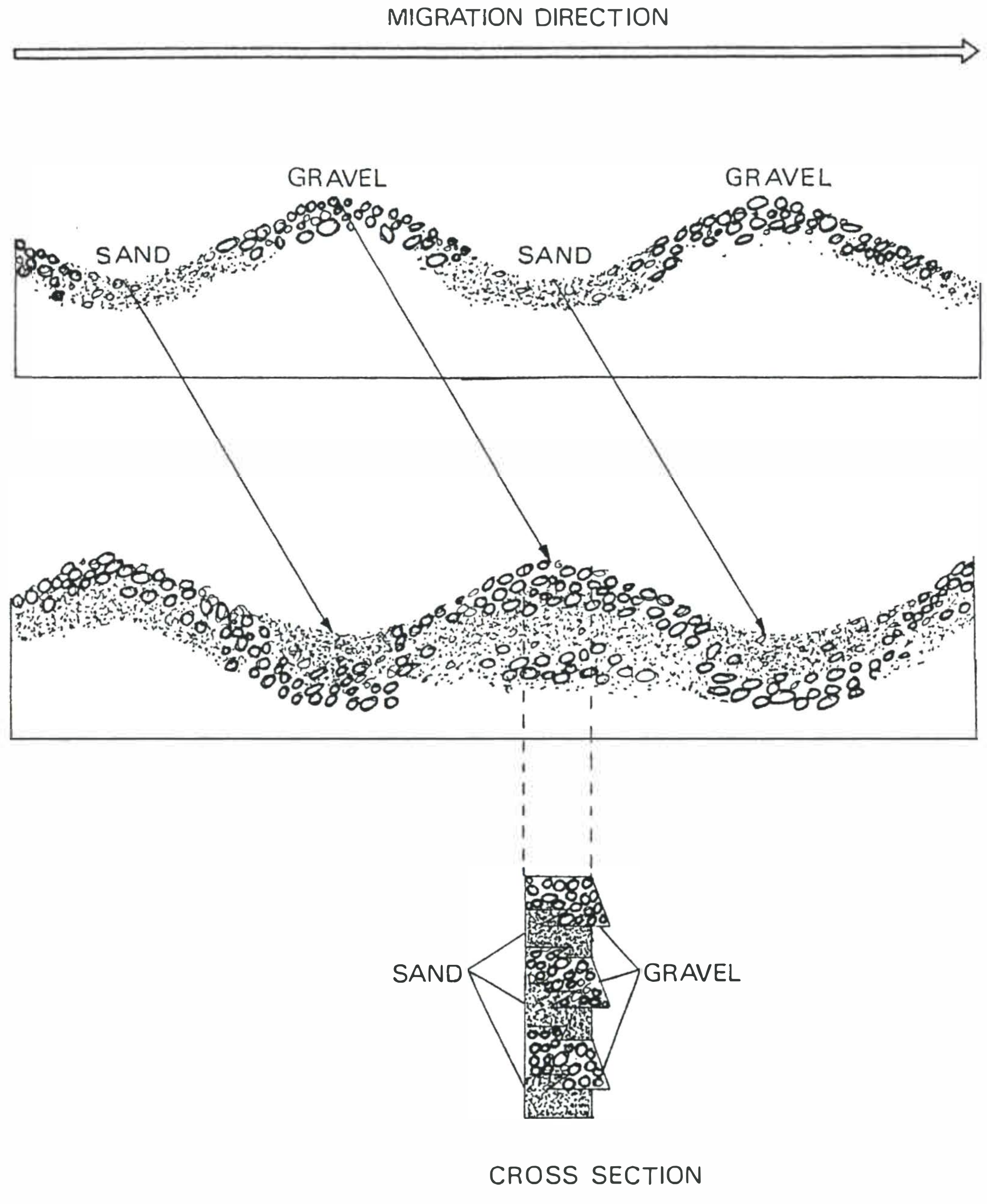


Figure 2.4 Development of Alternating Beds of Sand and Gravel Due to Cusp Migration

Washdyke Lagoon and Beach Road. The construction has been very erratic. New banks and drains have been placed further inland as pieces of the old ones were destroyed by the retrograding beach. Data collected from old surveys and aerial photographs were used to construct Map 1 (back cover). This map shows the dates and piecemeal approach for construction of the stopbank-drain system. In some places it can be seen that old stopbanks have been completely buried by the beach. This is further accentuated in Plate 2.4, showing a buried stopbank at Connolly's Road. Both intact and buried stopbanks are considered to influence the beach morphology. More will be said about this in Chapter Five.

The old Timaru City sewer outlet crosses the beach in a perpendicular fashion at Washdyke 1500 (Plate 2.5). The pipe was commissioned in 1966, with a designed life of 75 years (Todd, 1987, pers. comm.). Severe coastal retreat around the pipe meant that its operational life was far less than expected (21 years). A beach renourishment programme was undertaken in 1980 to stabilise the beach around the pipe, whilst a new offshore pipe was built at Seaforth Road (Kirk, 1982, Kirk & Weaver, 1985). The renourishment programme consisted of relocating 6600 m^3 of storm washover gravels from the backshore to the foreshore and crest. To this, 9800 m^3 of coaser gravels from the Opihi River were used to cap the structure (Kirk, 1982). Thus, the beach crest was raised by 2.0-2.5 m, reducing storm overtopping. Since all beach renourishment maintenance ceased in 1985 (Todd, 1987, pers. comm.), the structure has been severely eroded. At Washdyke 1400 and 1600, the crest has been lowered so overtopping can easily reoccur, whilst at Washdyke

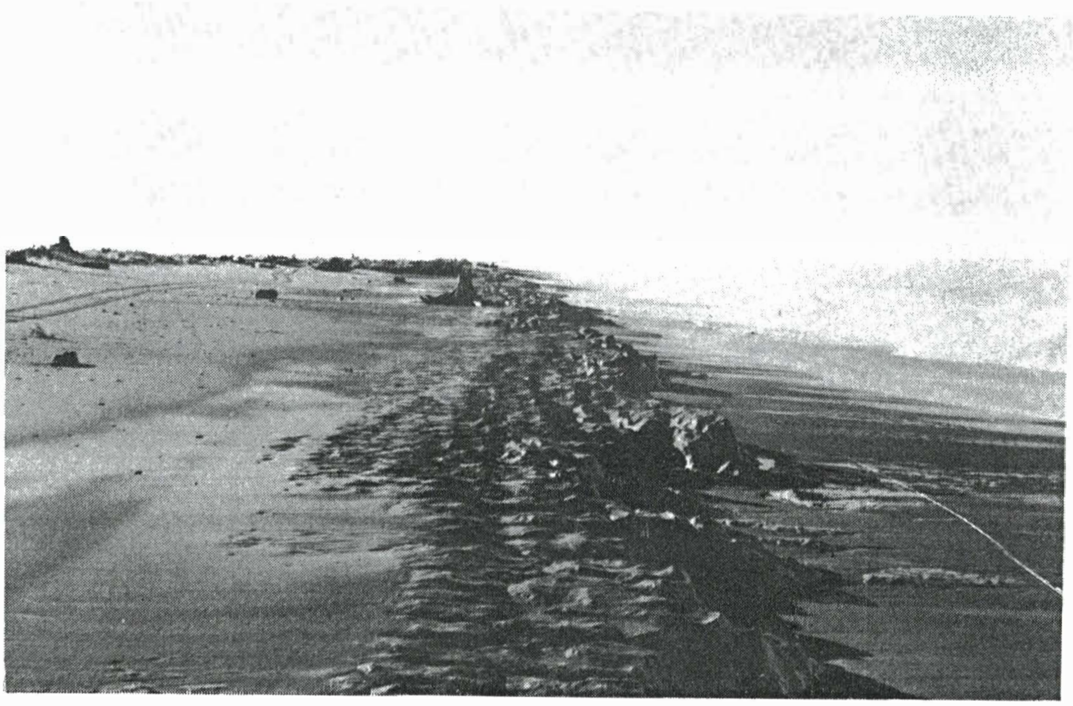


Plate 2.4 Stopbanks buried by Beach Sediments.
Connolly's Road
(Source: D. Todd, S.C.C.B.)

Plate 2.5 Old Timaru City Sewage Outfall. Washdyke 1500

1500, the erosion of the seaward faces has formed a vertical cliff (Plate 2.6).

2.5 CONCLUSION

The general characteristics of the study area have been discussed, covering a range of time scales. The study coast is geologically Recent in age. Sediments of the beach and hinterland plains are dominantly fluvio-glacial outwash gravels from the last glaciation. Present coastal morphology relates to Holocene sea level rise which has eroded the plains back to their present position and formed the broad continental shelf (Hardcastle, 1908; Kirk, 1967, 1969).

The major morphological features of the coast are Dashing Rocks, Washdyke and Milford Lagoons, and the buried forest. Dashing Rocks, a basaltic shore platform, is the oldest feature of the area, being about 2×10^{-6} m.a. The Washdyke and Milford Lagoons are both decreasing in size. Both of these lagoons serve important social and environmental functions. The Milford Lagoon is a prime recreation locality with many huts surrounding its edge, and the Washdyke Lagoon is an important wildlife sanctuary. The barrier beach also protects the major assets to the landward of the lagoon.

A buried lowland swamp forest approximately 1000 years in age stretches for most of the field site. The forest has been buried by fluvial sediments and subsequently exposed by coastal erosion. It is considered part of an ancient forest found further inland.

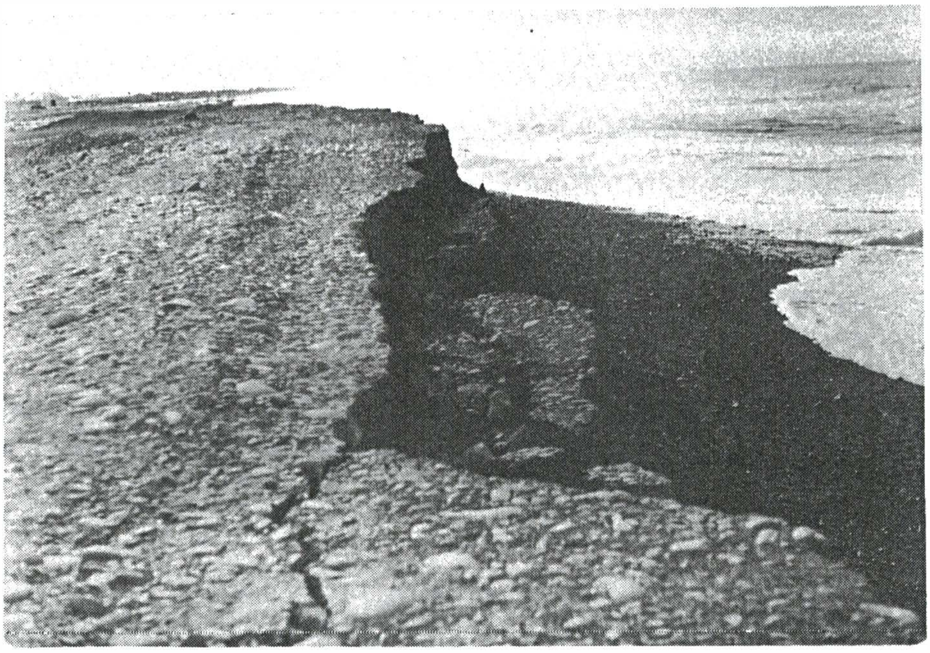


Plate 2.6 Erosion of the Renourishment Structure.
Washdyke 1500

The beach contains all of the "typical morphological features" of mixed sand-gravel beaches. These include narrow widths and steep foreshore slopes, the nearshore step (in most cases), a sharp transition between the beach slope and sea bed and washover lobes.

However, at three locations the nearshore step appeared to be absent. This could have been the result of the survey method used, or a real absence. It was observed that these localities were the only ones to contain terrestria derived sediment on the sea bed. Four types of internal structure were found - pure sand, pure gravel, gravel underlain by sand and alternating beds of sand and gravel. Sediment thickness control over water flow through and across the beach was considered responsible for this.

Artifical structures are also found on the beach. These include the stopbank-drain system, the old Timaru City sewer outfall and the beach renourishment. The influence of these structures on the beach is discussed in succeeding chapters.

CHAPTER 3

SEDIMENTS

3.1 INTRODUCTION

The main objective of this chapter is to present results from a sediment survey; identifying sediment characteristics and their spatial distribution. Samples were tested for size (Wentworth, 1922), sorting, skewness and kurtosis (Folk, 1965), shape (Sneed and Folk, 1958) and nominal diameter (Krumbein and Pettijohn, 1938). Emphasis is placed on mean grain size (M_Z), and sorting (σ_I). Where relevant, comparisons are made to previous studies.

As well as describing the beach sediment characteristics, this chapter also seeks to detect changes in these properties, by comparison with previous studies, and to infer processes responsible for sediment movement.

3.2 SAMPLE COLLECTION

Samples from Smithfield 06S1225 to North Aorangi were collected between the 17.11.1986 and 26.11.1986. The second set of samples, from Seaforth Road to Opihi 01S000 were obtained between 3.12.1986 and 12.12.1986. Samples were collected in the manner of Humbert (1968). Sample distribution was not evenly spaced as suggested by Krumbein and Slack (1956), but related to topographical features of the beach, or an obvious change in grain size (Humbert, 1968). Thus the number of samples from each profile varied.

In most cases, three samples were obtained from each profile line; one from the mid tide position, just below the crest, and half way down the backshore slope. Exceptions to this were Opihi 01S000, Washdyke 1600 (four samples each) and Connolly's Road and Smithfield Reef 06S1225 (two samples each). In all 63 samples were collected, their distribution being shown in Figure 3.1.

All sediment samples were taken from the beach surface. Sediments were put into labelled bags for identification in the laboratory. The amount of sediment retrieved from each site depended on grain size. To be statistically significant, more coarse material had to be collected than fine. This was purely a function of the number of grains per sample. This variance in grain size presented extreme difficulties in choosing a totally random sample. Most sediment sample localities were surveyed into position. Unfortunately, samples from Smithfield 06S1225 to Washdyke 1400 were not. These samples were collected for the writer shortly before he commenced work on the present study and the importance of surveying the samples into position was initially overlooked. An estimate of their positions was made as follows. It was known that the samples were collected from mid tide, just below the crest and half way down the backshore. From this an adequately accurate plot could be made.

3.3 SEDIMENT CHARACTERISTICS AND METHODS OF DETERMINATION

3.3.1 Grain Size (M_Z)

Grain sizes in this study are described using Wentworth's (1922) terminology and quantified by the phi (ϕ)

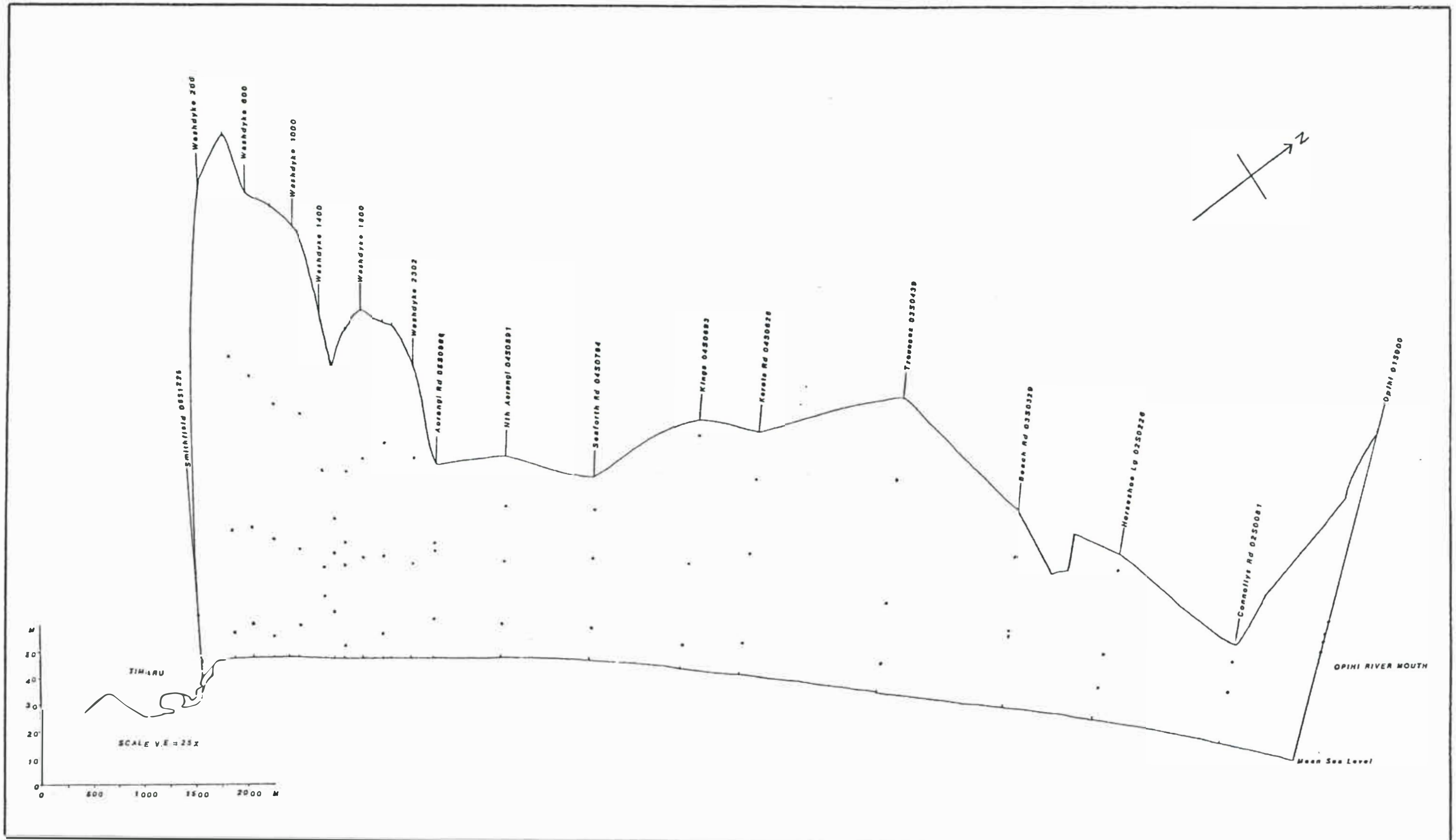


Figure 3.1 Sample Location Map

scale (Krumbein, 1934). These two systems are used because the Wentworth scale has easily remembered terminology and the phi scale is more practical than millimetres, especially in the fine-very fine size classes. Beach samples were analysed at the South Canterbury Catchment Board, using standard sieving techniques. Samples were washed and dried overnight at 140°C. Each sample was then weighed and sieved for 15 minutes on an "Endrock Endecott MK2" sieve shaker. Appendix 3.1 shows the mesh sizes used. These sieve sizes were chosen so the samples could be broken down into the main Wentworth size classes. Each grade coarser than medium sand was sieved into fine and coarse fractions. Hence the grades medium sand to granules had two sieves. The pebble mode used three sieves, being split into coarse, medium and fine pebbles.

The amount of sediment retained on each sieve was weighed and converted to percentages of the original weight. These values were subsequently plotted by a "Digital VT100" computer onto grain size-cumulative frequency curves. From these curves other parameters could also be obtained (Folk, 1965).

Grain sizes are compared to those of van Mechelen (1978) by use of an unpaired t-test (Hammond and McCullagh, 1978). Before the t-test could be performed, mean values had to be extracted from van Mechelen's size-sorting graph (pp.20-21), as his raw data were not available. This was done by developing a size class frequency diagram (Mills, 1955) with class intervals set at 0.5 ϕ. In using this method a very small difference was found between van Mechelen's mean grain size value of -3.2 ϕ and the one obtained of -3.15 ϕ. This difference is considered to be from the different methods used to determine the mean, and van Mechelen may have rounded his mean value to the nearest 0.1 ϕ, in which case there is no difference. Comparisons for statistical parameters against Kirk's (1967) data showed no statistically significant difference. This was thought to be because of the small sample size. Kirk had only eight samples in common with the present study (from four profiles between Smithfield and the Opihi River).

3.3.2 Sorting (σ_I)

Sorting is a measure of dispersion within a sample. According to Folk (1965), sorting is dependent on three factors;

(A) the size range of material available to the environment,

(B) the type of deposition, and

(C) current characteristics.

The measure of sorting used was Inclusive Graphic Standard Deviation (σ_I, Folk, 1965).

3.3.3 Skewness and Kurtosis (SK_I and K)

Skewness and kurtosis are measures of the shape of a distribution curve. Skewness measures the asymmetry of a curve, whilst kurtosis measures the peakedness of the curves. Positively skewed samples represent samples with excess fine material and negatively skewed samples have excess coarse material.

Kurtosis has been studied little and its geological significance is not known (Folk, 1965; Blatt, Middleton and Murray, 1980). Thus, little will be said about it in future discussion.

3.3.4 Shape and Nominal Diameter

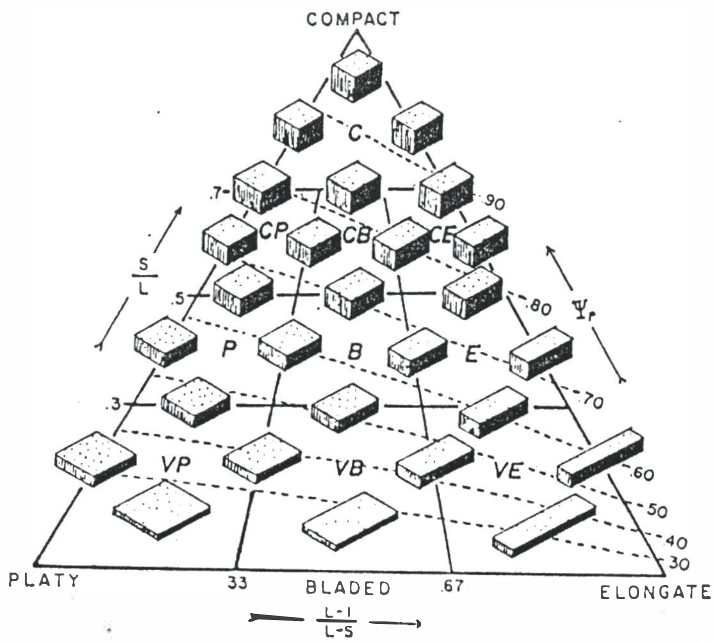
Over 4000 pebbles were measured to determine values for shape (Sneed and Folk, 1958) and nominal diameter (Krumbein & Pettijohn, 1938).

Samples were sieved into cobble, pebble and granule size classes. From each of these, 25 grains were measured if possible. In cases where less than 25 grains were present, all were measured. Grains were measured by callipers to an accuracy of 0.1 mm. These data were then entered into a B.B.C. Masters Series Micro-computer spreadsheet. A Geography Department computer programme was then used to tabulate the raw data to obtain values for the above mentioned parameters, and plotting the shape triangles as proposed by Sneed and Folk (1958, Figure 3.2). This method was preferred to that of Zingg (1935, in Blatt et al., 1980) because of the larger number of classes (ten compared to four).

Nominal diameter is the diameter of a sphere having the same volume as the particles (Krumbein & Pettijohn, 1938). As the three axes of pebbles were measured for shape analysis, the same measurements could be used to determine size by use of nominal diameters. Krumbein and Pettijohn (1938) found nominal diameters to closely reflect mean diameter and intermediate diameter. Thus direct comparisons, using the three axes measurements can be made between size and shape.

3.3.5 Results

Kirk (1967) noted that materials forming the Canterbury Bight beach are all alluvial in origin, except for a small percentage of volcanic rocks near Banks Peninsula. Kirk found the dominant lithology was greywacke, which was released



Legend

C	=	Compact
CP	=	Compact Platy
CB	=	Compact Bladed
CE	=	Compact Elongated
P	=	Platy
B	=	Bladed
E	=	Elongated
VP	=	Very Platy
VB	=	Very Bladed
VE	=	Very Elongated

Figure 3.2 Shape Triangle
(after Sneed and Folk, 1958)

from rivers and cliff erosion. Oxidised gravels released from cliff erosion were found to lose that surface feature rapidly on the beach, by wave action. Hence Kirk (1967) found few oxidised pebbles on the foreshore.

Greywacke was found to be the dominant lithology with small traces of quartz and lavas. Mussell shells were particularly common at Dashing Rocks. Two differences as the result of human influence can be detected in sediment composition since Kirk's (1967) survey. Firstly, stopbank and drain construction has added a large number of oxidised gravels to the beach surface. Secondly, volcanic blocks on the beach have been placed there during the renourishment programme (Todd, 1987, pers. comm.). They are not from the erosion of Dashing Rocks. Besides these small discrepancies, the natural material of the beach can be considered the same petrologically as most of the Canterbury Bight sediments. Finally, in accordance with Kirk (1967), the sediments were found to be texturally striking because of the wide range of sizes present.

Sixty-three samples were analysed. Three types of sample were evident, mixed sand and gravel, pure sand and pure gravel. The sand-gravel ratios of the mixed samples varied considerably. Graphic mean grain size (M_Z) ranged from -6.2 ϕ to 0.7 ϕ (cobbles to coarse sand). Appendix 3.2 shows the total range of mean grain size values.

The overall mean was -2.33 ϕ. Examination of the mean grain size values from the individual sediment sample curves showed 30 samples were in the pebble class, 20 were granules, 10 were sand, and two fell in the cobble class.

Sorting values (Appendix 3.3), ranged from 0.2 ϕ (well sorted) to 3.2 ϕ (very poorly sorted (Folk, 1965)). Figure 3.3 shows two dominant sorting populations. The first mode consists of very poorly sorted samples, ranging between 2.25ϕ to 2.75 ϕ. The second mode shows a population of moderately to poorly sorted samples, varying between 0.75 ϕ and 1.25ϕ respectively. Skewness varied from being strongly fine skewed (-0.6) to strongly coarse skewed (0.7). Mean skewness figure for the whole beach was 0.01 ϕ (Appendix 3.4); in Folks (1965) near symmetrical range. Kurtosis values showed similar extremities from being very platykurtic (0.5) to extremely leptokurtic (5.2). Kurtosis values averaged showed the beach to be mesokurtic (Appendix 3.5). Thus the beach sediment could be described as pebbly, moderately-poorly sorted, near symmetrical and mesokurtic.

Three shapes were dominant. These were bladed, very bladed and elongated. Bladed and very bladed grains were dominant on the upper foreshore, and bladed and elongated grains dominated the lower foreshore (Figure 3.4). Most of the grains were of intermediate shape - that is they plotted in the central region of Sneed and Folk's (1958) shape triangle (Appendix 3.6).

Nominal Diameter values ranged from -1.89ϕ to -4.96 ϕ, the mean being -2.95ϕ (Appendix 3.7). Figure 3.5 shows that the coarsest material occurs on the upper foreshore, as with mean grain size. Backshore and upper foreshore curves also showed an increase towards the north, whilst the lower foreshore curve remained relatively constant along the beach.

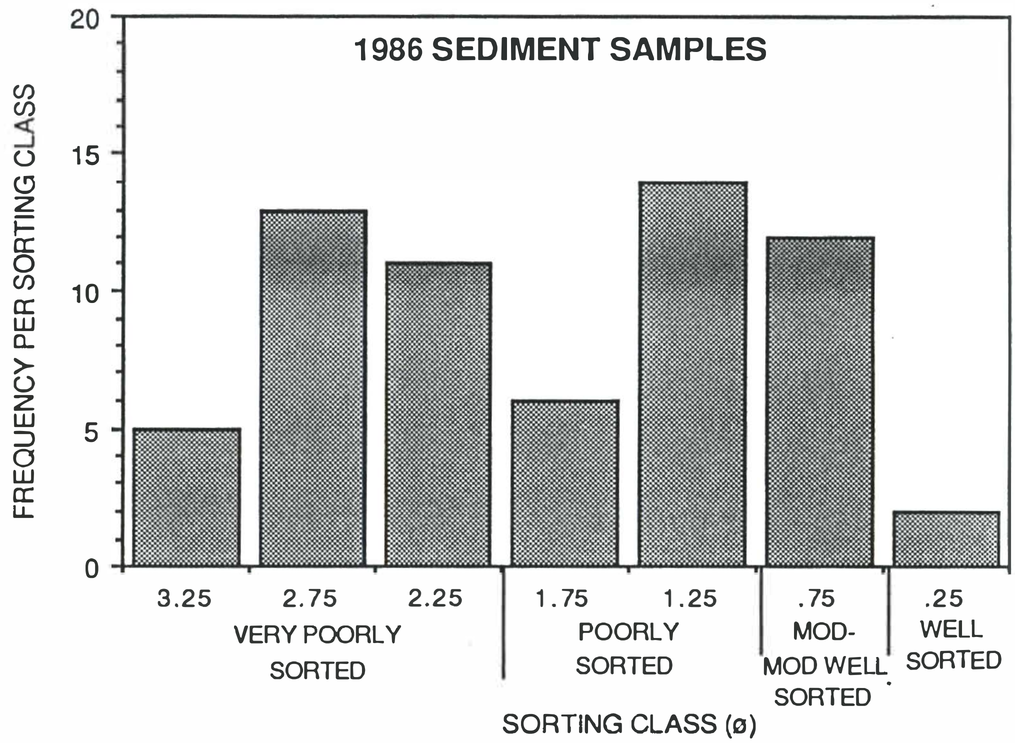
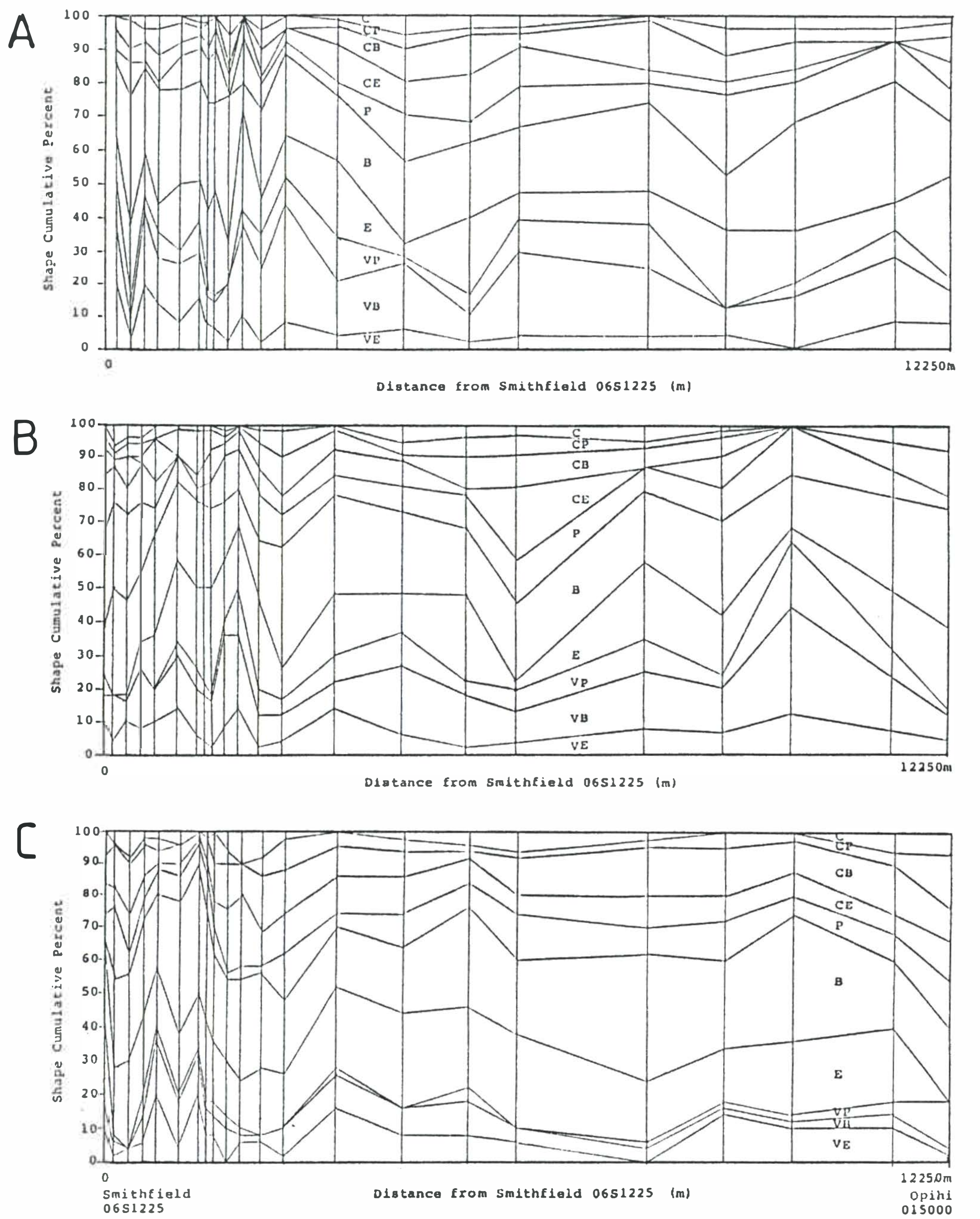


Figure 3.3 Sorting Populations Showing Two Modes



Legend

C	=	Compact
CP	=	Compact Platy
CB	=	Compact Bladed
CE	=	Compact Elongated
P	=	Platy
B	=	Bladed
E	=	Elongated
VP	=	Very Platy
VB	=	Very Bladed
VE	=	Very Elongated

Figure 3.4 Shape Cumulative Percentages Along the Beach

A = Backshore, B = Upper Foreshore, C = Lower Foreshore

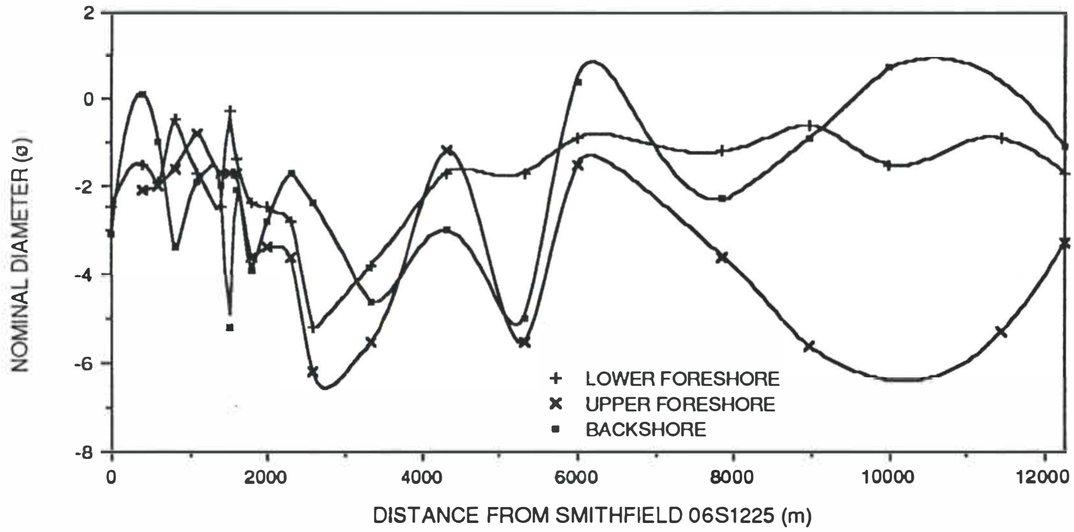
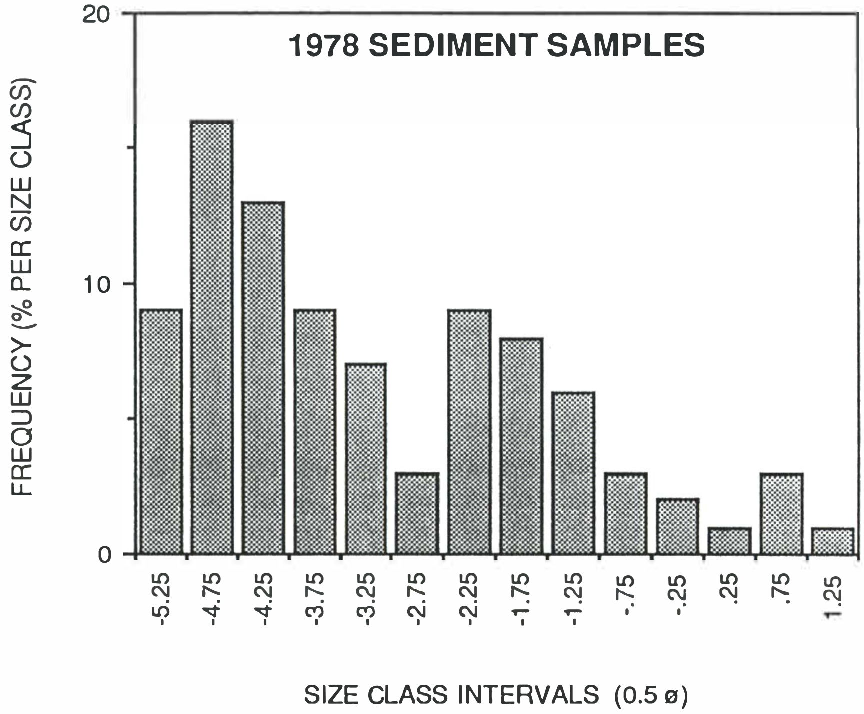


Figure 3.5 Nominal Diameter Values Along the Beach

3.4 DISCUSSION

3.4.1 Grain Size Changes Since 1978

There have been two schools of thought in the past, as to whether grain size has diminished over time on the study beach. Todd (1983) noted that long term residents around the Opihi River mouth had observed a decrease in the number of large cobbles on the beach. Likewise, Evans (1983) suggested grain size on Washdyke Beach had decreased since the harbour construction (1878). To the contrary, Kirk (1977b) stated there had been little evidence that grain size had decreased except for the largest cobbles. When the t-test was utilised, the result from the comparison of van Mechelen's (1978) data to that of the present study showed a highly significant difference. Grain size has decreased from -3.15ϕ in 1978 to -2.33ϕ in 1986 - a decrease of -0.82ϕ, with a significance level of $.0005 < p < .005$. Also illustrated from the grain size comparison was a change in the sediment structure of the beach. The present study shows the beach sediments to be bimodal, in common with van Mechelen (1978). However, groupings of data occur at different places on size-class-frequency graphs (Figure 3.6). The dominant size class of the present data occurs between -2.25ϕ and -0.75ϕ (fine pebbles to very coarse sand). This contrasts with van Mechelen's (1978) data where the dominant size class ranged between -5.25ϕ and -3.25ϕ (medium to coarse pebbles). Thus, it appears an increase in finer size grades has occurred at the expense of coarser material classes. It is not stated by van Mechelen whether he took samples from places of morphological change (Berms, cusp bays-horns, etc.) or sediment size change. The



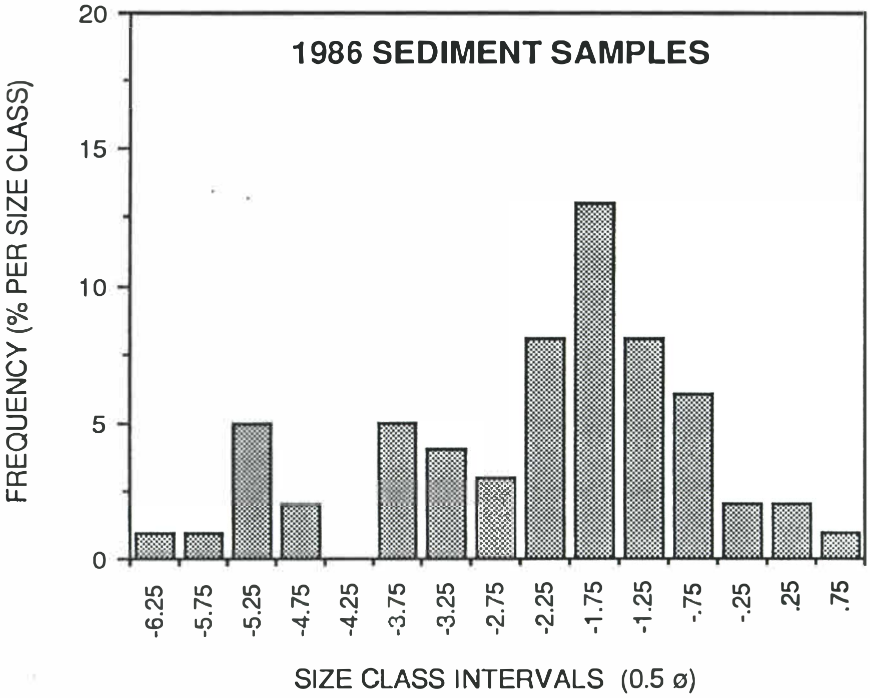


Figure 3.6 Frequency Grain Size Graphs

coarse material between -6.25ϕ and -4.75ϕ is dominantly from the renourishment site and site of excavations. More will be said about this later in the chapter.

3.4.2 Grain Size Distribution

Figure 3.7 illustrates grain size distribution over the beach by 1.0 ϕ contours. Immediately obvious are the cellular like distribution, the lack of linear decrease in grain size and great variability across the shore. These trends are consistent with those from other mixed sand-gravel beaches, as found by Marshall (1929), Kirk (1967), McLean (1970) and van Mechelen (1978). The most likely reason for the lack of linear grain size trend is the complex interaction of wave trains. Although waves striking the coast are dominantly from the south east (Davis, 1964), it was noted by Kirk (1967) and Hastie (1983), that a mixture of northerly and southerly waves was common. Also, Kirk (1967) noted that under particular conditions, grains of varying sizes on the Canterbury beach could move in different directions. Hence, it would be expected to find no longshore linear trends. This appears to be common on mixed sand and gravel beaches of the South Island, as cellular patterns of mean grain size (and sorting) were also found by McLean (1970) on two Kaikoura Beaches.

Cross shore grading of sediments relates to hydrodynamic conditions during deposition. Figure 3.7 shows that the coarse material is concentrated around the crest and upper reaches of the beach. This has been noted by numerous writers. Zenkovich (1967) observed that sand and gravel began motion simultaneously when waves broke. Gravels settled first due to decreasing swash velocity. Backwash set the

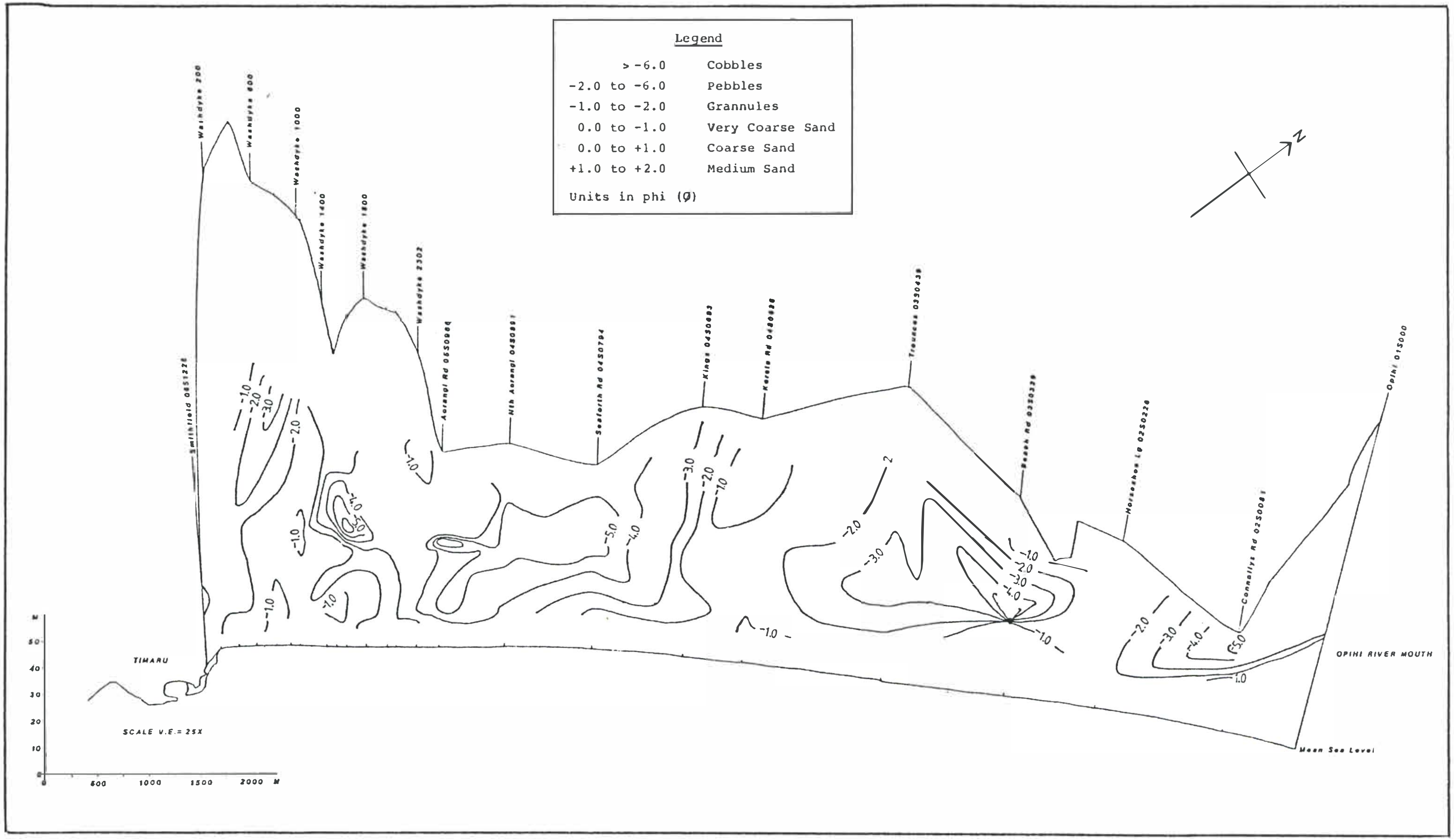


Figure 3.7 Grain Size Contour Map. Contour Intervals = 1.0 Ø

gravels in motion again for a short distance before encountering the swash of the next wave - depending on the state of phase (Kemp, 1960). Hence gravels tended to become concentrated on the upper foreshore, whilst sand could be in motion through the whole swash-backwash cycle. Vladimirov (1953, in Zenkovich, 1967) and Kirk (1975) found coarse material on mixed sand gravel beaches was concentrated at the landward limit of the swash, where velocity decreased rapidly (Kirk, 1975), and at the bottom of the nearshore face, the seaward limit of the gravels being controlled by the fact that gravels move very little under unbroken waves (King, 1959; Zenkovich, 1967; Kirk, 1975). Because of turbulence and murkiness when offshore surveying, the divers could not obtain samples from the nearshore face. Thus, it could not be determined if coarse gravel was concentrated in this area on the study beach.

McLean (1970) considered that variations in grain size and sorting across a beach are a response to the zonations of hydrodynamic processes and the characteristics of the available material. McLean (1970, p.158) goes on to state:

> "Where a large size range is available certain sizes may be preferentially deposited and distinctive textural zones parallel with the shore are produced. Large variations in size and sorting values across the beach may result."

Bands of alternating coarse and fine material were commonly found across the beach. The coarse material was thought to represent previous landward uprush limits, due to reasons suggested by Vladimirov (1953), Zenkovich (1967) and Kirk (1975).

Coarse material on the study beach was also found to be concentrated on the landward side of the crest. This is due to overwashing, where sediment carried in water is deposited as percolation increases down slope (Orford and Carter, 1982). Thus gravels, as in swash, are the first to settle out. The cell of coarse material midway along the Washdyke Barrier shows the influence of the injected renourishment material, whilst the coarse cells, between Aorangi Road and Seaforth Road and around Beach Road are considered the result of hinterland excavations. At Aorangi Road excavations have been carried out for drain and stopbank construction, and at Seaforth Road for the construction of the new Timaru City sewer pipe. At Beach Road excavations were undertaken for the launching of a fishing trawler in mid 1986 (plate 3.1). All of these diggings penetrated the underlying fluvial gravels, adding this coarser material to the beach surface. Evidence for this is the large number of oxidised gravels at these localities of the beach. These oxidised gravels are thought to be recent additions, as it was indicated previously that Kirk (1967) observed very few oxidised pebbles on the beach. Thus, the oxidised gravels' duration on the beach surface has been insufficient for swash and backwash to abrade the oxidised layer off.

3.4.3 Sorting Patterns

Sorting patterns closely reflect those of grain size (Figure 3.8 and 3.9). Initially, no longshore pattern could be determined. Nevertheless, it can be seen from Figure 3.9 that a reasonably strong longshore trend is evident on the foreshore. This is as expected as the lower foreshore is constantly under wave attack. Folk (1965, p.4) stated that:

> "currents working over thin sheets of grains continuously (as in the swash and backwash of a beach) will give better sorting than the 'city dump' method."

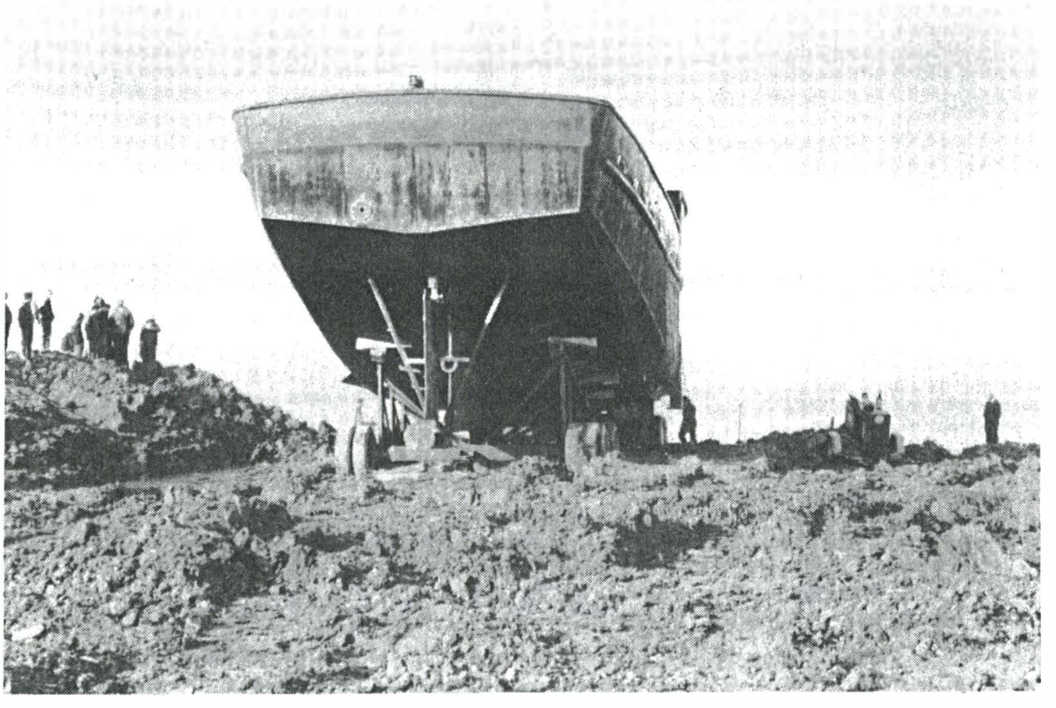


Plate 3.1 Launching of a fishing trawler, Beach Road. Note disturbance of beach stratigraphy.

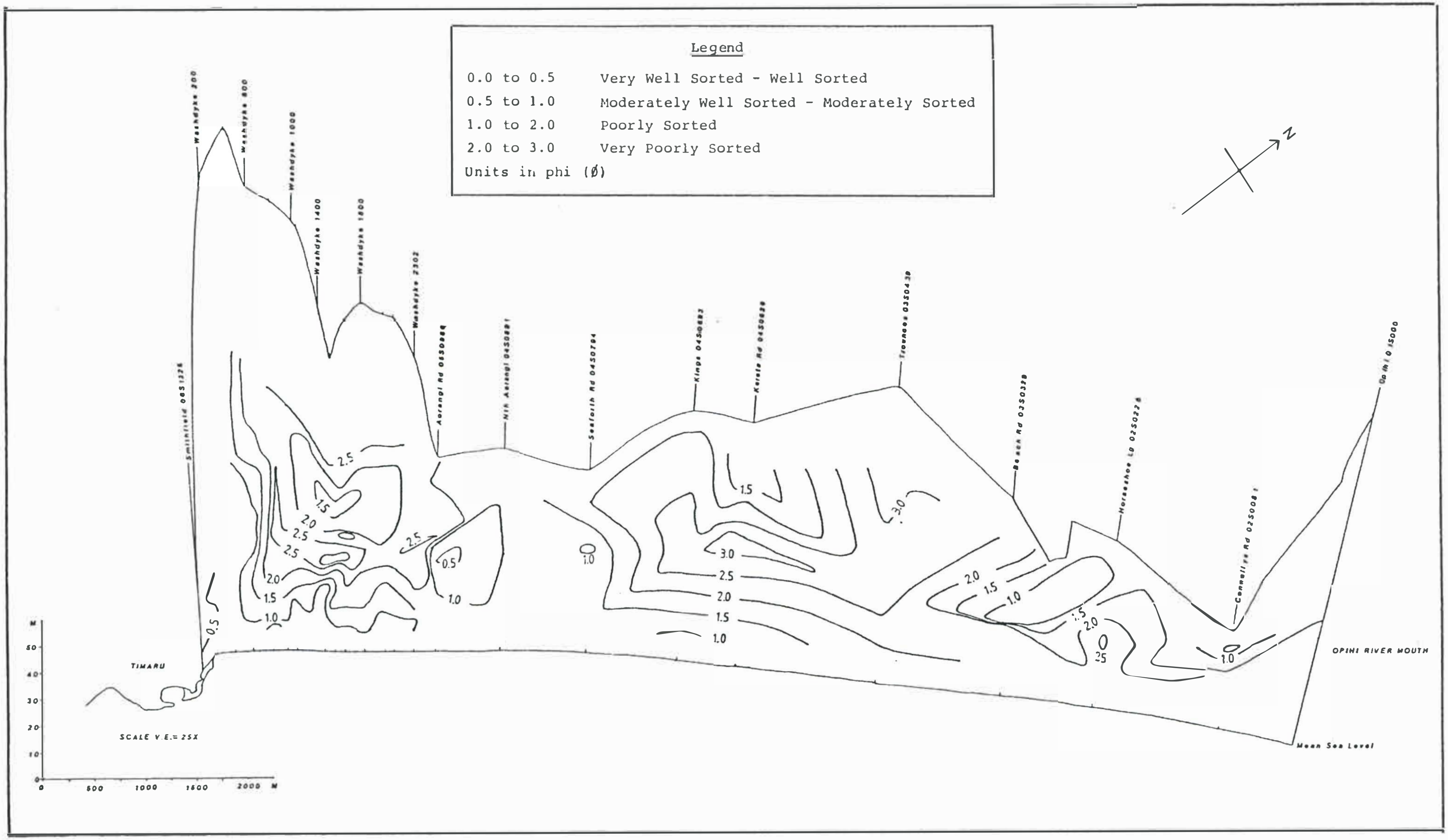


Figure 3.8 Sorting Contour Map. Contour Intervals = 0.5 Ø

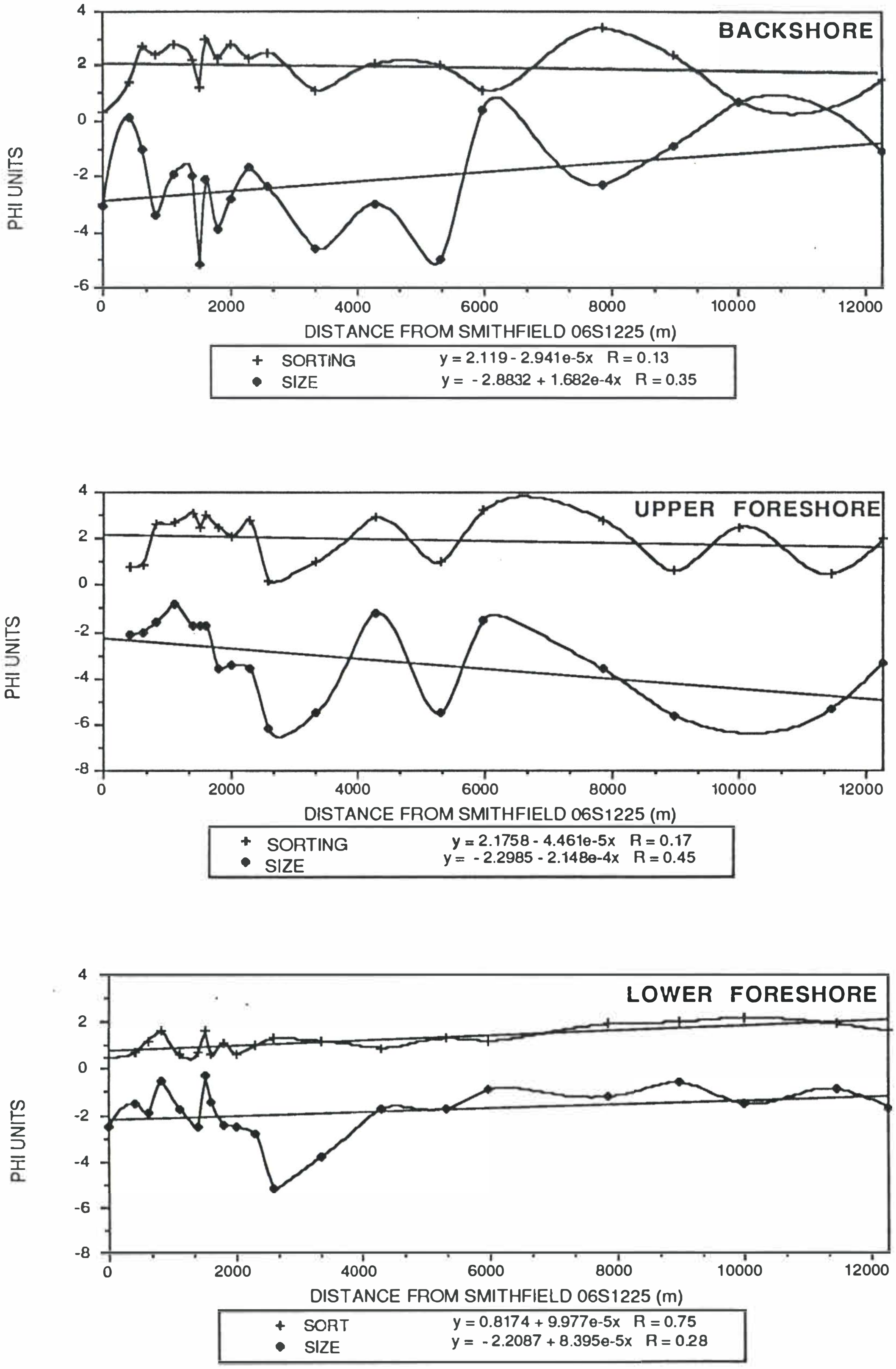


Figure 3.9 Grain Size-Sorting Trends

Figure 3.8 shows that sorting on the lower foreshore improves towards Smithfield Reef. This contradicts the net northerly drift, as it would be expected for sorting to improve down drift (Marshall, 1929; McLean, 1970. Longshore trends of grain size and sorting are shown in Figure 3.9. From these graphs inferred beach drift directions can be determined using the method of Sunamura and Horikawa (1972, Figure 3.10). This method assumes there is a potential source, and size is measured in millimetres, not phi units. Hence if the graphs of Figure 3.10 are converted accordingly, and assuming the Opihi River mouth is the potential source, it can be seen that a net southerly drift has occurred recently on the lower foreshore (Figure 3.10f). It is inferred that this must have been within the last 19 months. It will be shown in the following chapters that the breached section of the Washdyke Barrier has recovered substantially, and that beach crest heights towards the south have increased over ten years, thus indicating southerly drift. Chapter Four will show that southerly drift is considered the only possible source of sediment for the southern end of the beach. On the upper foreshore and backshore, no direction trends were determinable (Figure 3.10g,i).

It should be noted that Sunamura and Horikawa (1972) developed this method for sand beaches, thus its applicability to mixed sand-gravel beaches could be doubtful. Nevertheless, evidence presented in the previous chapter and to be given in the succeeding chapters shows that southerly drift has occurred.

The cross shore sorting trends displayed in Figure 3.9 and the cellular pattern shown in Figure 3.8, are considered

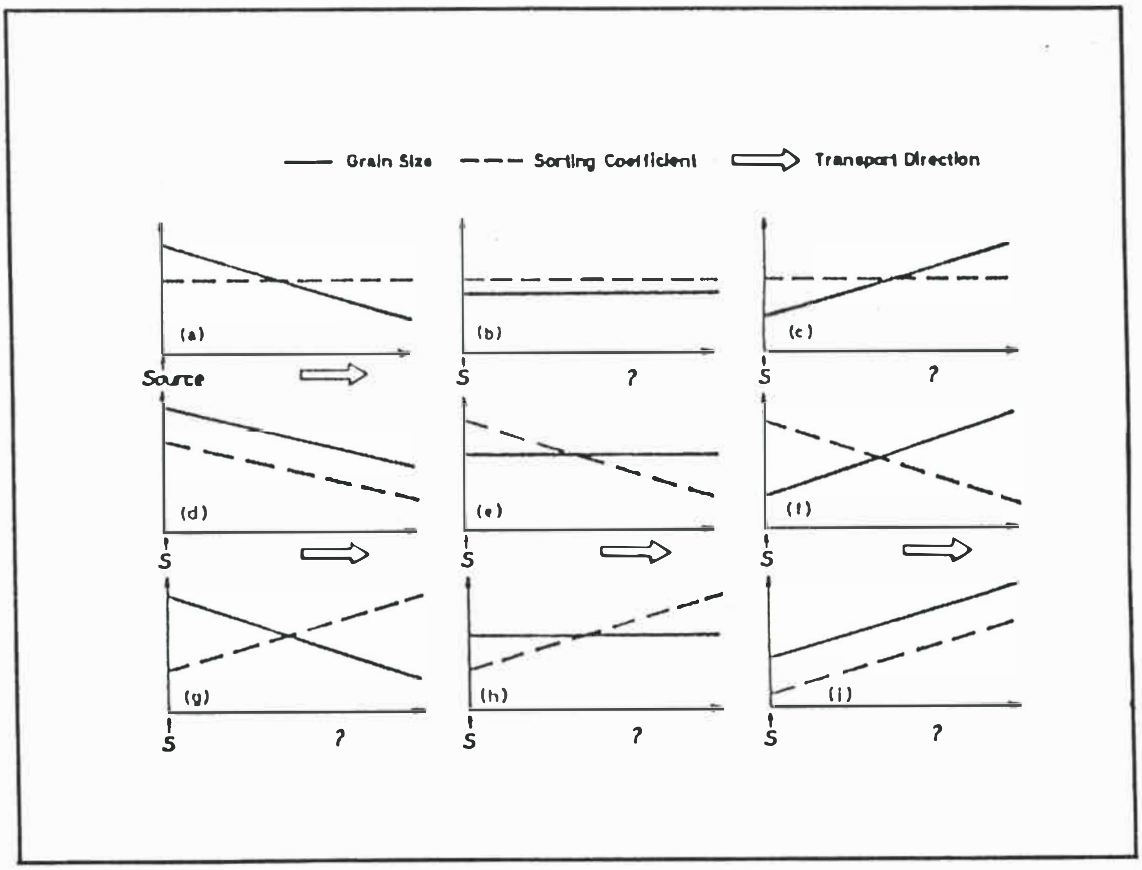


Figure 3.10 Criteria for the Inference of Transport Direction (Source: Sunamura and Horikawa, 1972)

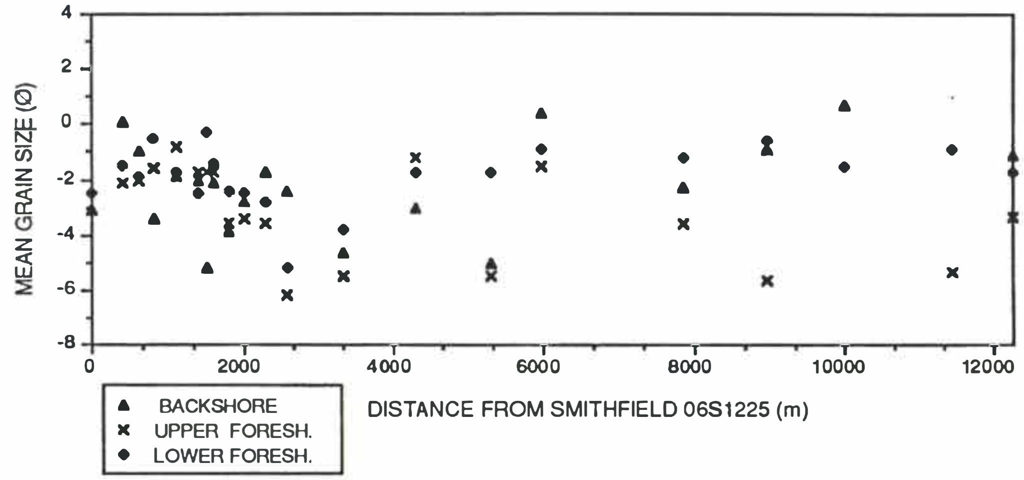
to occur for the same reasons as the grain size distribution, explained previously. Hence, sorting for the whole beach appears to be primarily a function of wave energy exposure. Best sorted samples have almost continuous exposure, whilst poorest sorted samples, as on the backshore, have least wave exposure. On a local scale the renourishment and excavations at the southern end of the beach have also contributed to the poorer sorting on the upper foreshore and backshore by introducing foreign material to the beach sediments (Figure 3.11).

3.4.4 Grain Size-Sorting Relationships

Folk (1965) suggested end member populations (clays, sand, gravel) were better sorted than those of mixed composition, producing a sinusoidal relationship when grain size is plotted against sorting. This has been studied on mixed sand-gravel beaches by Kirk (1967), McLean and Kirk (1969), McLean (1970) and van Mechelen (1978) and other workers. Figure 3.12 shows an Order 3 polynomial curve plotted onto a grain size-sorting graph. A poor relationship exists. All regressions from simple, to Order 9 were plotted with little difference in statistical significance. Order 3 was plotted because it was the first to show a vaguely similar form to the others.

When comparisons are made to those of previous studies it can be seen that the curve of the present study shows the highest (poorest) sorting values, especially for mean sizes between -3.0ϕ and -5.0ϕ.

This poor sorting in the coarse samples is thought to be due to artificial influences. Grain size values in Appendix 3.2 show coarse material to be associated with the renourishment site and excavation sites indicated earlier. Hence,



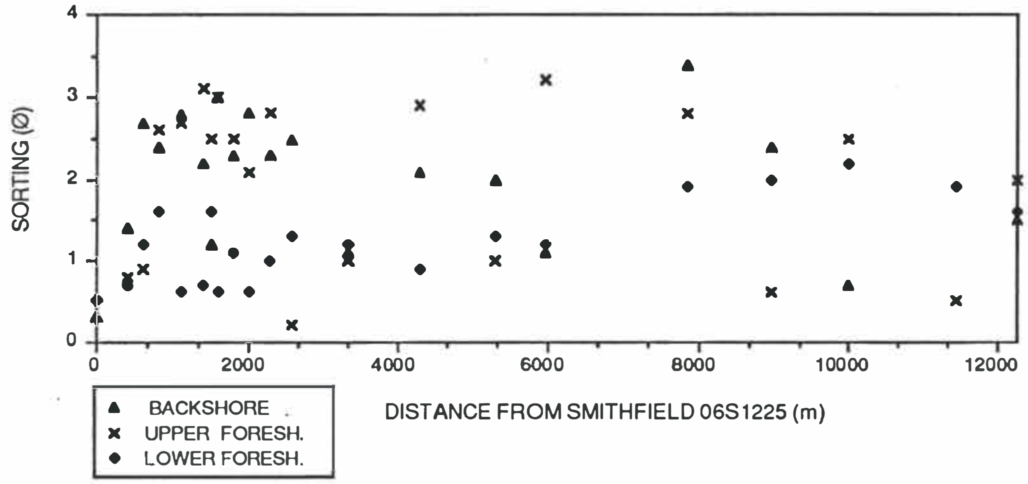


Figure 3.11 Grain Size and Sorting Scattergrams

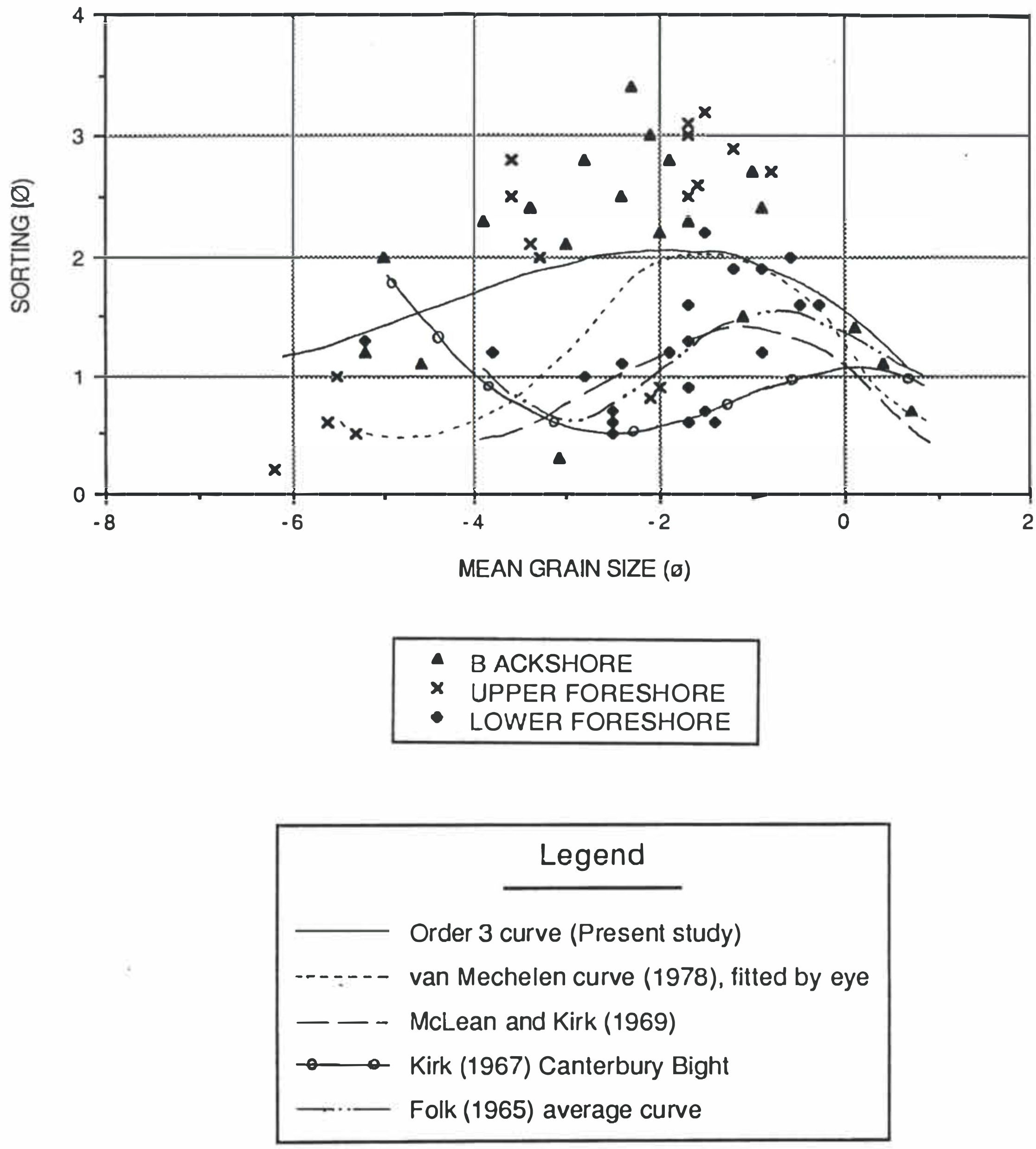


Figure 3.12 Grain Size Sorting Relationship

the foreign poorly sorted coarse material from the Opihi River gravels (Kirk, 1982) and substratum gravels mixed with native beach material is suggested as being responsible for the poorer sorted gravels than those of the previous studies.

3.4.5 Skewness

Skewness values show a wide scatter when plotted against distance with no longshore or cross shore trends immediately obvious. However, when the skewness values are averaged for the lower foreshore (0.004), upper foreshore (0.01) and backshore (0.04), a weak cross share trend can be seen (Appendix 3.4).

The lower foreshore has a slight excess of coarse material (lack of fines) compared to the other two environments. This is consistent with the winnowing of fine sands under the influence of swash and backwash as indicated by numerous writers (e.g. Friedman, 1967; Folk, 1965; Blatt, Middleton and Murray, 1980). The upper foreshore and backshore show a higher fine content due to less frequent wave action. In times of storm wave inundation, deposition on the upper foreshore and backshore is of the "city dump" type (Folk, 1965). Thus all grain sizes are left behind - winnowing of fines does not occur in this environment to the same extent as the lower foreshore.

3.4.6 Shape and Nominal Diameter

Evans (1983) suggested that as grain size diminished on Washdyke Beach due to gravel abrasion, shape altered correspondingly. Large discs (platy) became smaller and more spherical (compact) over time which caused crest height reduction and increased impermeability. This lead to overtopping by smaller waves. However, Evans gave no references or evidence backing these statements.

From the present shape analysis, it cannot be established if shape has changed over time. This is because no previous comprehensive shape examination has been undertaken on the study beach. Hence, the present study describing shapes and their distributions can be viewed as a base study for future comparisons.

Figure 3.4 demonstrates that shape, like other sediment parameters discussed, shows no significant longshore trends, but great variation across the shore. It can be seen that blades are the singular dominant shape across the shore, as they are most abundant in the lower and upper foreshore and on the backshore.

Other shapes were relatively common in association with blades depending on the beach position. On the backshore very bladed, elongated and platy grains were common. Very bladed, elongated and platy shapes were abundant on the upper foreshore, whilst on the lower foreshore, elongated grains were nearly as abundant as blades.

Bluck (1967) found the largest particles to be discoid (platy) and located on the upper foreshore. Smaller particles located on the lower foreshore were dominantly rods (elongated) and blades. Bluck suggested that local hydrodynamic conditions (swash, backwash and percolation) combined with the settling velocities of different particles, to be responsible for the cross shore shape zonations. Comparisons of size (nominal diameter) and shape in the present study show the coarsest material to be dominated by blades and very bladed pebbles. These are located on the upper foreshore and backshore.

Finer material on the lower foreshore is dominated by bladed and elongated grains.

These deviations from the zones and size-shape relationships described by Bluck (1967) can be attributed to a number of factors. The main difference is considered to be lithology. Bluck was working with four lithologies whereas the study beach is comprised of dominantly one lithology - greywacke. This relates to other factors causing variations in shape as noted by Krumbein and Pettijohn (1938, p.278) such as: (a) the original shape of the fragments; (b) the structure of the fragment such as bedding, etc.; (c) the exposure to energy; and (d) the time or distance to which the energy has acted on the grains.

The pebbles of the study beach are of a much younger age than those examined by Bluck (1967) and are basically sound. That is they contain very few fractures or planes of weakness such as schistocity, cleavage and bedding. In common with Bluck (1967), settling velocities, and hydrodynamic variations across the beach, which produce variation in mean grain size and sorting (Kirk, 1967; McLean, 1970) are thought to be responsible for the distribution of cross shore shape zonation by selective sorting. It is suggested that the largest particles - dominantly bladed and elongated - are selectively transported to the upper foreshore and backshore in storm seas and deposited rapidly. Hence the erratic trends in nominal diameter along the shore.

On the other hand, elongated and smaller bladed particles tend to relate to the constant wave action of the lower foreshore, as in the winnowing effect responsible for sorting in this area. This is reflected in the more uniform longshore trend line of nominal diameter (Figure 3.5). Other shape categories appear to be spread reasonably equally across the beach, suggesting they occur in all sizes and are transported under the local wave energy conditions with equivalent ease. It was expected that a major shape difference would occur around the renourishment and excavation sites (being foreign to the beach). However, none was found, suggesting these materials are dispersed through the beach sediments to "filter out" any shape anomalies.

3.5 CONCLUSION

The main aim of this chapter was to analyse sediment characteristics, their distribution and processes responsible for this. Statistical analysis on six sedimentary parameters showed the beach sediments to be pebbly, moderate-poorly sorted, near symmetrical and mesokurtic. The dominant lithology was greywacke.

The emphasis was placed on detecting changes to grain size, and sorting. A distinct size decrease of about -0.8ϕ since Van Mechelen's (1978) survey was found. This difference may have been produced by the method of sampling or could reflect a real decrease due to abrasion. The reasonably large difference combined with the high level of significance and principles of gravel abrasion (Marshall, 1927; Adams, 1978) implies a real decrease in mean grain size may have occurred. Two strong sorting modes were found - one in the very poorly sorted class and the other in the moderate-poorly sorted class. In general no longshore trends for the sedimentary parameters could be determined. The exception to this was the lower foreshore sorting trend, which improved towards the south.

The relationship between mean grain size and sorting was poor. An Order 3 polynomial curve was fitted, and compared to those produced by Folk (1965), Kirk (1967, McLean and Kirk (1969) and van Mechelen (1978). The major difference illustrated was the poorer sorting for mean sizes in the coarse pebble range. This was shown to be due to the addition of foreign material to the beach by beach renourishment and excavations. Comparisons of mean grain size and sorting against distance, following the method devised by Sunamura and Horikawa (1972) was used to determine beach drift directions. It was inferred that net southerly drift may have recently occurred.

Cross shore variations of the parameters were prominent. It was found that coarsest materials were concentrated on the upper reaches of the beach and were dominantly bladed and very bladed. In accordance with Bluck (1967), platy grains were also more common on the upper foreshore and backshore than on the lower foreshore. The finer material found on the lower foreshore was dominantly bladed and elongated. Other shapes were scattered reasonably evenly across the beach. Meaned skewness values became slightly more positive in a landward direction. These cross shore trends were thought to be produced by a combination of hydrodynamic variations across the shore and the origin of the beach sediments.

CHAPTER 4

THE SEDIMENT BUDGET

4.1 INTRODUCTION

A beach sediment budget is a model used to show volumes and directions of sediment transport and to identify sediment gains and losses. As shown in Figure 4.1, Johnson (1959) suggested that for sand beaches, streams, gullies, cliff erosion, onshore-offshore movement by wave action, wind action and in situ addition of biogenous materials represented gains. Movement offshore into deep water including submarine canyons, sand mining, wind action, abrasion by wave action, and accretion against littoral barriers were potential losses.

Most sediment budgets presented for South Canterbury either concentrate on sediment drift around Timaru Harbour, or include the study beach as part of a larger scale study (Blair, 1890; Maxwell, 1930; Tierney, 1969; Kirk, 1977a, 1978; Gibb & Adams, 1982; Hastie, 1983; Fahy, 1986; and Kirk, 1987). These studies do not consider the Smithfield-Opihi Beach specifically.

Hence the aims of this chapter are to establish the volume of the remaining sediment, its thickness and its distribution. Within the discussion, volume changes since 1977 (the period covered by the South Canterbury Catchment Board survey data) will be noted. These changes are important in identifying areas of erosion and accretion, and for future prediction purposes (Chapter Six).

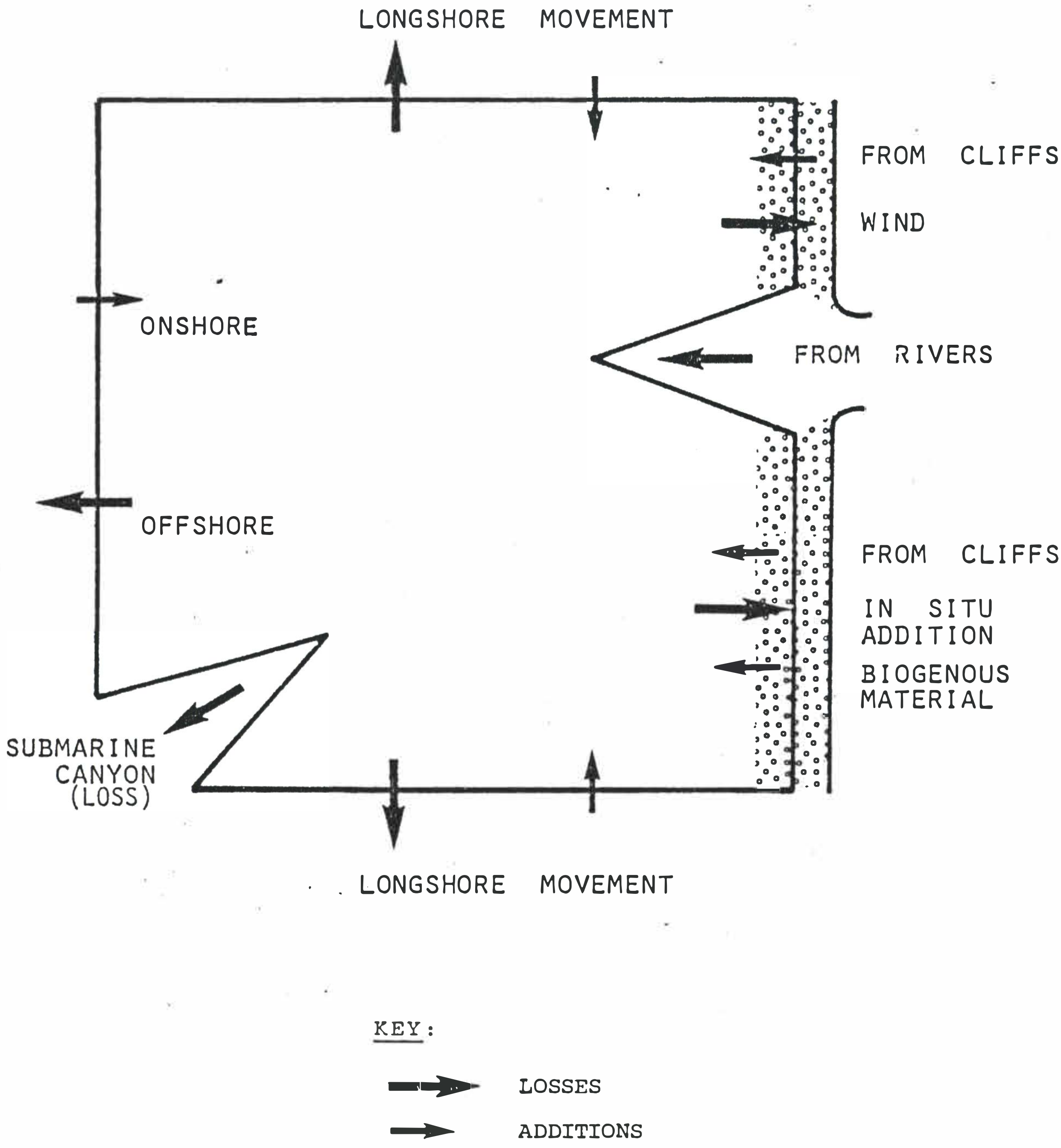


Figure 4.1 The Sediment Budget Model
(after: Johnson, 1959)

4.2 METHODS

Two methods were employed to calculate sediment volume and thickness. The first was a development of standard profile survey techniques (calculating the cross sectional area of a beach profile curve and multiplying it by a unit of length). This method involved surveying both the beach surface and substratum profiles (where possible). Digging through the beach with an excavator (Plate 4.1) until the substratum surface was reached, enabled surveying of that surface to be carried out. Beach volume was determined by calculating the cross sectional area between the beach and substratum profiles and multiplying the value by a representative scale factor. This method was superior to the standard profile survey method for two reasons. First, the standard procedure assumes the total area between the profile curve and a right angled axis is beach sediment. Figure 4.2 shows the beach surface in relation to the substratum and a right angled axis. It can be seen that the beach cross sectional area is exaggerated on the right angled axis. Thus, the method employed is considered more accurate. Secondly, in using this method, beach thickness can be directly measured.

Three limitations of the method were found. First, although the excavator had the potential to dig to a depth of three metres, the maximum depth reached was approximately 2.2 m. Loose, unconsolidated sediment would dry avalanche and cause the excavator to become unstable. Secondly, the method is limited by cost, being approximately $1000 for two days excavator hire.

Plate 4.1 Digging through the Beach with an Excavator.
December 1986

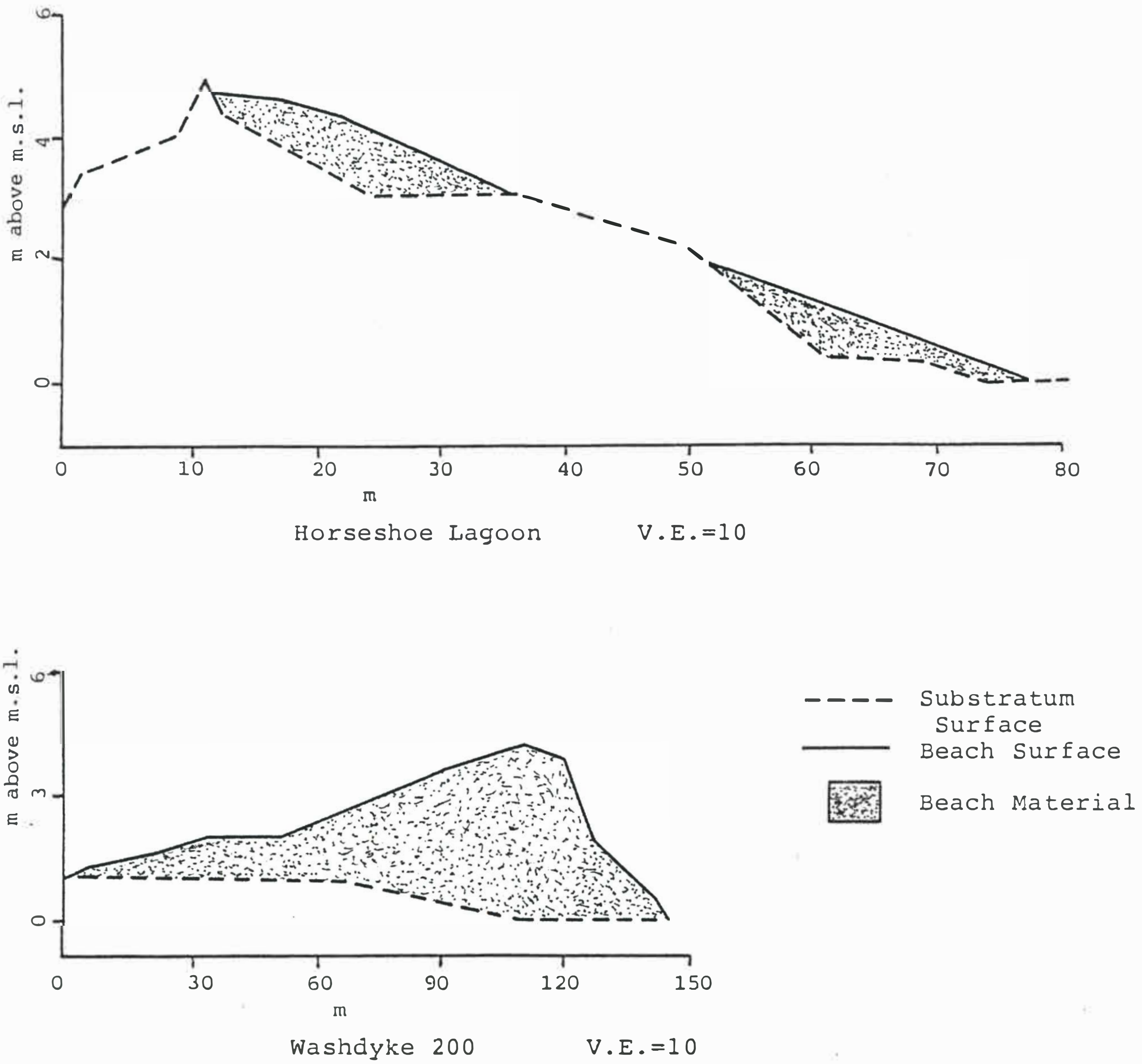


Figure 4.2 Comparison of Profile Cross-sections

Additional holes were dug through the beach at low water Ordinary Spring Tide, with a shovel, to reach the substratum as far seaward as possible, and at the back of the beach, to determine buried stopbank positions. As when using the excavator, both beach surface and substratum profiles were surveyed into position. Map 2 (back cover) shows the position of all excavations carried out.

The second method determining sediment thickness was seismic profiling, using the University of Canterbury Geology Department's MD9 Soil Test, single channel enhancement seismograph. Briefly, this involved sending shock waves through the beach by use of a sledgehammer and bash plate. The shock waves are refracted off an underlying surface of greater density; the signals received by a single channel geophone, are recorded on an oscilloscope. Tabulation of the data enabled the profile to be plotted. Reciprocal seismic profiling is a standard geophysical procedure and is fully described by Hawkins (1961). This method was used to establish sediment thickness at Dashing Rocks (Figure 4.3), where the excavator could not reach the substratum. This method also highlights the relationship between the basalt reef, substratum and beach sediments.

Because this method has not been tested on unconsolidated beach material before (as far as the author is aware), two precautions were necessary. First, the position of the bash plate was critical, as was a single definite hammer blow, to ensure optimum energy transfer through the beach. Secondly, it was noted that waves breaking on the foreshore created 'noise' on the oscilloscope. However, this proved to have no effect on the final results.

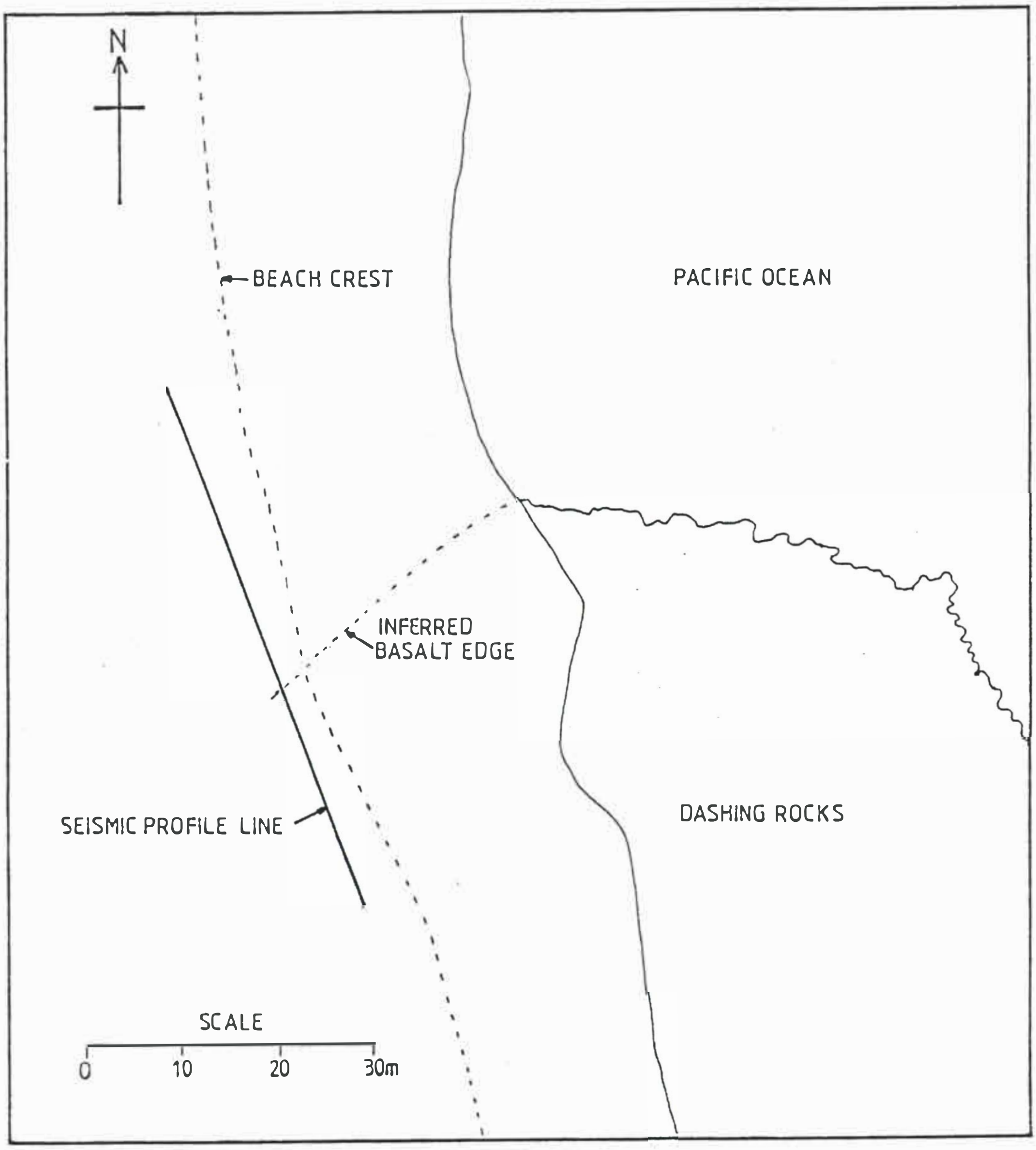


Figure 4.3 Seismic Profile Location

4.3 SEDIMENT THICKNESS DISTRIBUTION

Little work has been undertaken in establishing the sediment thickness of the study beach. The only previous observation of sediment thickness was from excavations through the beach at the new sewer outfall (Kirk, 1987). Table 4.1 shows sediment thicknesses observed during the excavations of this study (December 1986). It can be seen that sediment thickness varies along the beach, generally decreasing towards the Opihi River mouth. The Washdyke Barrier sediments on average were 1.84 m thick, compared to 1.23 m for the Seadown Coast. The major difference found in the sediment thickness distribution was on the lower foreshore. The Washdyke foreshore on average was 1.84 m thick compared to the Seadown foreshore of 0.84 m. Backshore thicknesses were very similar (1.84 m and 1.85 m respectively).

At many profiles along the Seadown Coast the substratum was exposed. In contrast, the seismic profiling at Dashing Rocks showed beach sediments to be resting in a depression, against the basalt, and were over 7.0 m thick. Above the reef, the cover was approximately 2.5 m (Figure 4.4).

A knowledge of sediment thickness is important to the understanding of erosion patterns. It has been known for some time that a thin veneer of sediment offers the substratum little protection (Timaru Herald, 23.4.1879, p.4). Secondly, as already mentioned in Chapter Two, a thin sediment cover leads to beach saturation and mass movement of sediment (especially finer size grades). Regarding the observations from the new sewer excavations, Kirk (1987, p. 121), maintained:

Table 4.1 Observed Gravel Thickness (m)
December 1986

Location		Upper Foreshore	Backshore
Washdyke 200	1.84	>2.76	1.73
Washdyke 600	2.03	-	2.4
Washdyke 1000	1.7	-	2.1
Washdyke 1400	1.7	-	1.67
Washdyke 1800	1.6	-	1.78
Washdyke 2302	2.11	-	1.43
Aorangi Road	0.87	-	2.61
North Aorangi	0.54	-	2.29
Seaforth Road	0.55	-	1.52
Kings	1.83	-	1.03
Kereta Road	1.28	-	1.78
Trounces	0.66	-	1.8
Beach Road	0.65	0.0	-
Horseshoe Lagoon	0.47	1.16	-
Connolly's Road	0.77	0.0	-
Opihi 01S000	>1.81	-	>1.54

Average Thicknesses (m)	
Washdyke Total	1.84
Seadown Total	1.23
Washdyke Foreshore	1.83
Seadown Foreshore	0.84
Washdyke Backshore	1.85
Seadown Backshore	1.83

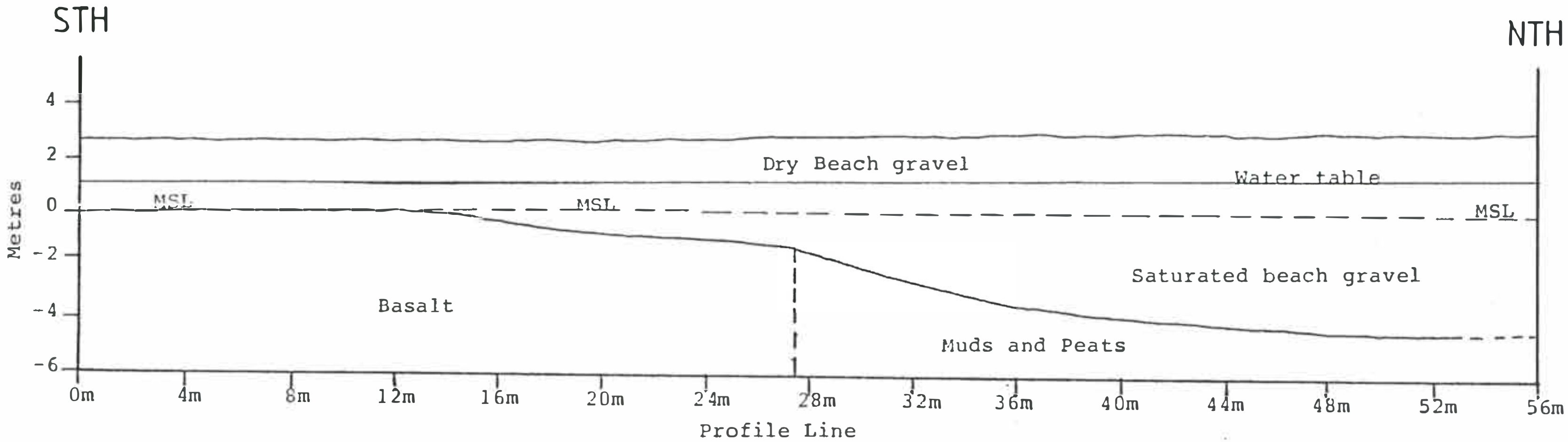


Figure 4.4 Seismic Profile Cross Section of the Beach

> "... it is evident that active beach sediments form only a thin veneer, gradually less than 1 metre thick overlying peats and other erosion incompetent materials of the hinterland. The available beach volume in absorption of wave energy is thus very small and is being rapidly reduced.... the basement for the most part is both impermeable and has a high water table, the prognosis for the pattern and intensity of future erosion (and for associated inundations) is extremely weak".

4.4 CHANGES IN SEDIMENT VOLUME; 1977-1987

Beach volume changes for the 1977-1987 period are shown in Figure 4.5 (all volume data are lodged at the South Canterbury Catchment Board, Timaru). Several important patterns can be seen. The first is that the Washdyke Barrier has greater volume per 100 m of beach than the Seadown Coast. This is a function of beach width and substratum height. However, more sediment in total occurs along the Seadown Coast because of its length compared to the Washdyke Barrier. Secondly, areas of erosion and accretion can be determined. Areas of erosion are indicated where the 1987 curve falls below the 1977 curve. Accretion is represented by the opposite trend. It can be seen that most of the beach has been in an erosional phase since 1971, except for the Washdyke Barrier. Beach volume has decreased from 1,749,048 m^3 to 1,466,074 m^3 between 1977 and 1987. This represents a total loss of 283,974 m^3 at a rate of 28,397.4 $m^3.yr^{-1}$. The total loss can be subdivided to show that the whole Washdyke Barrier has gained 39,214 m^3 of sediment, whilst the Seadown reach has lost 323,188 m^3. In 1977 the Washdyke Barrier contained 620,245 m^3 of sediment, and the Seadown Coast 1,128,803 m^3. The 1987 value for each of these reaches was 659,459 m^3 and 805,615 m^3 respectively.

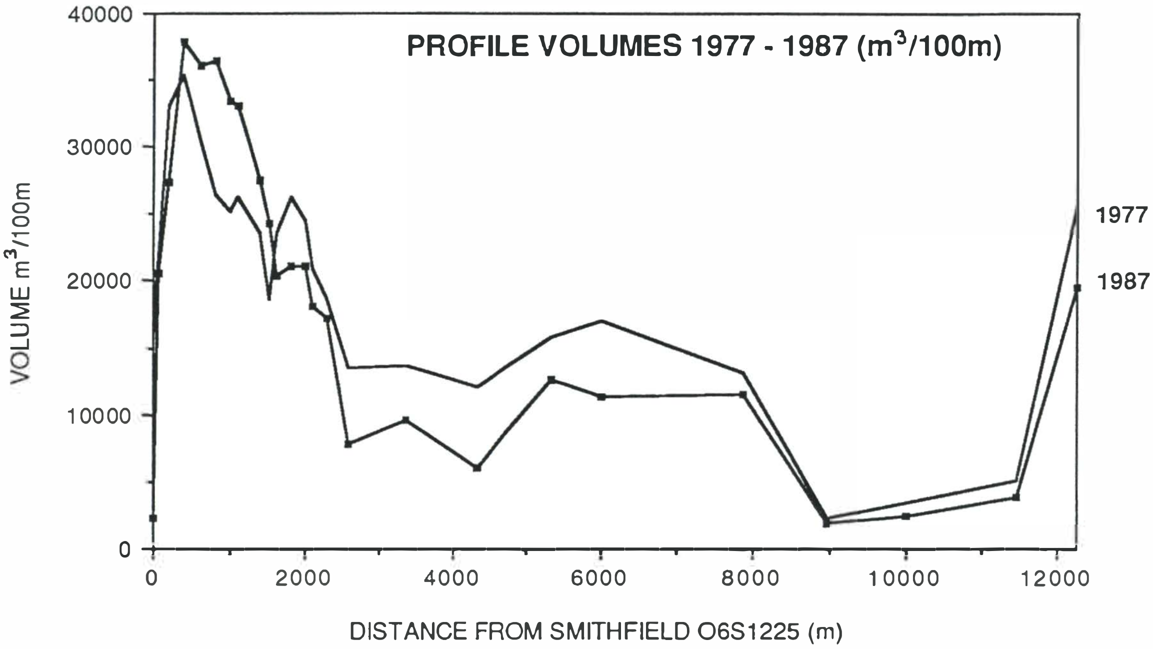


Figure 4.5 Comparison of Beach Volumes, 1977-1987

Subdividing the beach into even smaller units, it was found that between Washdyke 1500 and Smithfield 06S1225, 40,194 m³ of sediment has been deposited since 1977. Part of this can be directly attributed to the injection of material at the renourishment site. However, if the 29,000 m³ of renourishment material is removed (total input - Todd, 1987, pers. comm.), the barrier beach still has gained approximately 11,000 m³ of sediment.

Figure 4.6 shows absolute and percentage volume changes for each profile line between 1977-1987. Erosion clearly dominates, being offset by accretion in the southern section of the Washdyke Barrier. Figure 4.6 also indicates that profiles with the smallest volume show the greatest percentage changes. This is common along the Seadown Coast towards the Opihi River mouth.

The values shown for Horseshoe Lagoon (9990 m), Smithfield 06S1205 (75 m) and Smithfield 06S1225 (0 m) can be considered anomalous. Horsehoe Lagoon values represent a three year period instead of ten. This profile was positioned by the South Canterbury Catchment Board in 1984. Hence short term effects are included in the longer period. The Smithfield 06S1225 profile shows a disproportionately large percentage loss compared to the other Washdyke profiles. This also reflects short term fluctuations, as this profile was established in 1982. More significantly, this large percentage change reflects the sediment loss due to the breaching of the Washdyke Barrier in March 1986. Similarly, the accretion shown at Smithfield 06S1205 is thought to represent the partial recovery of the breach.

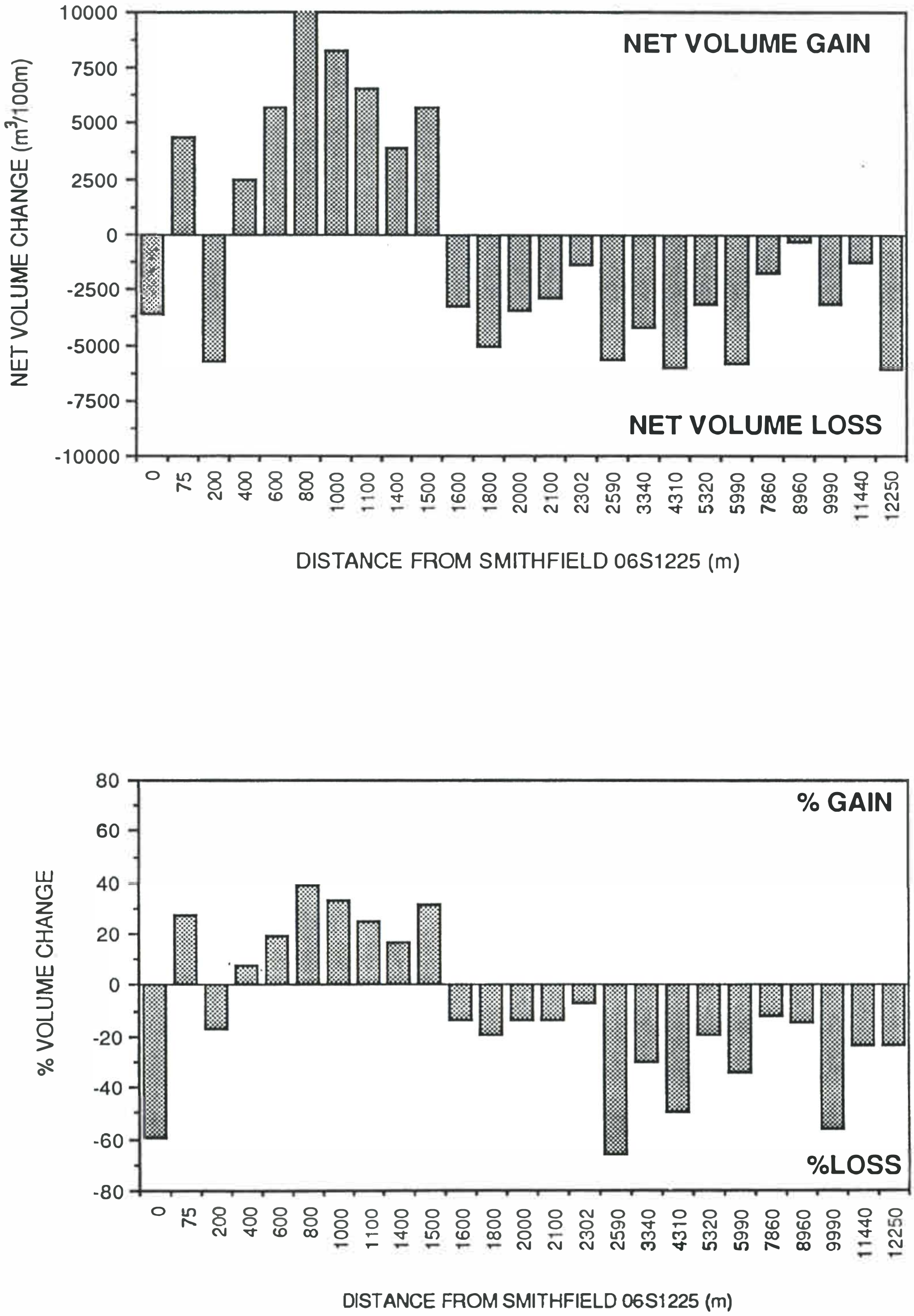


Figure 4.6 Net Volume Changes and Percentage Changes, 1977-1987

Finally, if the beach is sub divided into foreshore and backshore volumes, it can be seen that a sharp contrast exists between the Washdyke Barrier and Seadown Coast (Figure 4.7). The Washdyke Barrier can be seen to be dominated by backshore volume, whilst the Seadown Coast is foreshore volume dominated. Chapter Five will show that stopbanks along the Seadown Coast hinder backshore development, as washover deposition is restricted. For the Washdyke Barrier, Kirk (1982) suggested that 20-30% of annual volume losses were due to storm overwashing. Overwashing of sediment in the present study is not considered as a permanent loss, in the development of the sediment budget model. It will be shown in Chapter Five that as the beach retrogrades, material from the backshore is re-entered into the active beach sediment system.

4.5 SEDIMENT BUDGET, 1977-1987

4.5.1 Sediment Budget Model Construction

The sediment budget model constructed for the 1977-1987 period was based on the model of Kirk and Hewson (1979), where the beach was divided into cells to detect transport directions within the beach. Four cells based on morphological features were adopted. The Washdyke Barrier was divided into two cells; one north and one south of the renourishment. Another cell was created between Aorangi Road and Trounces, a heavily stopbanked section of the beach. The final cell, between Beach Road and the Opihi 01S000, was considered to be under the influence of the Opihi River.

When constructing the model, several assumptions were made. Littoral drift from the south of Dashing Rocks was not

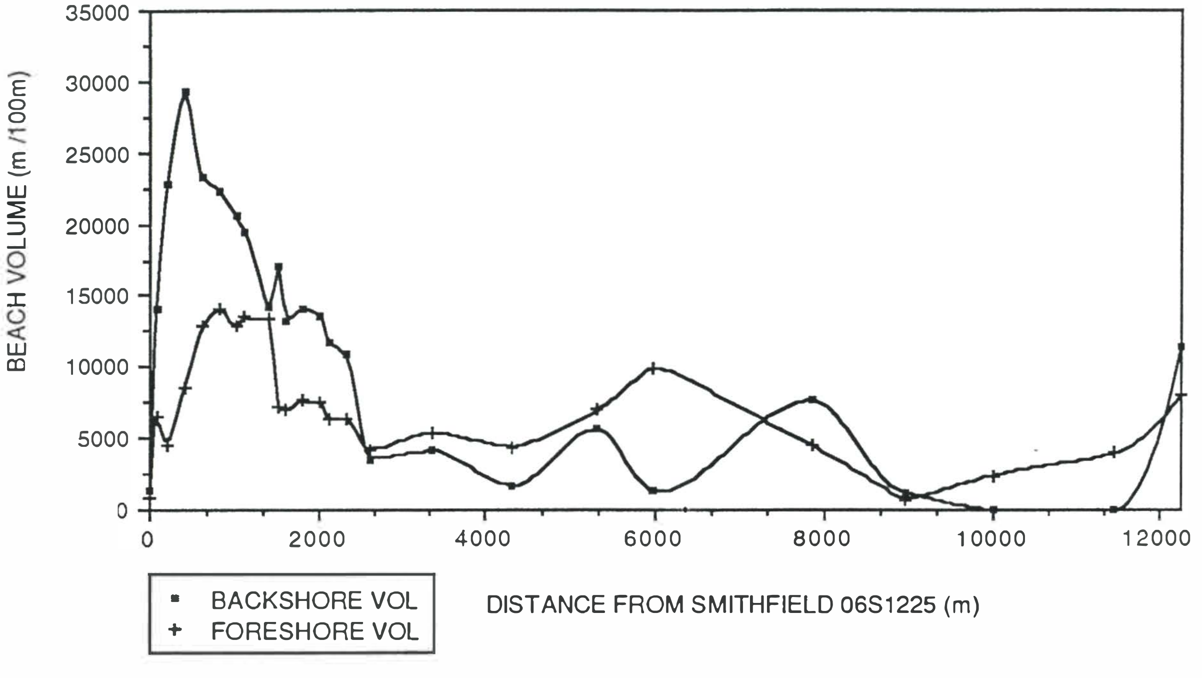


Figure 4.7 Comparison of Backshore and Foreshore Volumes

considered a source, due to accretion behind the breakwater. The input from the eroding substrata was also rejected as this was an unknown quantity. Kirk (1967) noted it was difficult to determine the source of beach gravels (River or Cliff). This also applies to substratum gravels. Adams (1978) concluded that abrasion on coarse grained beaches may be as much as 30% greater than that found in his tumbler experiments. This value has been used by Kirk (1980) to infer that for the Canterbury Coast, three to five percent of active beach gravels are lost offshore annually. Thus, it is assumed that an annual three percent (minimum) offshore loss occurs on the study beach. Onshore transport was assumed to be nil, following Carter and Heath (1975) and Hastie (1982, 1983). It was postulated that the material injected into the renourishment has remained within the original cells. Finally, it was considered that sediment transport to the backshore was not considered a loss, as previously indicated.

Therefore, within each cell, the value of net volume change for the time period was entered. From this total, three percent was indicated as being lost offshore. To balance the volume of each cell, the remainder was shown to travel in a longshore direction. The direction depended on whether the adjacent cell had lost or gained sediment within the given time period.

4.5.2 Sediment Budget, 1977-1987

Figure 4.8 shows the sediment budget calculated for this period. It can be seen that the greatest volume loss has occurred within the Aorangi Road-Trounces cell (-247,142 m^3), while the southern Washdyke Barrier has gained 40,194 m^3

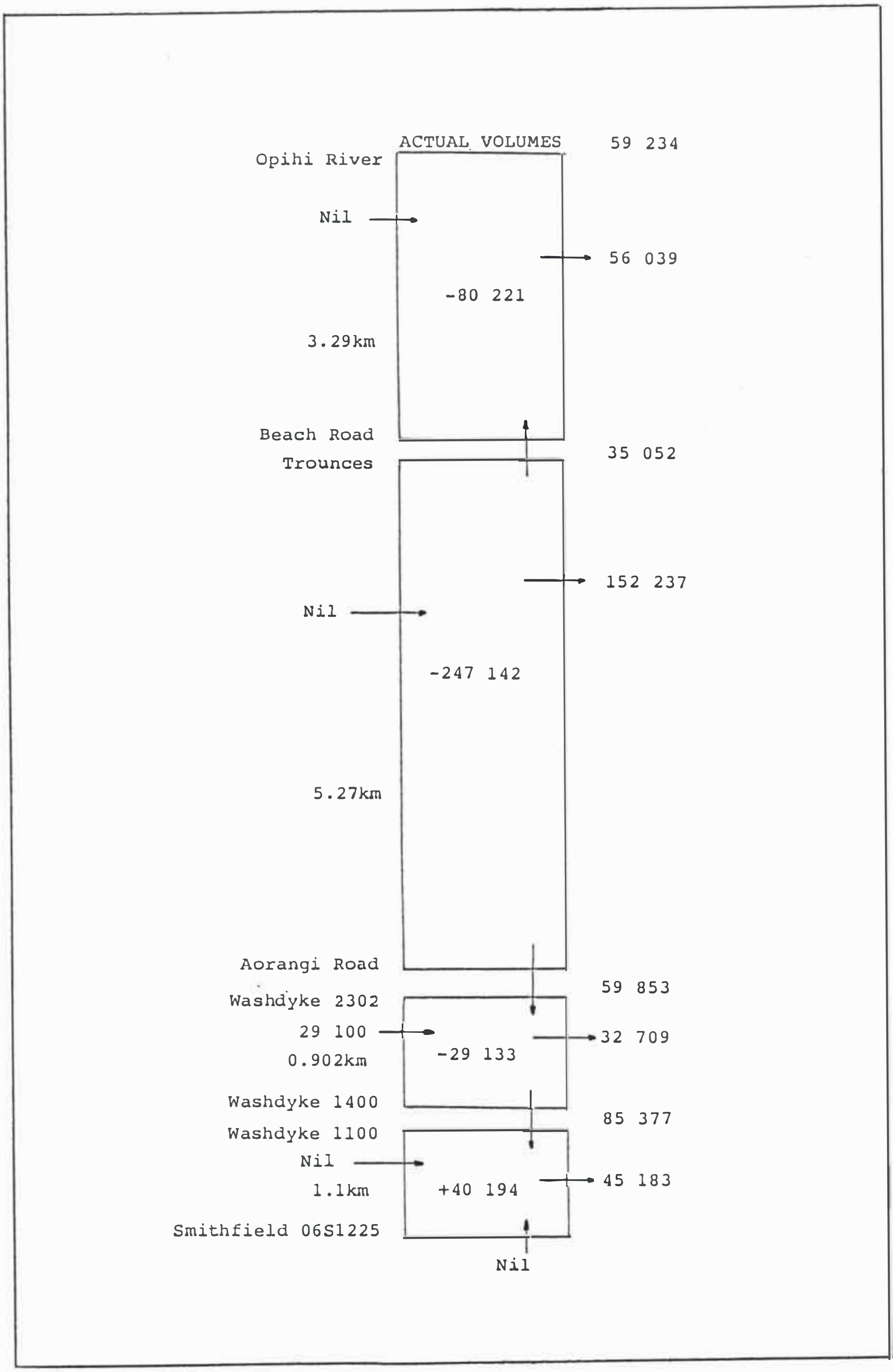


Figure 4.8 Sediment Budget, 1977-1987
Units in m^3

of material from the renourishment and natural sources as mentioned. Although net drift is considered to be in a northwards direction (Blair, 1890; Kirk, 1967, 1969; van Mechelen, 1978, etc.), it can be seen from Figure 4.8 that transport has occurred in both directions in this period. That some southerly drift has occurred, is supported by the grain size-sorting trends shown in Chapter Three, and the recovery of the Washdyke Barrier breach (March, 1986). South Canterbury Catchment Board survey data also show drift direction variations within this time. For example, between the 1977 and 1984 surveys, the cell between Aorangi Road and Beach Road showed a net loss of 215,519 m^3. During the next survey period (1984 to 1986) the same cell had gained 25,729 m^3. This accumulation was observed by Kirk (1987), who asserted:

> "Significantly, an area of net sediment gain and lower foreshore volume losses occurred in the vicinity of Beach Road. Why this should be so is uncertain but it serves to underline the complex pattern of erosion and may reflect longshore variation in the transport of beach sediments."

This complex variation of longshore transport has been confirmed by Neale (1987), examining beach drift on mixed sand-gravel beaches, south of Timaru. Neale found that sediment moves alongshore in erratic pulses.

The sum of the cell values divided by 12.25 (km) shows volume losses per kilometre of beach. This was found to be 25,820.57 $m^3.km.^{-1}$ for 10 years, or 2,582.05 $m^3.km^{-1}.yr^{-1}$. This loss is of a similar magnitude to that shown by Kirk (1987), who for 10.85 km of the study coast, suggested a loss of 26,420 $m^3.km.^{-1}yr^{-1}$ for nine years. These values appear to be average rates of sediment transfer, for the whole beach, as it is shown in Table 4.2 that rate of sediment transfer within each cell is highly variable. These variable transfer rates are considered to reflect the complex sediment transport systems described by Kirk (1987) and Neale (1987).

4.6 CONCLUSION

Although there has been a general appreciation of varying thickness of beach sediment overlying the substratum, previous studies in this area have not quantified the amounts. This chapter approached this using data from beach excavations, profile surveying and seismic profiles.

Maximum beach thickness was found to be at the intersection of the lava, beach sediment and substratum at the southern end of the beach. Minimum thickness was to the north (between Beach Road and Connolly's Road), where beach sediment was often found to be completely absent. On average, the Washdyke Barrier sediments were thicker than those of the Seadown Coast.

The Washdyke Barrier profiles were found to have more volume per hundred metres than the Seadown Coast. However, in absolute terms, the Seadown Coast contains more sediment. These patterns were considered a function of beach width and length. Backshore volumes dominated on the Washdyke Barrier where deposition by overwashing is unconfined. In contrast the Seadown Coast is foreshore dominated as stopbanking diminishes the development of washover lobe deposition.

A sediment budget model was developed in a similar fashion to that of Kirk and Hewson (1979). It was found that sediment transport had occurred in both directions with the

Table 4.2 Comparison of Sediment Transfers, 1977-1987

CELL	Sediment Gains & Losses $m^3.km.^{-1}yr^{-1}$
Smithfield 06S1225-Washdyke 1100	+3654.0
Washdyke 1400-Washdyke 2302	-3229.8
Aorangi Road-Trounces	-4689.6
Beach Road-Opihi 01S000	-2438.3

Note: -ve = loss, +ve = gain.

10 year period (1977-1987). The section of beach between Aorangi Road and Trounces has lost most sediment while at the southern end of the Washdyke Barrier, net accumulation of approximately 40,000 m^3 has taken place. Of this 29,000 m^3 was artificial input into the renourishment.

CHAPTER 5

THE HINTERLAND

5.1 INTRODUCTION

No previous examinations of the hinterland structure backing the Washdyke-Opihi beach have presented highly detailed accounts of its morphology as a whole. Most previous studies of the hinterland have been either on a small scale, expressing general sedimentary patterns and little detail, or have been orientated towards specific projects. Examples of this can be demonstrated by the New Zealand Geological Survey's sheet 20 (1967) and New Zealand Soil Bureau's sheets 4 and 8 (1954, 1964), which show general patterns covering a large area. Alternatively, boreholes have been drilled since the early 1960's and more recently in the mid 1980's (Fitzmaurice and Partners Ltd, 1985), relating primarily to the old and new Timaru City sewage projects respectively. Thus, the information obtained from these individual projects is very site specific.

The main objective of this chapter is to give a detailed account of the terrestrial structure immediately under and behind the beach. A knowledge of this kind is important as it is these sediments upon which the beach will migrate and ultimately erode. It will be shown that the sediments supplied to the beach are considered to influence patterns of erosion.

5.2 SAMPLE COLLECTION

Sediment samples of the substratum were obtained whilst digging through the beach as explained in the previous chapter. Only samples from the substratum's surface were collected, penetrating to approximately 0.5 m below its surface in most cases. This was due to three factors. Firstly, it is the substratum's surface material that is under the direct influences of the beach, particularly under the stresses of compression. Secondly, in many cases the excavator would become unstable when digging through thick, unconsolidated beach sediment, as indicated in the previous chapter. Finally, only surface samples were obtained, as these will be the first to erode as the beach encroaches onto the land behind it, thus exposing the underlying material to wave energy. This process has been documented as early as 1893 (Timaru Herald, 17.11.1894, p.4) when engineers examined the beach between Dashing Rocks and the Opihi River, and stated: "There are evidences that the beach rests upon a stratum of loamy clay, which is cut away and thrown further back as the sea encroaches further onto the clay beneath". This subsurface of clay was observed regularly during the field research, especially at the northern end of the beach, between Beach Road and Connolly's Road.

Like beach surface samples, substratum samples were placed in labelled bags for identification later. A total of 18 substratum samples were collected. All samples were analysed in the Geography Department's Geomorphology and Biogeography Laboratories.

5.3 METHODS

Substratum samples were analysed using sieving methods described in Chapter Three. However, borehole samples were analysed on the Geography Department's Rapid Sediment Analyser (R.S.A.). This method is based on the settling velocity of sediments in a fluid, its main advantages over sieving being the speed of analysis, and the automatic printout of results by a computer. It should be noted that sediments greater than 2.0 cm in diameter cannot normally be analysed by this method. This is due to the existence of a critical ratio between the sediment diameter and the dimensions of the settling column. The borehole samples were less than 2.0 cm in diameter.

Only substratum and hinterland samples with an obvious coarse element (sand or gravel) were analysed. It was considered that because coarse sand was the finest material found on the beach surface, material finer than this would be of little value to future sediment budgets. Thus, only nine of the substratum samples, and nine borehole samples were analysed for statistical parameters.

5.4 RESULTS

Table 5.1a shows that five of the nine substratum samples were dominated by gravel, four by sand and none by granules. Only four samples could be subjected to full analysis by Folk's (1965) parameters. This was because the largest sieve size used was $-2.0\,\phi$ (4.0 mm). Hence, on the grain size-frequency curves, material greater than 4.0 mm is

TABLE 5.1 Substratum Sediment Data

a) % Size Class

Sample Location	% Pebbles (< -6.0 ϕ)	% Granules (< -1.74 ϕ)	% Sand (> -0.77 ϕ)	% Clay (< 4.23 ϕ)
Washdyke 200 LF	76.64	7.64	15.32	0.4
Washdyke 600 LF	59.86	8.0	29.70	2.44
Washdyke 1000 BS	4.30	3.87	80.5	11.33
Washdyke 1400 LF	2.66	2.27	85.43	9.64
Washdyke 1400 BS	4.50	4.13	74.04	17.33
Washdyke 1800 LF	56.32	9.79	28.06	5.83
Washdyke 2302 BS	16.43	0.30	79.0	4.27
Kings LF	78.42	8.49	12.97	0.12
Horseshoe Lagoon LF	54.33	12.80	31.05	1.82

b) Folk Parameters

Location	M_Z	σ_I	SK_I	K
Washdyke 1000 BS	-1.73	1.628	-0.255	0.924
Washdyke 1400 FS	-1.95	1.861	-0.117	0.876
Washdyke 1400 BS	-2.03	1.445	-0.228	1.025
Washdyke 2302 BS	-1.60	1.33	-0.068	0.789

LF = Lower Foreshore

BS = Backshore

not subdivided and its upper limits are not specified (Appendix 5.1). Table 5.1b shows that mean grain size ranged from 2.03 ϕ (pebbles) to 1.6 ϕ (granules), and sorting (σ_I) varied between 1.88 ϕ to 1.38 ϕ (both poorly sorted). Skewness varied from being near symmetrical (-0.06) to coarse skewed (1.02), whilst kurtosis ranged from mesokurtic (1.02) to platykurtic (0.78).

Borehole data were similarly variable (Table 5.2), showing a slightly finer mean grain size than the substratum samples, ranging in size from -0.89 ϕ to 0.93 ϕ (very coarse to coarse sand). This variation is thought to be a reflection of local change in grain size rather than an actual decrease on a regional scale. Sorting values fluctuated between 1.48 ϕ (poorly sorted) to 0.61 ϕ (moderately well sorted). Skewness values ranged from -0.11 to 0.77 (coarse skewed to strongly fine skewed) and kurtosis values varied between 1.32 (leptokurtic) to 0.74 (platykurtic).

Thus, if the mean values for each parameter are taken (Table 5.2), the hinterland sediments could be classified as being a very coarse, poorly sorted, fine skewed mesokurtic sand. However, because of the wide variety of sediment sizes available and the highly local distribution of them, descriptions such as that above are of little use when concerning the regional area. It will be noted that silts and clays are absent in Table 5.2, although they are shown in the hinterland maps. These were removed by wet sieving so as not to contaminate the water column of the R.S.A.

TABLE 5.2 Rapid Sediment Analysis of Borehole Samples

Sample	$M_Z\ \phi$	$\sigma_I\ \phi$	SK_I	K	% Gravel	% Sand
1, 0-3 m	-0.58	1.09	0.16	1.05	38.45	61.55
1, 3-9 m	-0.89	0.66	-0.11	1.09	39.08	60.91
1, 4-12.5 m	-0.11	1.28	0.11	0.93	25.34	74.64
1, 12.5-15.5 m	0.43	1.18	0.29	0.89	4.67	95.33
1, 15.5-20 m	0.93	0.79	0.0	1.18	0.46	99.54
2, 0-11.5 m	0.48	1.48	0.03	0.74	18.8	81.2
2, 14.7-20 m	-0.64	0.85	0.02	0.95	0.01	99.99
3, 0-12.5 m	-0.72	1.3	0.27	0.96	45.9	54.1
3, 16-20 m	-0.76	0.94	0.74	1.32	41.86	58.13
MEAN	-0.206	1.06	0.16	1.01	23.84	76.15

Sample numbers (1,2,3) relate to positions on Figure 5.4.

5.5 SUBSTRATUM COMPOSITION AND SEDIMENT DISTRIBUTION

Several maps were constructed to emphasise the spatial distribution and variety of sediments composing the substratum surface and hinterland. The methodological approach towards the construction of the maps varied for the substratum and hinterland environments.

For the substratum sediments, the first step in the map construction process was to locate the sites where the substratum were observed by excavator and shovel. At these points, the types of sediments recovered were then plotted. As can be seen from Figure 5.1, large gaps occur between the observed sites. To rectify this, it was assumed that the midway points between the sites were the boundary points of the different sedimentary units. Although this method is not to a high scale of accuracy, it presents a more complete picture than has been forwarded in the past. For example, N.Z.G.S., sheet 20 (1967) implies the Washdyke Barrier substratum and immediate hinterland is constructed of uniform alluvium, beach and swamp deposits. This description is correct, but the map does not show the complex lenticular type pattern of the adjacent soil units, as demonstrated in Figure 5.2.

Figure 5.2 shows that the substratum can be divided into seven very general sediment categories; gravels, sands, muds, pugs, clays, peats and remnant stopbank material. Although the boundaries are highly generalised as already indicated, it appears that the substratum is far from being a simple uniform deposit. Rather, it is a series of complexly interlinked, individual sedimentary units. Map 2

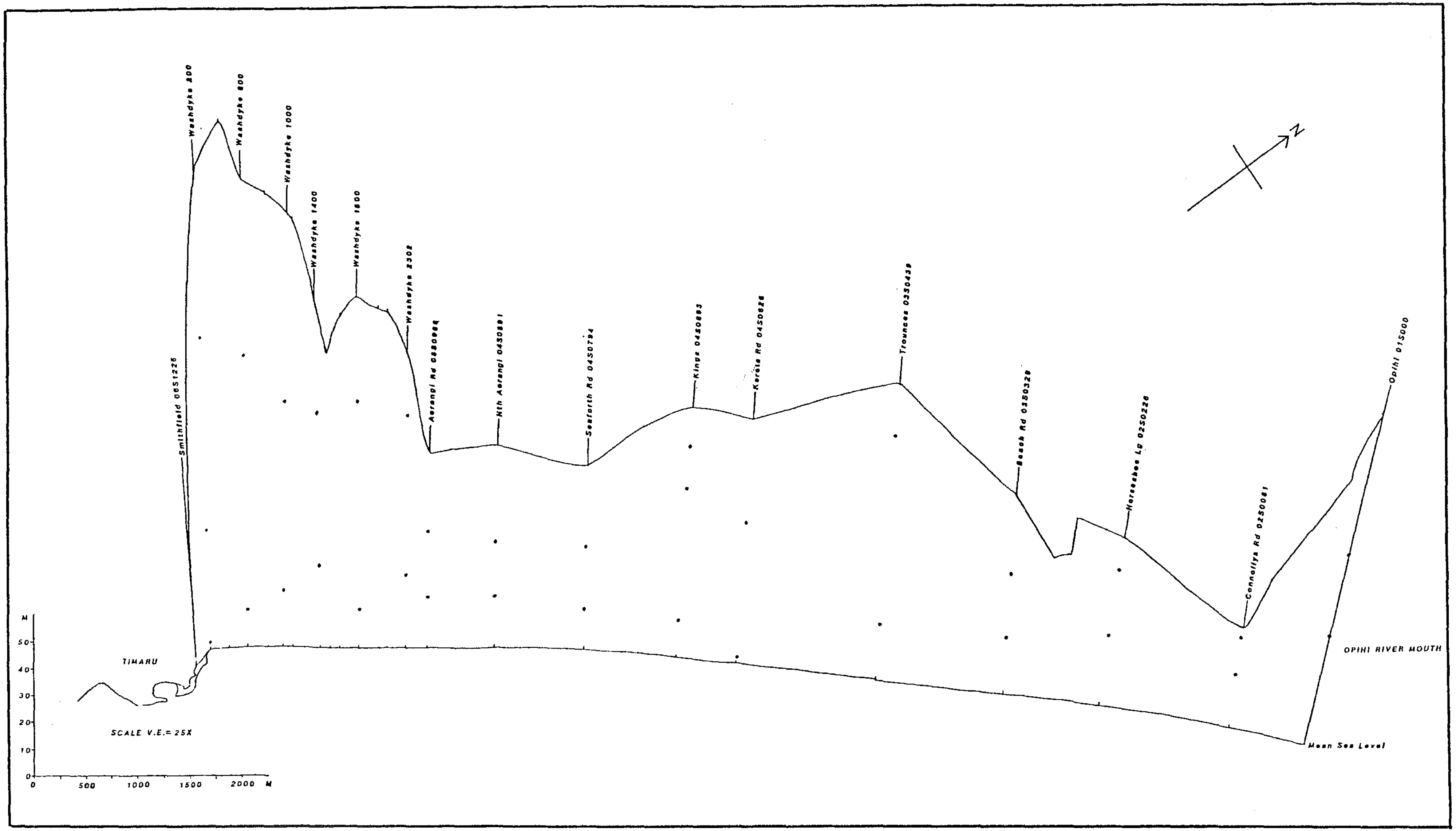


Figure 5.1 Excavation Sites for Substratum Sample Collection

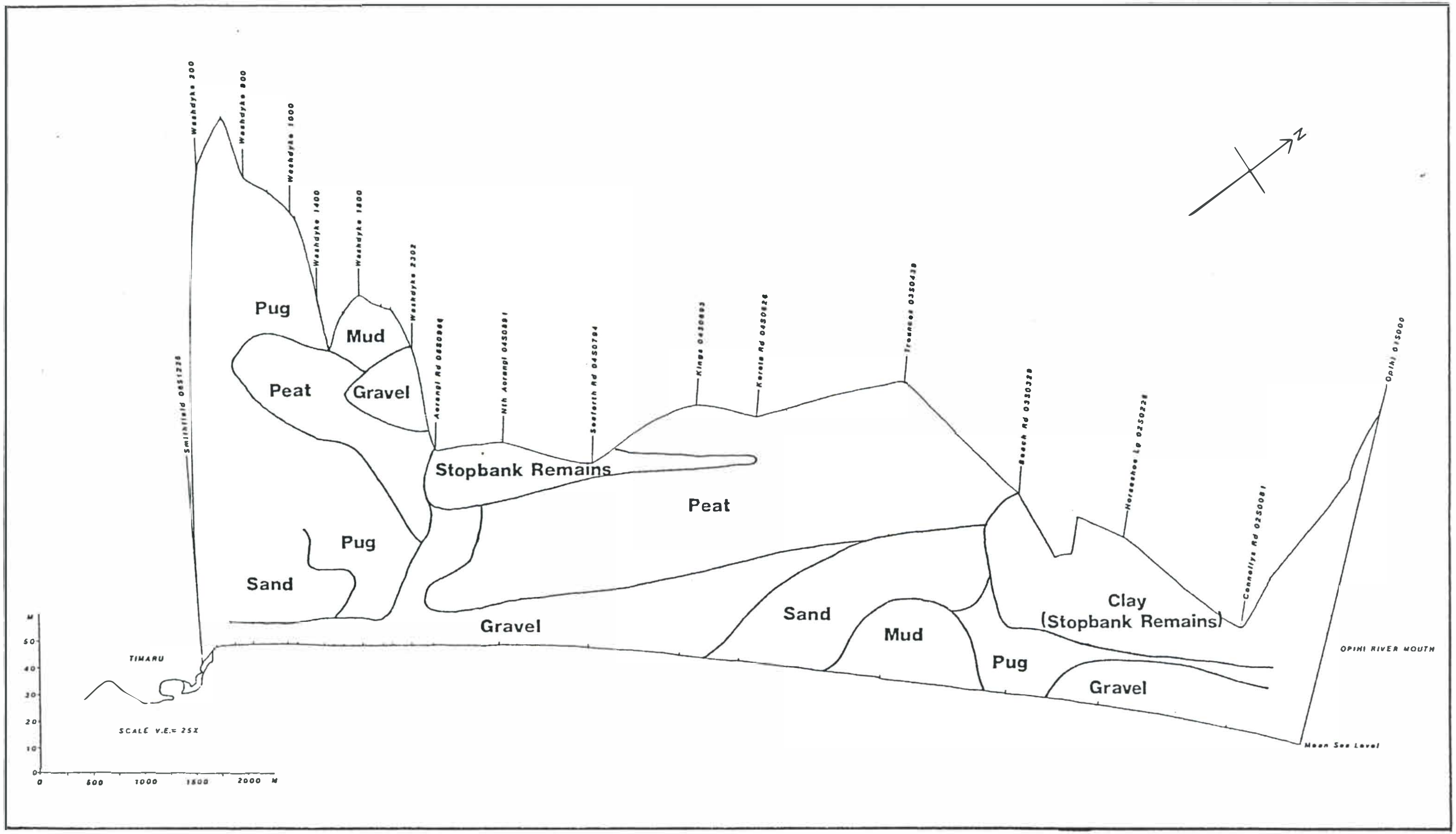


Figure 5.2 Major Sedimentary Units of the Substratum

(back cover) gives a more detailed version of Figure 5.2. This map shows all sites where the substratum materials were observed during the study, accompanied with relevant descriptions. From the descriptions offered, it is apparent that the seven major units (indicated by dotted lines) can be substantially subdivided when taking sedimentary detail into account. For example, the pugs can be divided into gravelly or sandy pugs; peats can be divided into muddy peats, gravelly peats, woody peats and so forth.

This highly erratic, non uniform pattern of sedimentation is consistent with that of migrating river channel deposition in low lying swampy areas, where the channels in their wake leave a variety of deposits ranging from gravels to silts and clays (Reineck and Singh, 1975). These sediments of the substratum are most likely to be palaeochannel deposits of the Opihi River. This is suggested for three reasons. Firstly, because of the visual difference in shape, the oxidised nature of the gravels, and the overall soil structure, the sediment appears to be fluvial in origin, with the Opihi River being the only one in the vicinity. Secondly, it can be seen from maps that all of the southern Canterbury Plains rivers are orientated nearly parallel to each other, in a NW-SE direction, except the lower reaches of the Opihi River, which runs almost due east. This suggests a channel migration similar to that of the Waimakariri River, north of Christchurch. This evidence is substantiated by the fact that aerial photographs reveal old channel marks on the ground surface.

5.6 SUBSTRATUM INFLUENCES ON BEACH MORPHOLOGY

The surveyed levels of the substratum height showed a progressive increase towards the Opihi River. Several correlations were undertaken to determine if this had any influence on ths beach morphology, including beach width, height, slope and thickness. Of the parameters above, only sediment thickness was found to be directly controlled by the substratum elevation. This was due to differential compaction of the substrata under the weight of the beach sediment. Along the Washdyke Barrier, the substratum composed of fine grained soft material, is easily compressed. However, along the Seadown Coast, gravels and old stopbank remnants provide a more solid base, hence compaction is minimal. Substratum profiles showing these differences are given in Appendix 5.2.

As the substratum elevation increased, sediment thickness was found to decrease correspondingly. Figure 5.3 shows this relationship. If the substratum and foreshore are considered as smooth, uniform planes (simplest case), then it can be seen that the beach sediment thickness remains constant along the beach. The cross sectional shape of the beach is also constant (Figure 5.3a). However, if the substratum height is raised relative to the foreshore at the northern end of the beach, then the sediment becomes thinner and the cross sectional shape of the beach changes along its length. This is because the crest height remains relatively constant along most of the beach. Hence changes in topography below the beach are responsible for sediment thickness changes.

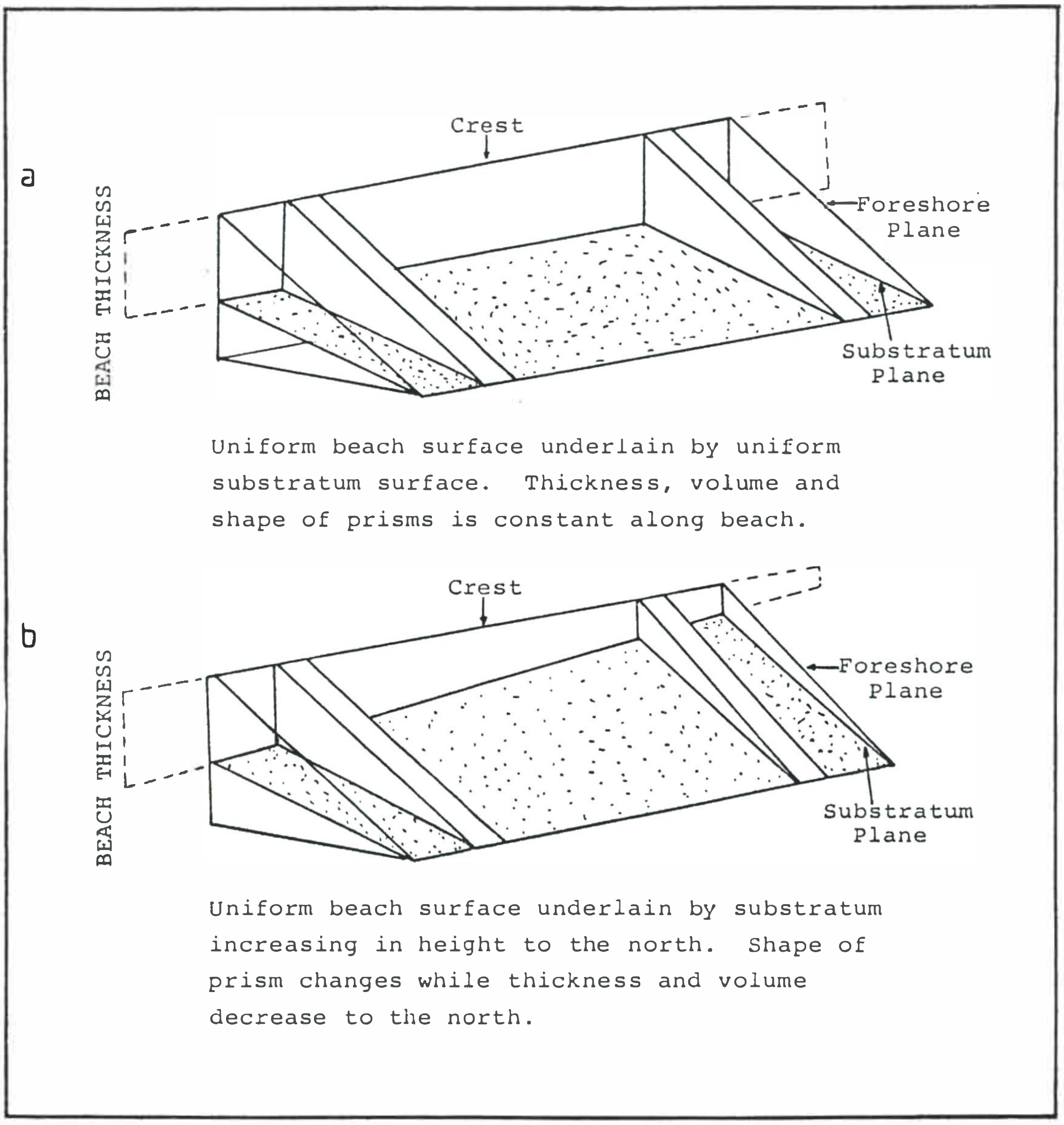


Figure 5.3 Relationship Between Substratum Height and Beach Thickness

5.7 THE HINTERLAND STRUCTURE

The hinterland backing the Smithfield to Opihi Beach is of low elevation and lacks topographic relief. Serious social/economic problems are caused by a combination of this low relief and heavy seas. Areas along the Seadown Coast for example, are particularly prone to seawater flooding. In April and July 1977, two severe storms, estimated to have a return period of 10 years, struck the coast. In the July storm the stopbanks were overtopped for 10.6 km, flooding 220 ha of prime farm land (Todd, 1987).

Being so low the hinterland is vulnerable to wave attack of this nature reasonably frequently, and thus the sea has little trouble in pushing the beach in a landward direction. Because of this it is important to understand the hinterland structure, to estimate which areas along the reach will put up most resistance to future wave attack, so appropriate measures can be taken to counteract the problem.

Basic hinterland structure, showing the major soil units have been published in maps by the New Zealand Soil Bureau (sheet 4, 1954 and sheet 8, 1964) and the New Zealand Geological Survey (sheet 20, 1967). The main use of these maps in relation to the present study, was to obtain ages for the various formations, and to get a broad indication of what sediments should be expected to be found. The two major points to emerge from these maps are that most of the soils are recent, and belong to the Templeton, Wakanui and Waimakariri silt loams, with varying amounts of gravel and sand. The Washdyke Lagoon sediments form part of the Temuka complex. Beneath these soils are the Cannington Gravels from the

Wanganui period. Hence, except for the Timaru Basalt, the area is one predominantly of alluvial outwash and channel deposits.

Data from 21 boreholes were collected. The locations of the boreholes are shown in Figure 5.4. From the log sheets it was apparent that correlation of sedimentary units would be difficult. In some cases correlation between holes was impossible, and hence constructing highly detailed, completely infilled plan maps was not attempted.

The most appropriate method of showing the spatial array of hinterland sediment was to construct maps, by plotting sediments in relation to elevation planes. Maps were constructed for the 1.0 m, 2.0 m, 4.0 m, 6.0 m and 8.0 m planes below the ground surface. These maps are shown in Figure 5.5 (a-e). It should be noted that these are not horizontal surfaces, but dip very gently towards the sea. The ground surface was used as the level of datum as the lack of a detailed hinterland contour map prohibited the fixing of sediment elevations to sea level. The gradients of the hinterland slope were small enough (commonly being less than 1:300) to be considered to have little effect on the map construction.

The maps in Figure 5.5 show the distribution of five types of material - topsoil, gravels, sands, peats and clays. The descriptions were simple for two reasons. First, the well log recordings lacked descriptive detail and, secondly, the emphasis is on the distribution of the major size class components.

It was commonly thought that the hinterland was composed dominantly of fine grained materials, such as peats,

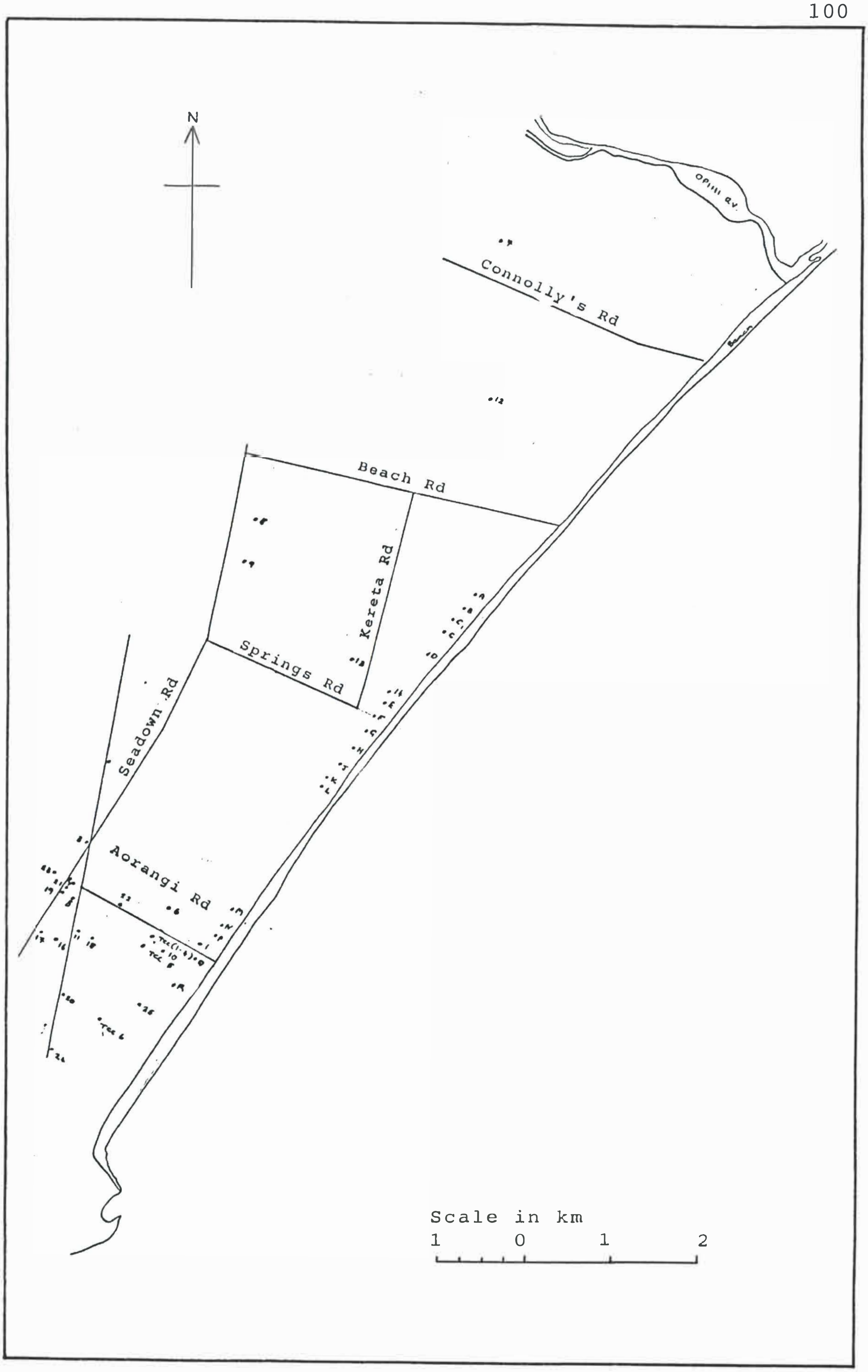


Figure 5.4 Borehole Location Map. Letters and numbers relate to references on Well Logsheets held by the SCCB.

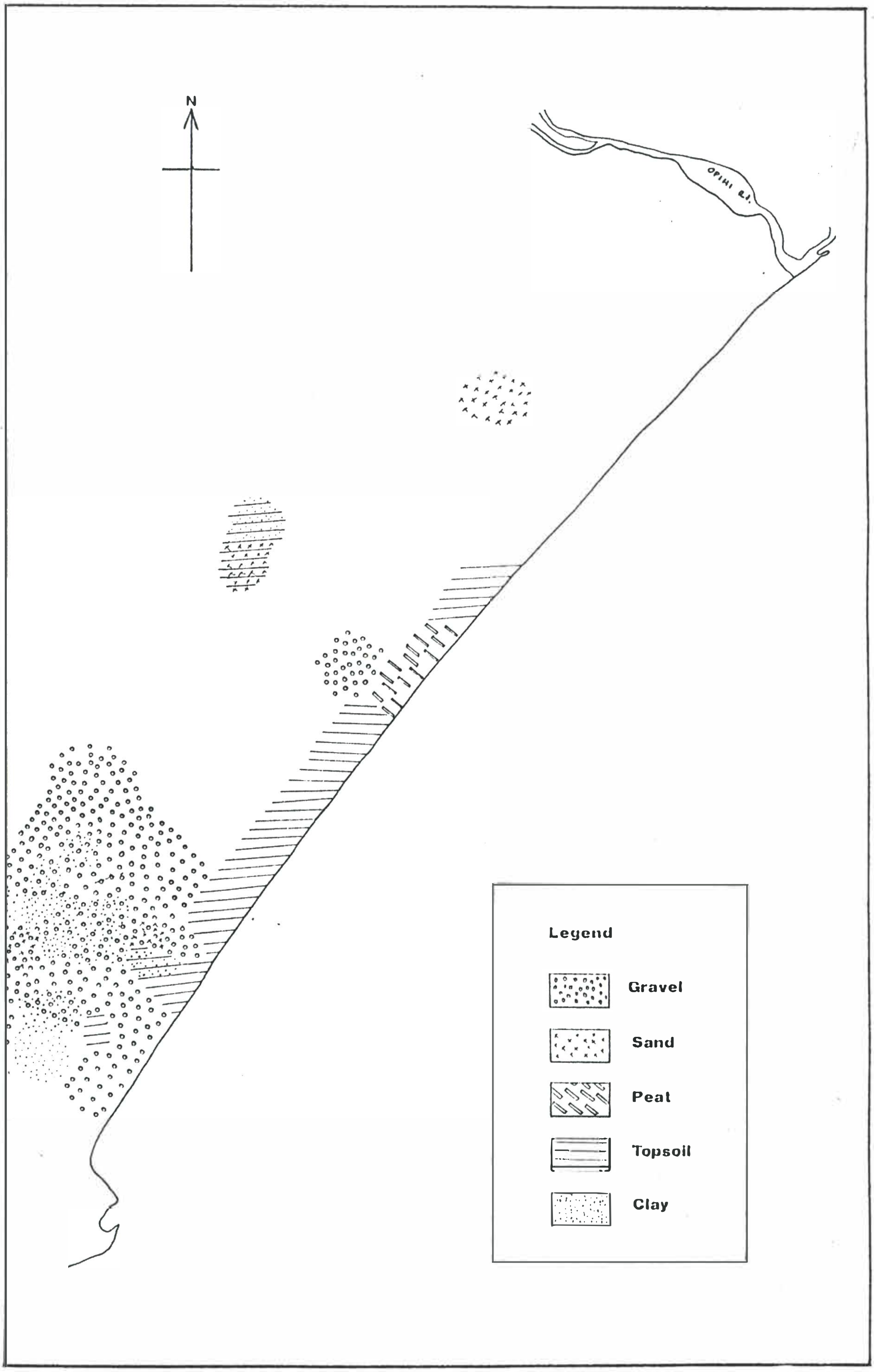


Figure 5.5a Hinterland Subsurface Sediments
One Metre Below the Ground Surface

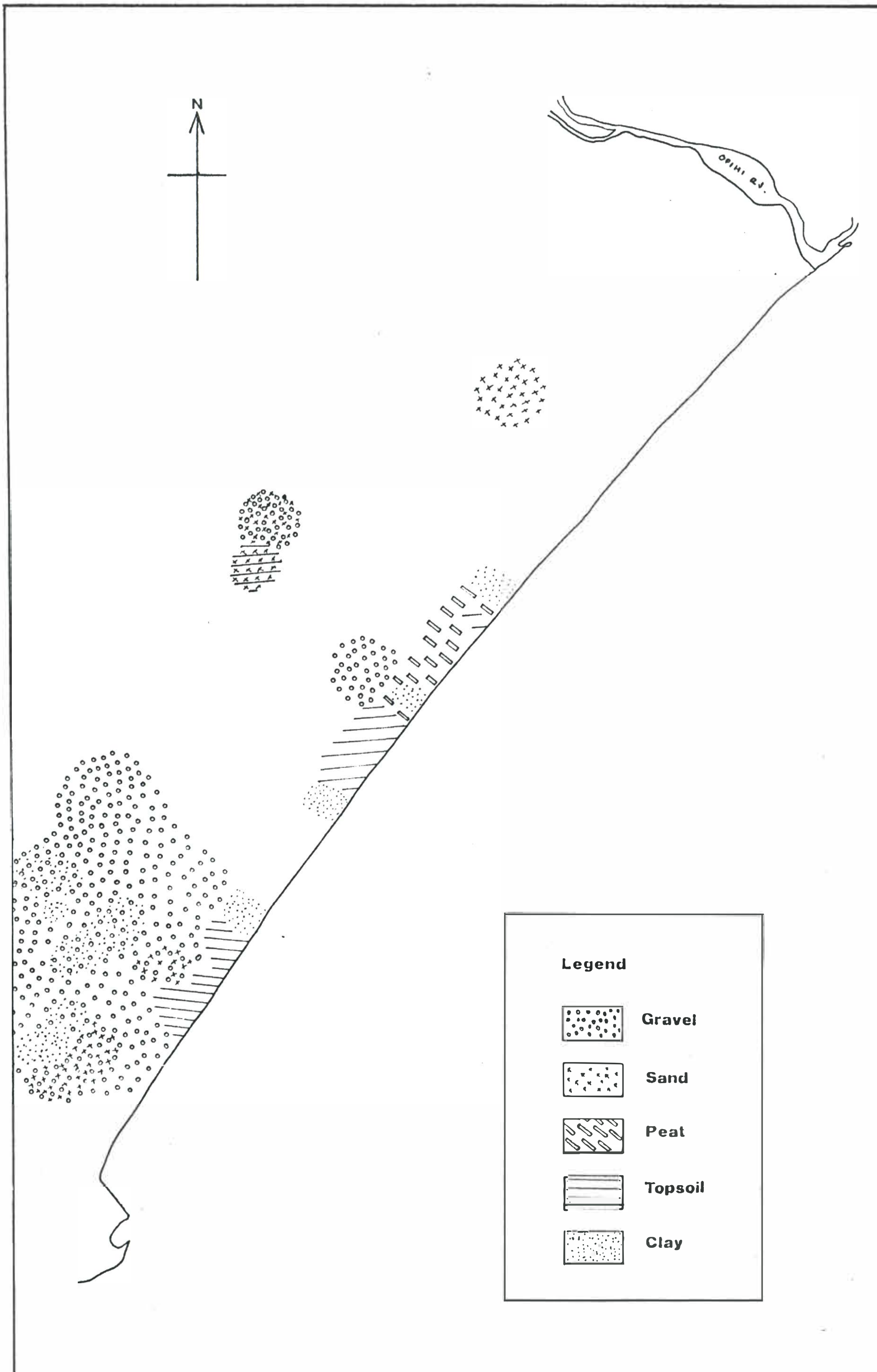


Figure 5.5b Hinterland Subsurface Sediments
Two Metres Below the Ground Surface

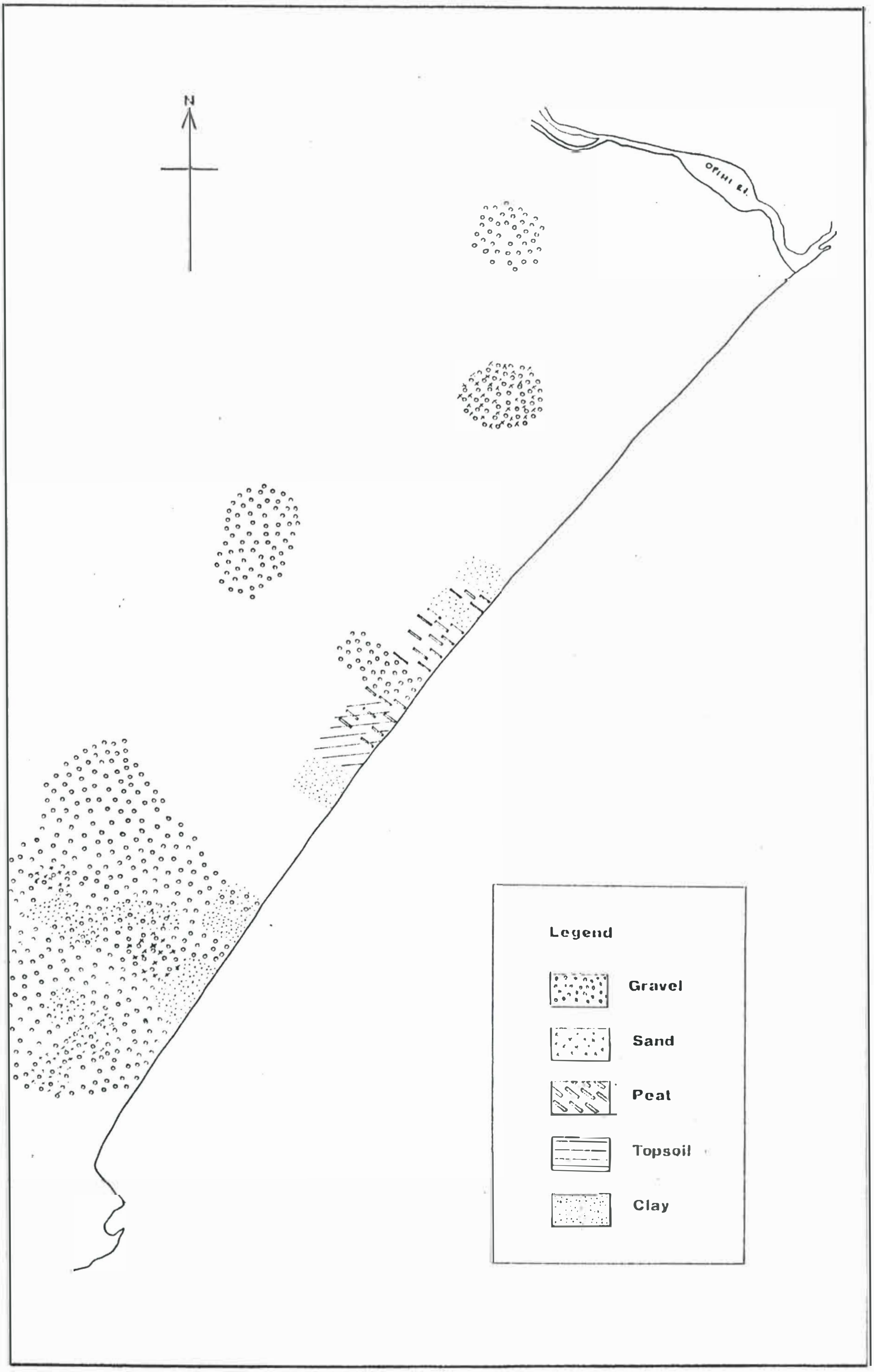


Figure 5.5c Hinterland Subsurface Sediments
Four Metres Below the Ground Surface

Figure 5.5d Hinterland Subsurface Sediments
Six Metres Below the Ground Surface

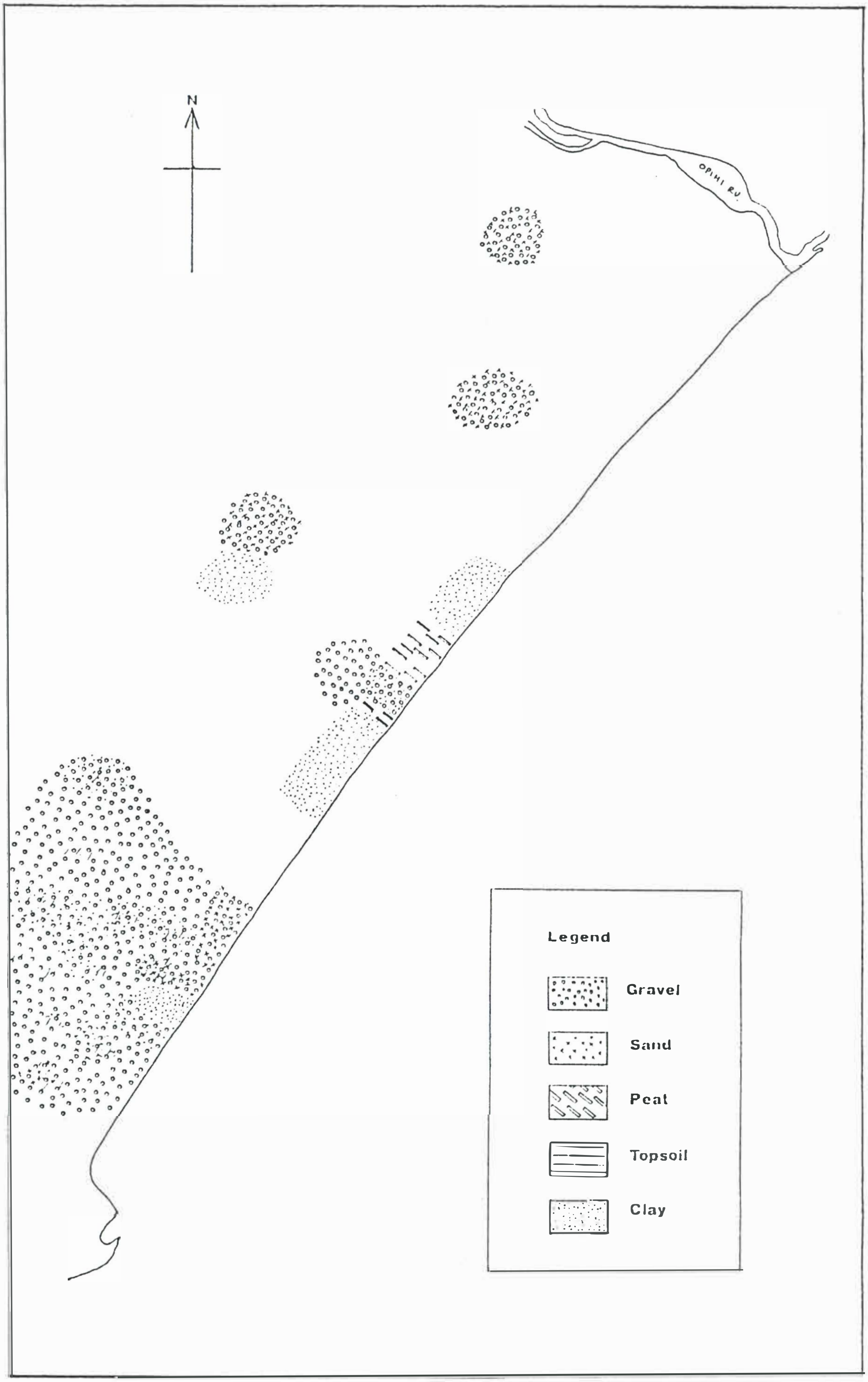


Figure 5.5e Hinterland Subsurface Sediments Eight Metres Below the Ground Surface

silts and clays (van Mechelen, 1978; Kirk, 1987). Examination of the maps in Figure 5.5 illustrate on all levels that gravel was commonly found. A notable feature shown in the maps is that the sediment tends to get coarser with depth and to the landward. Most of the fine material is concentrated within the top four metres of soil. This is significant, as it is these materials that will suffer the initial force of wave energy, when the beach encroaches on to the immediate hinterland. Hence, it seems that the first material subdued by the sea will offer little resistance to erosion.

Nevertheless, these fine materials (particularly peats) appear to be confined to a relatively thin strip, parallel to the coast. Holes further inland are dominated by sandy and silty gravels. If this is so, initial rapid erosion of the fine, soft sediments may be slowed down considerably upon reaching the coarser material inland. This theme will be expanded in the next chapter.

The gravels and sands are of large enough size to be contributed to the beach system, as was shown from the substratum samples and R.S.A. analysis. However, whether the gravels of the hinterland could be sustained on the beach remains to be seen. It was noted in Chapter Three that gravels from the substratum were quite often heavily oxidised. From descriptions of the well logs this is common in the hinterland samples also. These brown/yellow oxidised gravels are known to be weaker than the grey, unoxidised variety. This was shown by Kirk (1967) and was observed in the present study, where the oxidised gravels were easily broken relative to the grey gravels. Hardcastle (1908, p.24) observed the weakness of the lowland hinterland gravels and stated:

> "The gravels of the downs are yellow ..., and are so soft, so rotten, as to be practically useless for road making, the purpose for which gravels are most largely used. They crumble very quickly to clay under traffic, and even if only exposed to the weather."

If Hardcastle's statement is accurate it would be reasonable to assume that these gravels would break down rapidly under the pounding and grinding action of swash and backwash. Hence, the point to stress is that although the hinterland sediments in the main are large enough to be contributed to the beach, their internal strength may be such that they are of limited value in the long term.

5.8 THE INFLUENCE OF THE HINTERLAND ON BEACH MORPHOLOGY

At present the lowlying hinterland itself has little direct influence on the beach morphology. Nonetheless, if the stopbanking is considered to be part of the hinterland proper, then a strong relationship can be seen between the hinterland and beach width. It has been noted that the stopbanked Seadown reach consists of a narrower beach than at the unconfined Washdyke and Opihi lagoons (van Mechelen, 1978) and is dominated by foreshore volumes. This appears to be in response to the limitations imposed on landward migration of the beach toe by stopbanks. The phenomenon is represented in Figure 5.6. It can be seen from the diagram that the beach crest and toe are free to migrate contemporaneously. When stopbanks are installed, the beach toe - the leading edge of the retrograding beach encounters the stopbank, an obstacle to migration. Hence, the toe migration halts, but the crest migration continues, thus becoming out of phase.

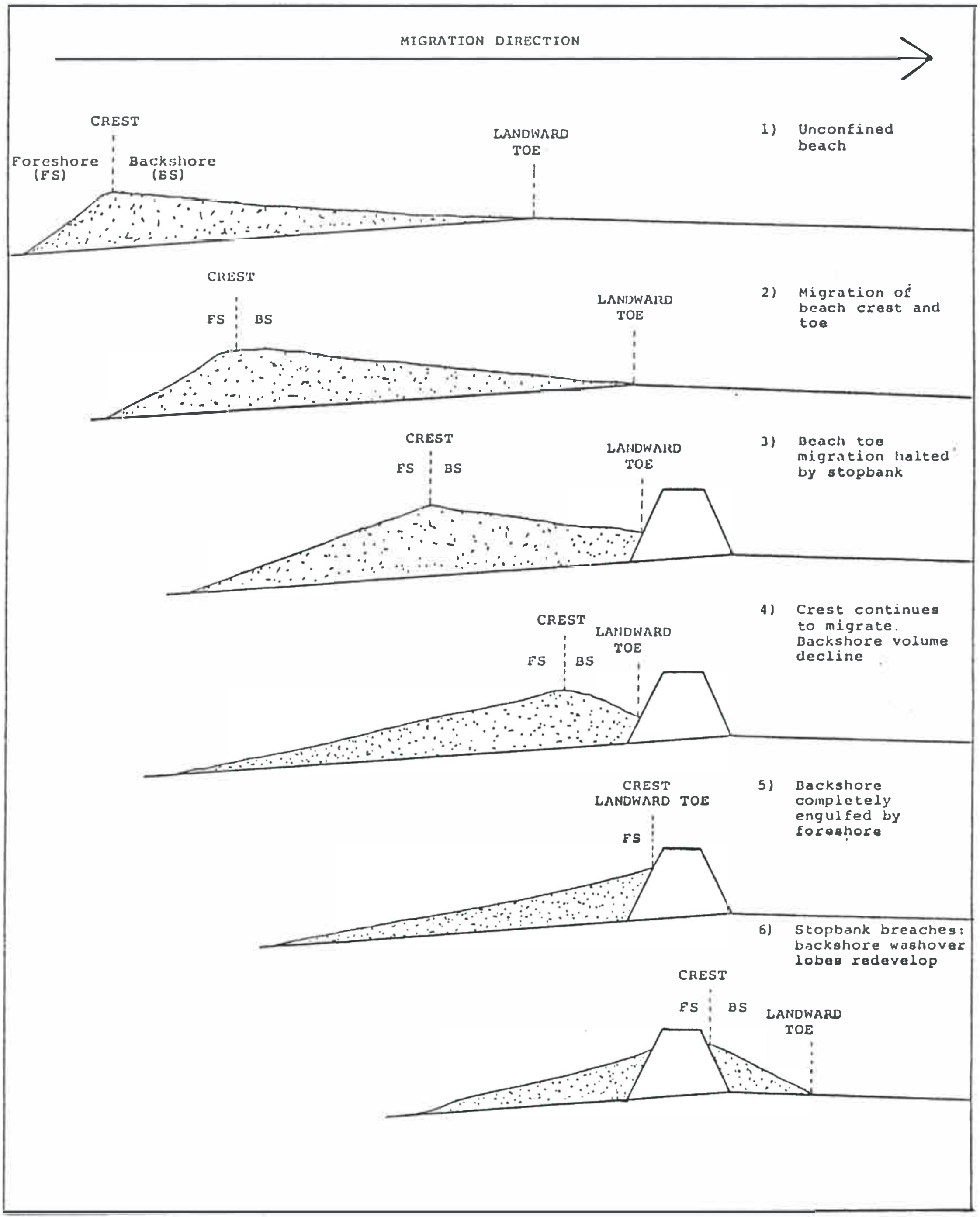


Figure 5.6 Changing Morphology of a Retrograding Beach Encountering a Stopbank

As the crest heads landward, the foreshore increases at the expense of the backshore, due to overwashing down the backshore being restricted by the stopbanks. The peak of this process is when the crest is juxtaposed on the halted toe position. The beach at this stage is totally comprised of foreshore.

The final phase of this process is when the stopbank is breached allowing renewed beach width expansion as washover lobes are deposited. If this process is plotted graphically (Figure 5.7), with X being the migration distance/direction and Y being backshore/foreshore width ratios, an asymmetrical inverted distribution curve is shown. As the crest continues to migrate towards the halted toe, the foreshore width increases simultaneously with backshore width decline, until the backshore has nil width and foreshore is completely dominant. When the stopbank breaches, initial rejuvenation of the backshore is relatively rapid, going from nil to (N) width in a single event. Backshore development then tapers off as washover is infrequent. If the process is carried through all its stages, the beach in profile tends to migrate similar to a giant sand wave (Figure 5.6). This process controlling beach width can be seen in all phases along the study beach from the unrestrained width at Washdyke, to the peak of development at Horseshoe Lagoon and Connolly's Road where backshore is non existent against the stopbanks. Localities such as Beach Road represent the final phase of development, as no backshore was present in 1977 (being confined against the stopbank), to the present situation where the stopbank has breached and a backshore has redeveloped.

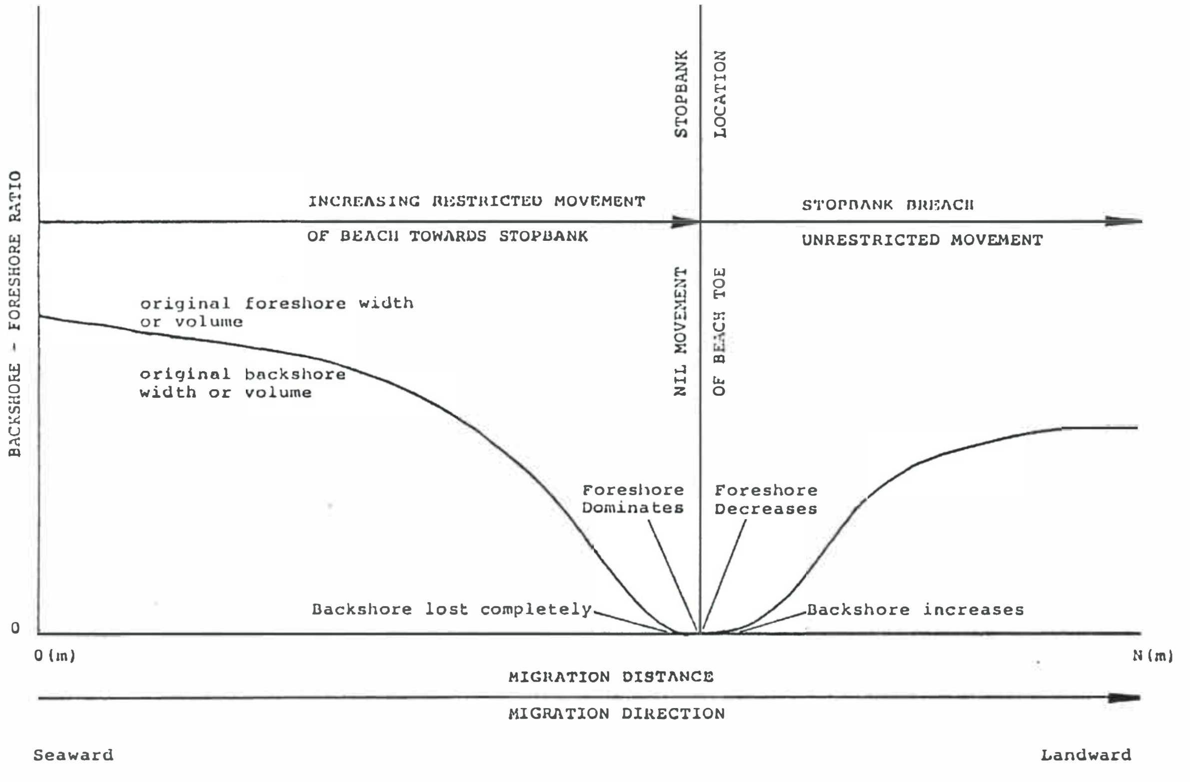


Figure 5.7 Changing Foreshore-Backshore Ratios of a Retrograding Beach Being Confined by a Stopbank

5.9 CONCLUSION

Sediment data were obtained first hand and from borehole information collected over approximately the last 20 years, to give an account of the hinterland and substratum structure along the study beach. The substratum and hinterland were found to be an association of complex channel-swamp-lagoon sediments, deposited by a palaeochannel of the Opihi River. Sediments from both environments ranged from silts and clays to quite coarse gravels. A significant quantity of gravel from the hinterland could be supplied to the beach - the amount increasing further inland. However, the gravels appeared to be of low strength, hence their value to the beach in the long term may be lessened. It should be noted that mechanical testing of rock strength was not carried out in this study.

Although the substratum affected gravel thickness it had little influence on beach surface features. Gravel was thicker at the Washdyke end of the beach. It was suggested that this was due to differential compaction rates between the soft natural deposits of the Washdyke Barrier substrata, and the generally harder, higher substrata of the Seadown Coast. Much of this was remnant stopbank material. The hinterland, particularly the stopbanking, has a direct influence on the beach width and its ability to move landwards. Upon reaching a stopbank the beach cross sectional shape was found to change. Unconfined beaches as at Washdyke are backshore slope dominated, whilst those confined by stopbanks (e.g. Connolly's Road) can be completely foreshore slope dominant.

CHAPTER SIX

COASTAL EROSION AND FUTURE SHORELINE PREDICTIONS

6.1 INTRODUCTION

Although this chapter examines one topic - that of coastal erosion, it is divided into two major sections. The first examines historical coastal erosion trends from 1865 to 1987. This section concentrates on the past positions of the coast and rates of erosion. Information determining these patterns was based on photogrammetric maps and ground survey data. Once past erosion trends have been established, the discussion will turn to future coastal predictions - the second section of the chapter.

Rather than predicting where the coast will be at given times, the emphasis will be placed on estimating the life span of the Washdyke Lagoon, the Seadown drain, and the remaining beach sediment. This approach was chosen as it was mentioned in Chapter One, that the Washdyke Lagoon and Seadown drain will be the first community assets to succumb to coastal erosion. Determining the life of the remaining beach sediments is also important as this is considered to be dwindling to vanishing point (Kirk, 1987, pers. comm.).

6.2 CALCULATION OF EROSION

6.2.1 Methods

Aerial photographs (1934, 1956, 1967, 1977, 1987) and the 1865 survey data were sent to the Department of Survey and Land Information, Photogrammetric Unit, Wellington. Here, past coastal positions were plotted onto large scale (1:2500 and 1:500) versions of the 1987 aerial photographs. It should be noted that the 1934 coastal position was not plotted. This was because of interpretation difficulties due to the poor quality of the photographs. Also, measurements are not given for the profiles Smithfield 06S1205 and Opihi 01S000 up to 1977. This was because the Smithfield profile was not plotted on the photogrammetric maps, and at the Opihi River mouth many overlapping lines made measurement difficult. The deletion of these profiles is not thought to significantly affect the overall results. The photogrammetric maps combined with the South Canterbury Catchment Board's ground survey data were used to determine coastal changes. Net erosion up to 1977 was measured by the following formula:

$$Gs = Md \times Ms,$$

where Gd = Ground distance (m)

Md = Map distance (mm between crest positions)

Ms = Map scale factor (either 2.5 $m.mm^{-1}$ or 5.0 $m.mm^{-1}$).

Having determined actual ground distances, erosion rates were calculated by the formula:

$$R = \frac{D}{T}$$

where R = Erosion rate ($m.yr^{-1}$)

D = Distance between crests (m)

T = Time interval between crests (years).

From 1956 to 1987 distances between beach crests were used. Between 1865-1956, the 1865 Mean High Water Mark (M.H.W.M.) to the 1957 beach crest was measured. This was due to the 1865 crest not being mapped. However, because of the narrower beach in 1865, the distance from M.H.W.M. to crest was not likely to be more than 20 m. This represents about 5% of the total erosion up to 1956. The 1865 M.H.W.M. was chosen as this is a standard reference line used. No attempt was made to estimate the 1865 beach crest position as it was not known if the crest-M.H.W.M. relationship has remained consistent over time. Kirk (1975) noted inherent errors in aerial photography interpretation. These included camera optic distortion, personal error and deviations of the aircraft from the correct flight path and altitude. To these Gibb (1978) added that surveyors in New Zealand used seven different reference lines as the shoreline (Figure 6.1). Except for radial distortion which had been removed in the photogrammetric maps, the above problems were encountered in this study. It was observed that the 1987 crest position on the photogrammetric maps was inconsistent with the South Canterbury Catchment Board's ground survey data. Kirk (1987, pers. comm.) suggested that on beaches with broad, flat crests (as on the Washdyke Barrier), determining the crest from aerial photographs was difficult. Hence ground surveys were more accurate. Thus, coastal changes between 1977-1987 are measured from South Canterbury Catchment Board survey data.

Different time scales are considered to detect differences in long and short term erosion trends. The 1865-1987 long term period is subdivided into four intervals. These include three short term intervals (1956-1967, 1967-1977, 1977-1987) and one of the long term (1865-1956). These intervals were based on the periods between each information

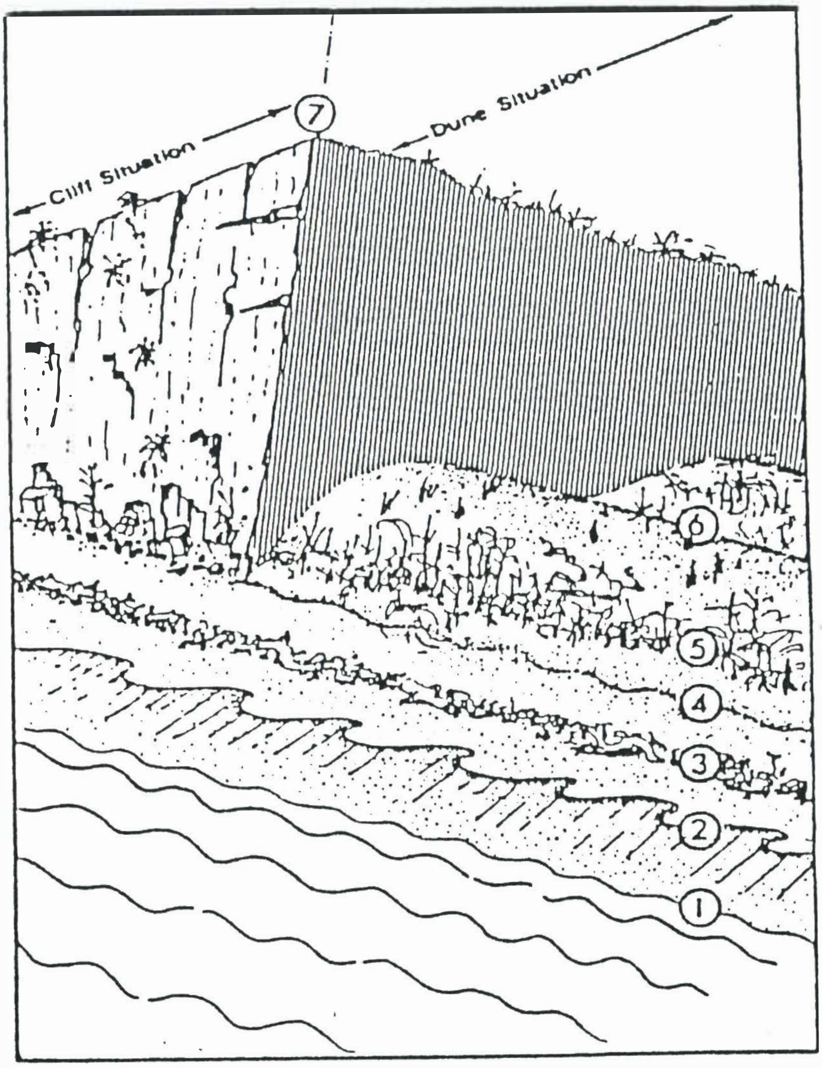


Figure 6.1

Seven reference lines used by New Zealand land surveyors to define the shoreline (MHWM) on cadastral plans over the century 1870-1970:
1 - Geodetic MNWM (average height of the high-tides over an 18.6 y period); 2 - "Wetted" line; 3 - Driftwood line; 4 - Toe of foredune or cliff; 5 - Vegetation line; 6 - Crest of beach ridge or foredune; and 7 - Top edge of cliff.

(after Gibb, 1978)

source. Methods of prediction will be discussed in the Future section of the chapter.

6.2.2 Results

Average erosion amounts and rates of erosion are shown in Table 6.1 (full measurements are in Appendices 6.1-6.3). These patterns show similar forms of erosion regardless of time scale. Erosion rates on average are highest along the Washdyke Barrier and decrease along the Seadown coast. This is in common with the findings of McIntyre (1958), van Mechelen (1978) and Kirk (1979, 1982, 1987). Places of highest and lowest erosion for the time periods fluctuate. These are shown in Figure 6.2.

Average erosion curves for the four time subdivisions are shown in Figure 6.3. It can be seen that the Washdyke Barrier and Total Beach curves show a general decrease, being interrupted by a large increase during the 1967-1977 period. The decline in erosion rates over the last ten years (1977-1978) is more rapid than the overall long term decrease (1865-1987). Erosion was declining at a rate of 0.01 $m.yr^{-2}$ for the Total Beach between 1865-1987. For the last ten years this rate of decrease accelerated to 0.2 $m.yr^{-2}$. Corresponding values for the Washdyke Barrier were 0.01 $m.yr^{-2}$ and 0.23 $m.yr^{-2}$. Between 1865 and 1977 erosion at Seadown increased very slightly. Erosion increased at a rate of 0.003 $m.yr^{-2}$. The 1977-1987 decline of erosion for Seadown occurred at a rate of 0.15 $m.yr^{-2}$.

Net beach movement has been greatest at Washdyke 200. Here the beach has retrograded approximately 440 m since 1865 (1865 mean high water mark to 1987 crest). Erosion has been

Table 6.1 Average Erosion Amounts and Rates (1865-1987)

Erosion Amounts (m)

	1865-1956	1956-1967	1967-1977	1977-1987	1865-1957
Total	-249.28	-25.85	-31.90	-11.35	-321.06
Washdyke	-292.42	-26.80	-37.41	-13.9	-374.1
Seadown	-186.16	-24.38	-23.33	- 7.79	-238.55

Erosion Rates ($m.yr^{-1}$)

Total	-2.73	-2.34	-3.18	-1.13	-2.62
Washdyke	-3.2	-2.43	-3.73	-1.39	-3.06
Seadown	-1.99	-2.21	-2.33	-0.77	-1.95

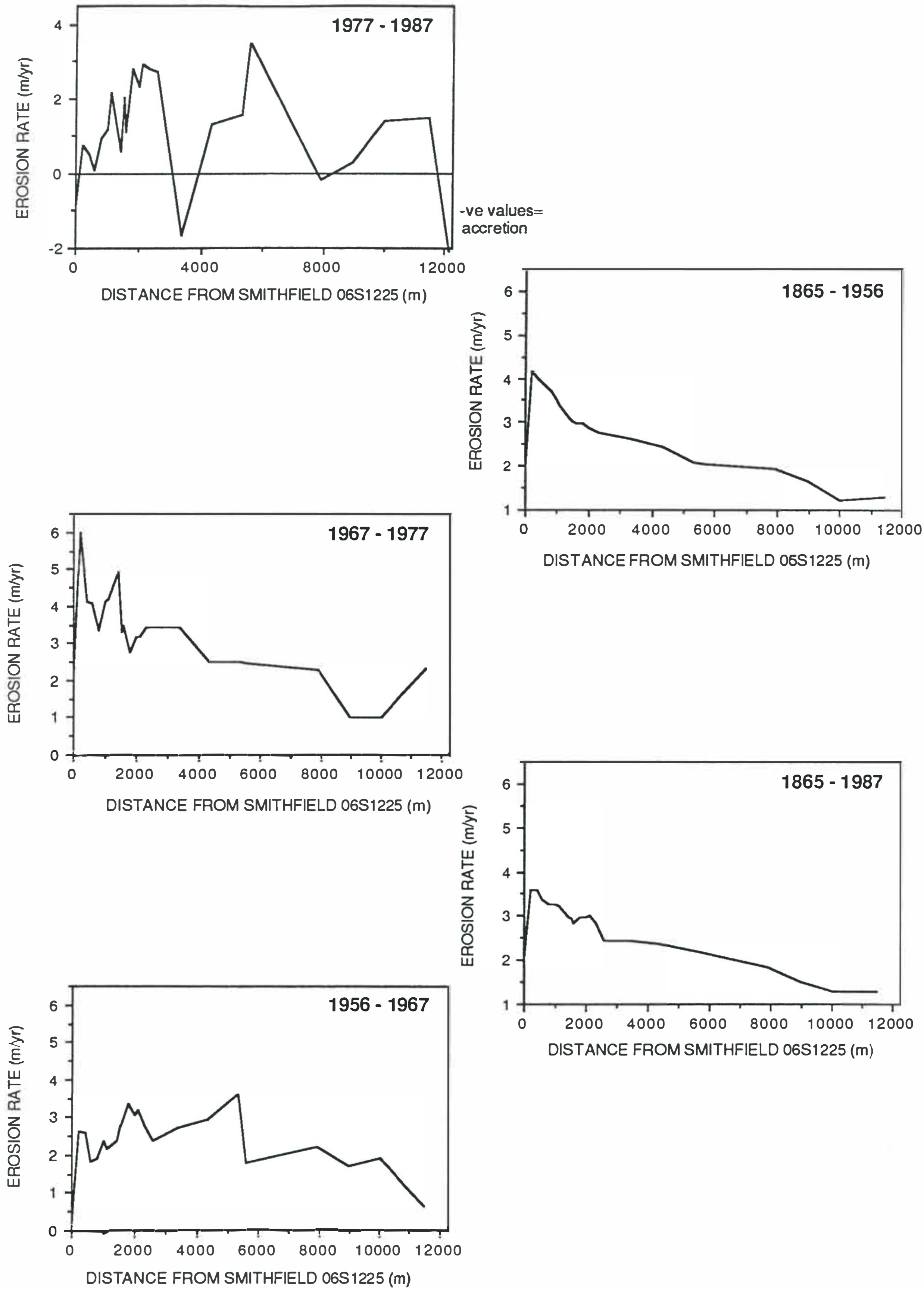


Figure 6.2 Average Erosion Rates for Each Time Period

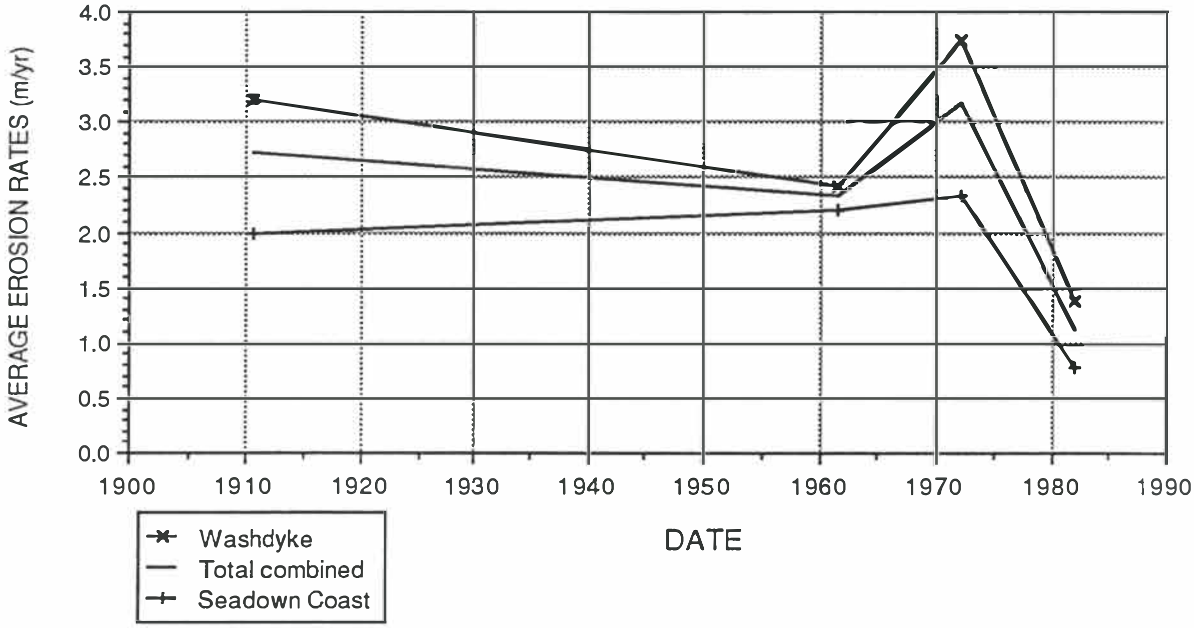


Figure 6.3 Average Erosion Rates for the Washdyke Barrier, Seadown Coast and Total Beach

least at Horseshoe Lagoon and Connolly's Road. Both have retreated 157.5 metres since 1865.

6.2.3 Comparisons with Previous Studies

Gibb (1978), van Mechelen (1978) and Kirk (1982) have all presented erosion rates covering various sections of the study beach. Care should be taken when comparing the previously calculated values to those of the present study. This is because different time scales are being considered. It is well known that short term erosion rates show greater fluctuations than long term values. For example, the highest erosion rate calculated was -6.0 $m.yr^{-1}$ (1967-1977) at Washdyke 200. This compares to the highest 1865-1987 value of -3.6 $m.yr^{-1}$ at Washdyke 200.

The method of measurement is also critical as large differences in erosion rates can occur for the same area. Table 6.2 shows a comparison of van Mechelen's (1978) erosion values measured directly off aerial photographs of 1956-1977, to those measured off the photogrammetric maps for the same period. It is apparent that rates of erosion calculated in this study are generally much less than those presented by van Mechelen (1978).

For the Smithfield-Opihi Beach, van Mechelen (1978) found the highest erosion rate at approximately 700 m along the Washdyke Barrier, being -4.3 $m.yr^{-1}$, decreasing to -2.9 $m.yr^{-1}$ near the Opihi River mouth. Gibb (1978) for selected sites along the study beach, found the Washdyke Barrier to be eroding at a rate of -5.75 $m.yr^{-1}$ (1934-1956), Seaforth Road at -8.0 $m.yr^{-1}$ (1967-1973) and South Opihi at -4.0 $m.yr^{-1}$ (1967-1977). Kirk (1982) considered the erosion rate

Table 6.2 Comparison of van Mechelen's 1978 Erosion Rates and Those of the Present Study (1956-1977)

Profile	van Mechelen (1978) ($m.yr^{-1}$)	Present Study ($m.yr^{-1}$)
Aorangi Road	-2.2	-3.01
Seaforth Road	-3.2	-2.73
Kereta Road	-2.5	-2.11
Just south of Beach Rd	-2.8	-1.88
Horseshoe Lagoon	-2.7	-1.42

to be increasing exponentially along the Washdyke Barrier, with rates of over $-9.0\ m.yr^{-1}$ being recorded. The values presented by Gibb (1978) and Kirk (1982) are also higher than those given in the present study. It should be noted that van Mechelen (1978) is the only one of these authors who state how many profile lines he took measurements from (four). The present study took measurements from 14 profiles along the barrier. This no doubt produces different average rates of erosion.

6.2.4 Coastal Changes Between 1865 and 1987

Figures 6.2 and 6.3 show the relationship between temporal and spatial variation of erosion. It is apparent that erosion is not uniform either spatially or temporally along the coast. Places of maximum and minimum retreat can be seen to vary within each time period, and between successive time periods. The three short term periods display greater variance than the two long term intervals. It can be seen in the long term that erosion rates are consistently higher along the Washdyke Barrier, and decrease along the Seadown Coast towards the Opihi River mouth. This trend follows the findings of McIntyre (1958), van Mechelen (1978) and Kirk (1979, 1982, 1987).

In examining the changing coastal positions since 1865, it was found that the Washdyke Barrier has undergone greater retreat than the Seadown Coast within the same duration. The southern end of the Washdyke Barrier has retreated up to 440 m since 1865, compared to the northern end of the beach (Horseshoe Lagoon and Connolly's Road) which has receded 157.5 m.

This difference in erosion can be attributed to the stopbanks which are known to hinder erosion along the Seadown Coast (van Mechelen, 1978) and the sediment supply. Kirk (1979) noted that because net northerly drift occurred, localities to the north received a cumulative increase in sediment supply, thus counter-acting the erosion. It was demonstrated in previous chapters that net southerly drift can occur. Thus sediment from the Opihi River could be expected to slow erosion at the northern end of the beach.

Maps 3a-b (back cover) show the changing positions of the Washdyke Barrier and Seadown Coast. It can be seen that the two sections of coast behave quite differently. The Seadown Coast has retreated in a parallel fashion, whereas the Washdyke Barrier has rotated significantly, particularly across Dashing Rocks. The beach between Smithfield 06S1225 and Washdyke 200 has rotated anti-clockwise by approximately 53°. This rotation is maximum at Dashing Rocks and decreases northwards. It is thought that the reef presence is responsible for this. It will be noted that Smithfield 06S1225 consistently displayed the lowest erosion rates along the barrier beach (Appendix 6.2). Immediately adjacent, at Washdyke 200, a relatively large increase in erosion occurs. This implies that the reef provides protection to that section of the beach. The U.S. Army Coastal Research Centre (C.E.R.C., 1977), note that wave energy is dissipated across shore platforms, due to the rapid transition of deep water waves to shallow water waves, and friction. Because multiple wave breaking occurs across the platform, smaller, lower energy waves reach the foreshore but do not break directly on it. These processes were found to be working at Dashing Rocks. Multiple breaking across the reef occurred at high tide, and waves were consistently smaller than at the exposed foreshore to the north. At ordinary low tides the reef offers the southern beach complete protection - waves do not reach the foreshore.

Determining an average long term trend for the beach is difficult because of the limited data points, and the inconsistent time intervals used. Examining the average long term curve for the total beach (Figure 6.3) a superficial decrease in the rate of erosion is apparent, being interrupted by the rapid increase between 1967-1977. It would be expected for erosion to increase as suggested by Kirk (1981). As the beach volume diminishes, crest heights and foreshore slopes are reduced, thus overwashing can occur more easily.

It is suggested that erosion may not be decreasing, but that the curve presented (based on four data points) crudely represents an average for a much more complex trend (Figure 6.4). Figure 6.4 shows that erosion could be increasing, but is not reflected because of the few data points available. This appears the more likely situation as there is no apparent reason why erosion should be slowing down.

Thus Figure 6.3 probably represents short term variations within a long term trend. The short term fluctuations since 1967 can be explained in relation to storm events and stopbank breaching. The rapid propagation of erosion between 1967 and 1977 was probably due to at least six major storms. These storms were all classed by Kirk (1987) as significant, indicating overtopping lasted for two or more high tides (12 hours plus). These storms happened in 1968, 1969, 1974

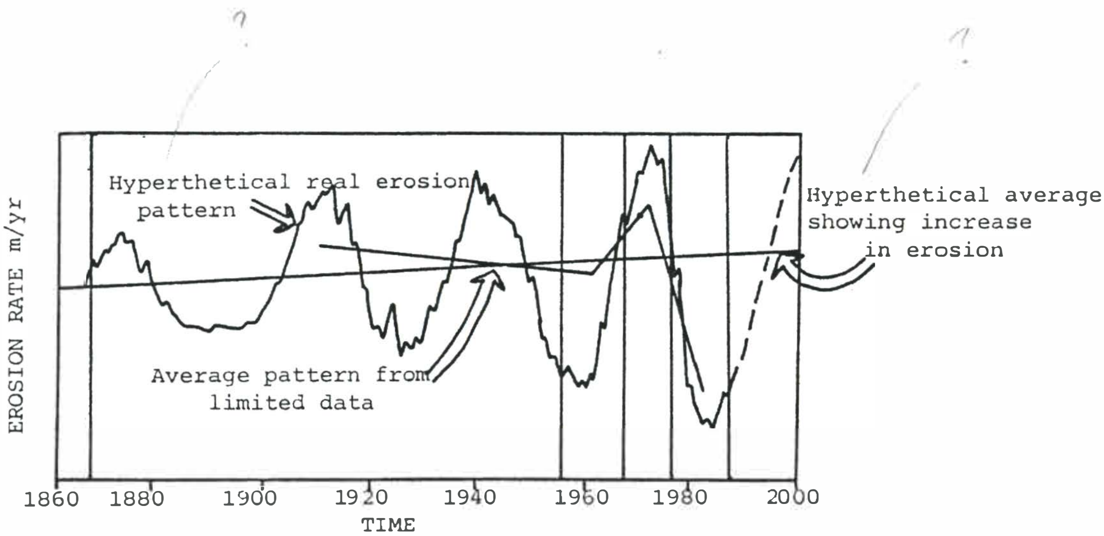


Figure 6.4 A Comparison of the Calculated Average Rate Biased on Limited Data, to a More Probable Erosion Trend

(two) and 1977 (two). The two 1977 storms were responsible for most damage, and occurred before the aerial photographs of that year were taken. Hence, the short term effects explained earlier, would contribute to the large peak on the graphs. For specific details of these storms, one is referred to Kirk (1987, pp.114-116). Conversely, the significant reduction of erosion in the last ten years (1977-1987) has been due to a lack of significant storms.

Kirk (1980) noted that southerly storm waves could strike the east coast of the South Island between 10-15 times per year, with no significant seasonal variation. Kirk (1987, pers. comm.) suggested that repeated storms in quick succession were responsible for greatest coastal damage, and within the last ten years there have been few events of this nature. Rather, storms striking the coast during this period have mainly been isolated events.

The most significant coastal storms in the last ten years were those of July and August 1977, with an estimated return period of ten years, and in 1985 (Kirk, 1987; Todd, 1987). In all cases, large scale flooding of the hinterland occurred, and in 1977, large scale stopbank breaching occurred (Todd, 1987). The most serious event in recent times threatening the existence of the Washdyke Lagoon was the South Canterbury floods of March 1986, where a large section of the barrier was breached (Plate 6.1). However, it should be stressed that this breaching was from the landward side, and not from seawave attack.

It was found that the 1977-1987 period was the only one to show any areas of accretion (Figure 6.2a, Appendix 6.1). This is considered a simple reflection of the

Plate 6.1 Breaching of the Washdyke Barrier, during the South Canterbury flood, 14.3.1986

repeated surveying (South Canterbury Catchment Board), detecting a short term fluctuation, which could not be determined on the photogrammetric maps.

6.2.5 Changes to Beach Geometry 1865-1987

It is well established that retrograding barrier beaches become wider, lower, and flatter in the long term (Zenkovich, 1967; Oxford & Carter, 1982). This is a response to overwashing removing material from the upper foreshore and crest, and depositing it down the backshore as mentioned. Little data exist to determine historical changes of crest height and foreshore slope of the study beach. However, measurements from the photogrammetric maps and ground survey data showed the Washdyke Barrier has increased in width considerably. The Washdyke Barrier has increased from an approximate average width of 61 m in 1865 to 137 m in 1987. Only the Washdyke Barrier was considered at this time scale, as it has naturally responded to the local coastal processes. The Seadown beach (examined in the 1977-1987 time period) is artifically narrow due to the stopbank confines.

The 1977-1987 period showed much less change. Figure 6.5 compares changes of beach width, foreshore slope and crest height. Several important features can be determined. The first is that the Washdyke sections of the graphs show greater variation than the Seadown stretch, thus supporting the notion that the two sections of coast behave differently. Second, beach width has changed very little, confirming a lack of large scale overwashing in this period (Figure 6.5a).

The fluctuations of foreshore slope over the last ten

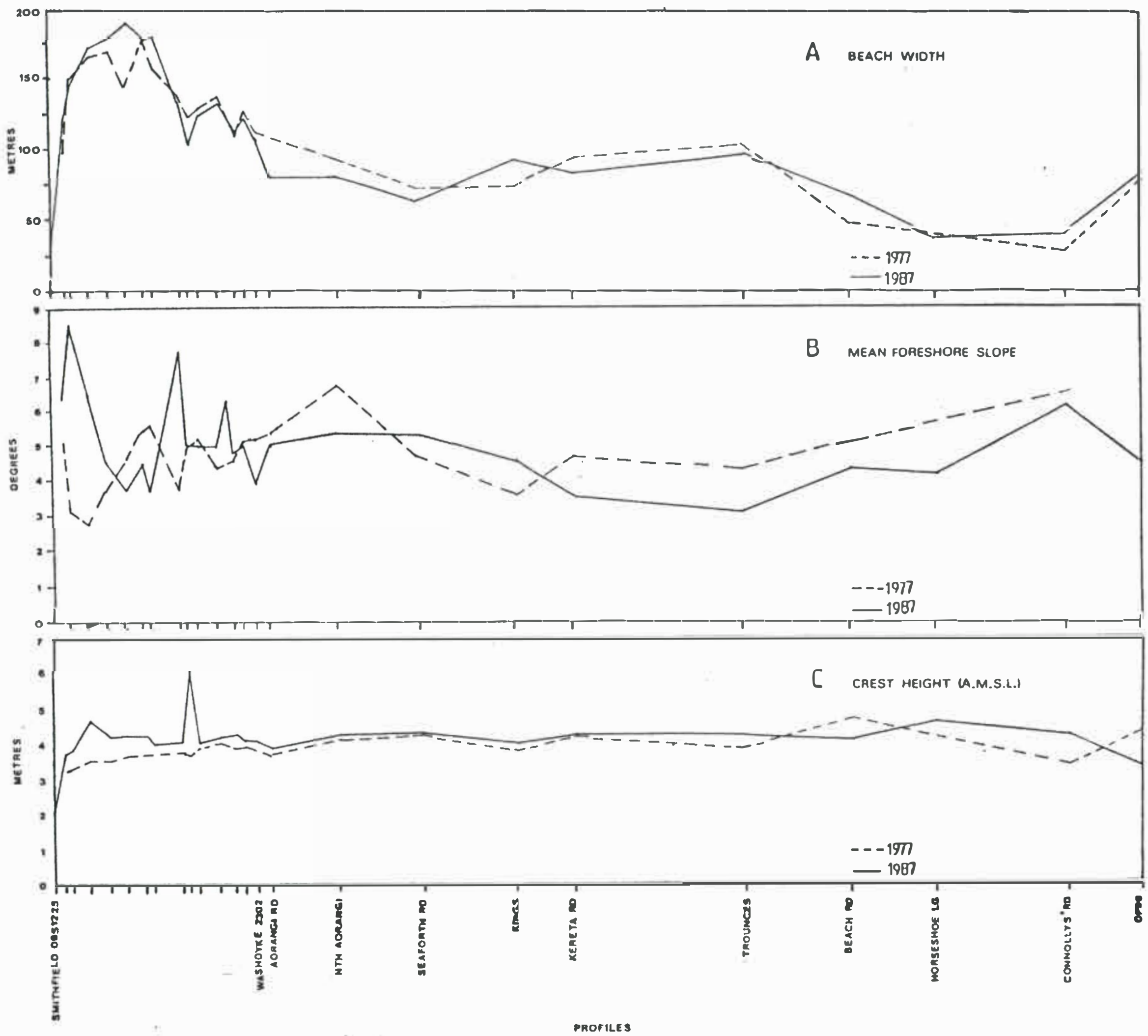


Figure 6.5 Changing Geometric Dimensions of the Beach

years can be attributed to two possibilities (Figure 6.5b). First, along most of the Seadown Coast changes are in the order of 1.0°-2.5°. These small differences could be simply due to survey discrepancies. However, along the Washdyke Barrier changes are much larger (up to about 5.5°). It is suggested that this is in response to the accreting nature of this section of beach. Bascom (1960) suggested flat summer swells built up the berm and prograded the foreshore face forming steep profiles. Conversely, winter storm waves eroded the face and lowered the foreshore angle. Although accretion may be responsible for the increased foreshore slope, it was noted by Kirk (1980) that during erosion, fines may be removed, leaving coarser material, and hence a steeper slope. It is shown in Figure 6.5c that the greatest crest height increase has been along the Washdyke Barrier (even if the renourishment peak is removed). This increase in crest height, combined with the quite rapid recovery of the major barrier breach, implies that net southerly drift has occurred, since at least March 1986.

One of the main aims of the thesis was to predict future positions of the coast. This is now possible having just established the erosion rates and trends characteristic of the field area.

6.3 PREDICTION OF FUTURE CONDITIONS

6.3.1 Methods

Future predictions are based on the simplest model, that of extrapolating the long term erosion rates (1865-1987). Kirk (1979) noted that this was simplistic to the extreme because erosion rates and beach geometry are held constant over time. However, the method was employed because models are not available in the literature for mixed sand-gravel beaches. Sand beach models (Komar, 1983) could not be applied because of the differing behaviour of the two beach systems. Scale modelling was not considered as being feasible due to the lack of facilities, and the time and space factors involved.

In addition to the extrapolation of long term erosion rates, the future of the Washdyke Lagoon was calculated by plotting the lagoon area against time to predict when the lagoon will infill. The life expectancy of the Seadown Drain was determined by the following:

$$T = \frac{D}{R}$$

where T = Time (life expectancy in years)

D = Distance between the landward edge of the beach and the landward edge of the drain (m) and

R = Average long term erosion rate ($m.yr^{-1}$).

This was calculated for each profile between Trounces and Washdyke 2000 (where the drain runs parallel to the coast). The values were then totalled and averaged to give an average life of the drain.

6.3.2 Predicted Life Expectancy of the Washdyke Lagoon

The area of the Washdyke Lagoon has decreased notably this century (Wilson, 1949; McIntyre, 1958; Evans, 1983). This is simply a response to the ongoing sediment starvation from the south, and net long term littoral drift to the north of the remaining sediments. This process is a repeat of the events that lead to the destruction of the Waimataitai

Lagoon (1 km south) in the 1930's (Wilson, 1949; McIntyre, 1958; Kirk, 1979). Since the Waimataitai Barrier was lost, the Washdyke Barrier has had to feed on the sediments within itself.

It was found that the landward edge of the beach would take 89.17 years to reach the most inland point of the lagoon edge. This was at Washdyke 800. Map 4a (back cover) shows the predicted position of the coast in 89.17 years. This was calculated by multiplying 89.17 by the erosion rate for each profile, to determine how many metres inland the coast would be. Besides the lagoon being lost it can be seen that a large section of farmland between Aorangi Road and Washdyke 1400 will also be destroyed. Included in this area is a large section of the Seadown drain. This prediction is considered an optimistic view (because all variables are held constant), and contrasts to that of Kirk (1979, p.12) who indicated: "In the most optimistic view - one in which erosion is maintained at its present rates - the lagoon will have disappeared in about 50 years". Simple extrapolation assumes the lagoon is only being infilled from the retrograding barrier beach. It is apparent from aerial photographs that a significant infilling from the landward occurs as the Washdyke Creek discharges sediment into the lagoon. This is evidenced by the relatively large delta at the creek mouth.

Infilling from both directions is taken into account when examining lagoon area trends. Area data were obtained from the present study (1934 aerial photograph; 1987 photogrammetric maps) and from Evans (1983; 1881 survey; 1955 aerial photograph; 1983 survey). Lagoon areas are plotted against time in Figure 6.6. This signifies a more serious future for the lagoon. It can be seen that the lagoon is infilling in a linear fashion, at a rate of 1.9 $ha.yr^{-1}$. This implies the lagoon will vanish by the year 2005.4 - approximately 18 years into the future. This is in accordance with Kirk (1979), who suggested the lagoon would be lost within two decades of the time of writing. It was considered that 18 years would be the minimum life of the lagoon. To determine a maximum from these data, curvulinear lines were plotted. Exponential and logarithmic curves showed an unrealistic life expectancy greater than 200 years. However, an Order Two Polynomial curve displayed the same R value as the linear trend and terminated at the same date - 2005.4. Hence, 18 years is probably the maximum expected life of Washdyke Lagoon. This method of predicting the lagoon's life has previously been ignored, but is considered to be relatively reliable. This is because lagoon area can only diminish over time. Hence, fluctuations such as those encountered in measuring crest position or sediment volume are not present.

Predicting when the barrier will be permanently breached is less certain. This is due to the limited detailed data relating to beach volume and crest height. South Canterbury Catchment Board survey data have shown these parameters to fluctuate considerably between 1977-1987. Extrapolation of data for the last ten years implies that the barrier will not breach within the next ten years. It has been shown that much of the barrier's crest height has increased and has moved seawards, and sediment volume has increased since 1977. Also, the only breaching event of the

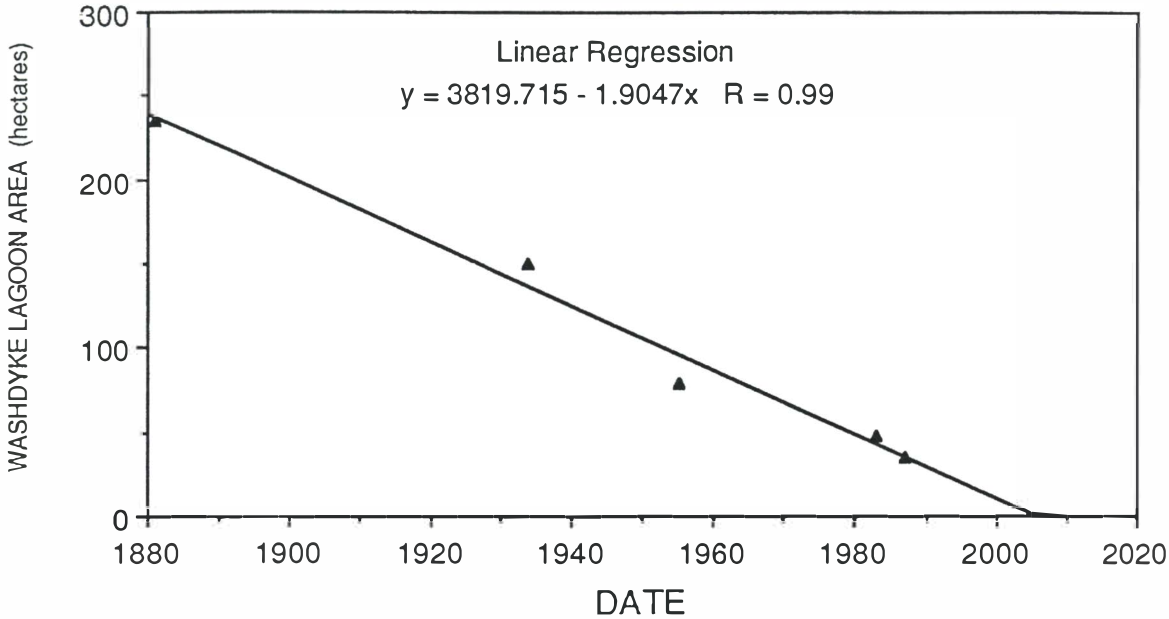


Figure 6.6 Washdyke Lagoon Area Over Time

barrier within modern history has been from the landward - not the seaward. Hence, with presently available data, predictions of barrier breaching are difficult to make as all evidence suggests accretion along this stretch of beach. However, this accretion phase is thought to be a short term phenomenon. Although historical accounts of the Washdyke Lagoon lack descriptive detail, it is apparent that the barrier elevation has lowered considerably since late last century. Therefore, this long term trend could be expected to continue. Even within the last ten years some profiles along the barrier have lowered significantly. Thus barrier breaching is likely to occur, but when remains unknown at this stage.

The consequences of breaching have been described by Kirk (1979). The main points stressed by Kirk were that when this happened, a newly developed beach would occur on the present landward edge of the lagoon, and that erosion at the lagoon's northern end would be increased. This would be a response to the northern end of the lagoon becoming a headland to the newly developed embayment of the lagoon basin. Hence, the industrial estate at the northern end of the lagoon would face even greater erosion than it is already experiencing.

6.3.3 Life Expectancy of the Seadown Drain

As indicated in Chapter One, the South Canterbury Catchment Board relocated its drains in 1984, to a position considered safe for the next 30 years. Using the prediction methods described, it was found that it would take the landward edge of the beach a minimum of 22.05 years to reach the drain at Seaforth Road. The maximum time that this would occur is 63.52 years at Aorangi Road. The average time for the drain to fall to erosion was 36.02 years. A predicted coastal position at this time was constructed by following the formula:

$$m_I = 36.02 \times R$$

where m_I = The inland distance of Landward edge of the beach (m);

36.02 = average time for the beach to reach the drain (years)

R = Long term erosion rate ($m.yr^{-1}$).

Map 4b (back cover) shows the position of the coast in 36 years. It can be seen that destruction of the drain will not occur evenly along the coast. The first section of drain to be destroyed will be the "dog leg" between North Aorangi and Seaforth Road. This section of the drain is closest to the beach, and at current erosion rates will be destroyed in approximately 22 years. Despite the fact that the average life expectancy of the drain is approximately six years greater than its designed life, it is suggested that the large sections destroyed before this period (particularly between Seaforth Road and North Aorangi) will diminish the functional operation of the drain.

6.3.4 Future Sediment Budget

It was shown in Chapter Four that in 10 years the beach has lost 341,308 m^3 of sediment. The present volume is 1,466,074 m^3. At the present rate of decline (28,397.4 $m^3.yr^{-1}$) the beach will lose all its volume within 51.6 years. Although sediment volume has decreased in the last ten years, the probability of the beach dwindling to zero volume is remote, for a number of reasons. Firstly, it has been demonstrated that southerly drift can occur. Hence, this would supply material to the coast, at least some of the time. Secondly, it has been known since last century that the exposed substratum provides material to the coast, as the sea encroaches onto it. Although the volume of this supply could not be quantified, it is expected to increase as the sea migrates landwards. Reasons for this were given in Chapter Five. Thirdly, it is unlikely that the situation will be allowed to deteriorate to this situation without protection measures being taken. Thus, artificial input of sediment as in the renourishment programme could be carried out on a larger scale. Finally, the sediment volume record only spans 10 years. Thus, the registered decline in volume may in fact be a short term fluctuation within the internal beach transport system. However, it should be noted that the sediment loss has occurred during a period of relatively low storminess. In periods of higher storminess volume losses would be expected to be higher.

6.4 CONCLUSION

Erosion patterns of the field area have been examined. Historical patterns and rates of erosion were used as a foundation to predict the life expectancies of the Washdyke Lagoon and the Seadown Drain - the first community assets to succumb to erosion.

It was found to be difficult to establish long term erosion trends because of the limited historical data.

However, erosion rates calculated in this study were considerably slower than those presented in previous works. This was considered to be a function of the different information sources used. The knowledge of slower erosion rates will be of benefit for planning decisions along this coast. It was found that long term rates were more consistent than those of the short term. The Washdyke Barrier erodes considerably faster than the Seadown Coast.

Simple extrapolation of long term erosion data showed the Washdyke Lagoon to have a maximum life of 89.17 years. In contrast, it was shown that the lagoon could infill within 18 years, with sediment coming from the migrating beach and the Washdyke Creek. The likelihood of barrier breaching was difficult to determine because the sediment volume record is short (10 years). All evidence suggests the barrier is in a short term accretion phase and will not breach by sea action within the next ten years.

The life expectancy of the Seadown drain on average was approximately 36 years. The section of drain between North Aorangi and Seaforth Road would be the first to be destroyed. Thus, the drain life is greater than the 30 years it had planned for, although its operational usefulness could be as low as 22 years.

Although it was shown that sediment volume would vanish in 51.6 years, this prediction should be treated with caution. This is because of

(a) 1977-1987 was a period of low storminess. It would be expected far more sediment to be removed in a period of high storminess.

(b) The hinterland is expected to contribute more sediment to the coast as the sea migrates landwards.

(c) Coastal protection measures would probably be taken to prevent the beach from vanishing completely.

CHAPTER SEVEN

CONCLUSION

7.1 SUMMARY OF MAJOR FINDINGS

The aims of this thesis as stated in Chapter One were to give an account of the general morphology and sediments of the beach and hinterland systems, and to establish past and present erosion trends and to apply this information to future coastal erosion predictions.

Morphologically, the study area consisted of a combination of natural and artificial features. Natural features included the mixed sand-gravel beach backed by a low hinterland, two major coastal lagoons (Washdyke and Milford), a basalt reef (Dashing Rocks) and a buried lowland swamp forest. Artificial features included the experimental beach renourishment project, the old Timaru City sewer outfall, stopbanks and drains.

Sediment surveys revealed that grain sizes ranged between $-6.2\ \phi$ and $0.7\ \phi$. Most of the coarsest material was found to be associated with various construction projects on the beach.

Major works were the experimental beach renourishment, stopbank and drain construction, and the new sewer outlet construction.

A comparison of overall mean grain size between the present study and that of van Mechelen (1978) showed a decrease of $0.8\ \phi$. This decrease could have been real, or could reflect different sampling techniques between the two studies. However, it was noted that this decrease occurred despite the addition of coarse materials to the beach since 1978, by the various construction works. This suggested a real grain size decrease as the addition of coarse material would bias the mean grain size in the coarse direction. The beach sediments were found to contain two sorting populations. One occurred in the very poorly sorted class, and the other in the moderate - poorly sorted class.

The distribution of grain size and sorting values showed a similar cellular pattern to that described by McLean (1970) and van Mechelen (1978). Cross shore variation of these parameters was more pronounced than long shore trends. On the basis of the methods of Sunumara and Horikawa (1972), grain size-sorting relationships indicated southerly drifting of sediment.

Beach excavations and seismic profiling showed sediment thickness and volume varied considerably along and across the beach. The Washdyke Barrier contained sediments over seven metres thick and contained most sediment within the backshore. In contrast, many localities along the Seadown Coast frequently displayed an exposed substratum, and contained most sediment within the foreshore. The main factors controlling the distribution of sediment thickness and volume were the presence (or absence) of stopbanks, and substratum elevation.

A sediment budget model was constructed to show sediment transfers between 1977-1987. It was found that the greatest sediment loss has occurred between Aorangi Road and Trounces (-247 142 m³). In contrast the Washdyke Barrier has accumulated 40 194 m³. Of this, 29 000 m³ was injected material into the renourishment project.

This accretion at Washdyke was also regarded as part of the evidence suggesting southerly drift has occurred. However, it was recognised that the accretion was probably a short term fluctuation within a long term erosion trend.

Sediments of the beach substratum and hinterland were found to be fluvial in origin. The sediments were typical of a lowland coastal lagoon environment, being dominantly clays, muds, peats and gravels. These sediments were deposited by a palaeochannel of the Opihi River. Fine, erosion incompetent materials of the hinterland were found to be confined to the ground surface area, and to a narrow strip parallel to the shore. Coarser gravels were found at depth and inland. Therefore, it was suggested that as the beach continues to retrograde, the hinterland would contribute an increasing supply of sediment to the beach. Nevertheless, it was also noted that the hinterland gravels were oxidised and weak. Hence, their value to the beach in the long term may be limited. It was shown that stopbanks restricted the landward migration of the beach landward edge. This played a major role in the changing morphology of the retrograding beach. Upon meeting a stopbank the beach in cross section changed from being backshore dominated to foreshore dominated.

Historical and photogrammetric information identified the highest long term erosion rate as $-3.6\ m.yr^{-1}$ and the highest short term rate was $-6.0\ m.yr^{-1}$. These rates rose substantially less than those presented in previous studies for comparable areas of the beach. It was established that the Washdyke Barrier and Seadown Coast behave quite differently.

Maximum retreat since 1865 has occurred along the Washdyke Barrier (-440 m), associated with a significant beach rotation. This rotation was thought to be a result of the protection Dashing Rocks offers the beach foreshore at the southern extremity of the beach. Net retreat and erosion rates were found to decrease towards the Opihi River mouth. At Horseshoe Lagoon and Connolly's Road the beach has retreated 157.5 m. The Seadown Coast has undergone parallel retreat. The presence of the stopbanks was again considered responsible for these differences.

The predicted life expectancies of the Washdyke Lagoon, Seadown Drain, and remaining beach sediments were approximately 81 years, 36 years and 51 years respectively. These life expectancies were based on linear extrapolation of long term erosion rates, and can therefore be considered as optimistic.

Through the findings specifically related to the study area, further knowledge has been added to the understanding of mixed sand-gravel beaches in general. The main additions to this knowledge were:

(a) The nearshore step may not always be present. This may enhance onshore-offshore sediment transfers.

(b) At least four types of internal beach characteristics have been recognised, and the processes responsible for these outlined.

(c) Retrograding mixed sand-gravel beaches behave differently and have different morphological features, depending on whether landward migration is confined or unconfined.

7.2 IMPLICATIONS

The study coast has suffered a long history of natural erosion, being accentuated by the accumulation of littoral drift sediment behind the Timaru Harbour Breakwater. Much concern has been expressed over the loss of the Waimataitai Lagoon in the 1930's and the apparent 'replay' of events occurring at the Washdyke Lagoon. Most concern has regarded the threatening of many private, community and national assets should the Washdyke Barrier breach.

The examination of the local coastal erosion in this thesis has proved valuable for a number of reasons. First, two sediment sources have been identified, which have the potential to offset future erosion. These were the southerly drift of sediment and the gravels of the hinterland.

Second, because erosion rates were calculated as being much less than previously suggested, more time can be taken in making wise management decisions governing the area.

Third, the study proved valuable in that a new field technique for beach study in general has been developed. Seismic profiling has not been undertaken on loose unconsolidated beach sediments before. This study proved it was a practical and reliable method of determining beach sediment thickness, and determining the relationship between the beach sediments, the water table and the substratum.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

This thesis addressed several specific aspects of coastal erosion along the Washdyke-Seadown Coast. Further research is required in several areas to develop a better understanding of the erosion phenomenon. These fields of research include:

(a) Continued surveying of the beach at regular time scales to monitor changes in response to both local wave conditions at short time scales, and variation in sediment supply over longer time scales.

(b) Undertaking a comprehensive study of the wave and current conditions at the foreshore, rather than concentrating on offshore studies. This is because shore dynamics on mixed sand-gravel beaches are a product of changes in the swash system rather than the nearshore.

(c) Examining in detail the influence of the beach water table on erosion. This could be particularly important along the Seadown Coast where commonly the substratum is impermeable, the water table is high and the sediment cover is thin. It would be expected that this combination of factors would lead to beach saturation and mass movement, thus enhancing erosion.

(d) Future studies of grain size and shape will allow extension of the sampling time and further comparisons of changes of these variables.

(e) A more comprehensive investigation into the hinterland structure is necessary to extend the coverage of the hinterland sediment maps.

(f) The economic implications of coastal erosion and appropriate engineering responses need to be considered in the light of physical coastal investigations. These responses range from the extremes of a no option policy to "hard" concrete seawalls. Intermediate solutions such as expansion of the renourishment project could be the most practical prospect, both environmentally and economically.

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APPENDICES

Appendix 3.1

Sieve Sizes Used

Sieve size mm	Phi (ϕ)	Wentworth 1922 Size Class
54 mm	-5.75	Pebbles
9.53 mm	-3.25	Pebbles
4.74 mm	-2.25	Pebbles
2.36 mm	-1.24	Granules
2.00 mm	-1.0	Granules
1.18 mm	0.24	Very coarse sand
600 μ	0.74	Very coarse sand
425 μ	1.23	Medium sand
300 μ	1.75	Medium sand
150 μ	2.74	Fine sand
63 μ	4.0	Very fine sand
Pan		Silts and clays

Appendix 3.2

Graphic Mean Grain Size (ϕ)

Profile	Lower Foreshore	Upper Foreshore	Backshore
Smithfield 06S1225	-2.5	No sample collected	-3.1
Washdyke 400	-1.5	-2.1	0.1
Washdyke 600	-1.9	-2.0	-1.0
Washdyke 800	-0.5	-1.6	-3.4
Washdyke 1100	-1.7	-0.8	-1.9
Washdyke 1400	-2.5	-1.7	-2.0
Washdyke 1500	-0.3	-1.7	-5.2
Washdyke 1600	-1.4	-1.7 (crest -6.2)	-2.1
Washdyke 1800	-2.4	-3.6	-3.9
Washdyke 2000	-2.5	-3.4	-2.8
Washdyke 2302	-2.8	-3.6	-1.7
Aorangi Road	-5.2	-6.2	-2.4
Nth Aorangi	-3.8	-5.5	-4.6
Kings	-1.7	-1.2	-3.0
Seaforth Rd	-1.7	-5.5	-5.0
Kereta Rd	-0.9	-1.5	0.4
Trounces	-1.2	-3.6	-2.3
Beach Rd	-0.6	-5.6	-0.9
Horseshoe Lagoon	-1.5	Computer error in size plot	0.7
Connolly's Rd	-0.9	-5.3	No sample collected
Opihi 01S000	-1.7	-3.3	-1.1 (L.M.C., -1.5)

L.M.C. - Landward of Mouth Channel

Appendix 3.3

Inclusive Standard Deviation (Sorting, σ_I)

Profile	Lower Foreshore	Upper Foreshore	Backshore
Smithfield 06S1225	0.5	No sample collected	0.3
Washdyke 400	0.7	0.8	1.4
Washdyke 600	1.2	0.9	2.7
Washdyke 800	1.6	2.6	2.4
Washdyke 1100	0.6	2.7	2.8
Washdyke 1400	0.7	3.1	2.2
Washdyke 1500	1.6	2.5	1.2
Washdyke 1600	0.6	3.0 (crest 1.0)	3.0
Washdyke 1800	1.1	2.5	2.3
Washdyke 2000	0.6	2.1	2.8
Washdyke 2302	1.0	2.8	2.3
Aorangi Rd	1.3	0.2	2.5
North Aorangi	1.2	1.0	1.1
Seaforth Rd	0.9	2.9	2.1
Kings	1.3	1.0	2.0
Kereta Rd	1.2	3.2	1.1
Trounces	1.9	2.8	3.4
Beach Rd	2.0	0.6	2.4
Horseshoe Lagoon	2.2	2.5	0.7
Connolly's Rd	1.9	0.5	backshore
Opihi 01S000	1.6	2.0	1.5 (L.M.C., 2.6)

Appendix 3.4

Skewness Values (SK_I)

Profile	Lower Foreshore	Upper Foreshore	Backshore
Smithfield 06S1225	-0.1	-	0.3
Washdyke 400	-0.4	-0.1	-0.3
Washdyke 600	-0.5	-0.3	-0.6
Washdyke 800	0.2	0.0	0.5
Washdyke 1100	-0.2	-0.6	-0.3
Washdyke 1400	0.2	-0.5	-0.2
Washdyke 1500	0.1	-0.2	0.5
Washdyke 1600	-0.5	-0.6 (crest 0.4)	-0.3
Washdyke 1800	0.1	0.7	0.5
Washdyke 2000	0.1	0.1	0.3
Washdyke 2302	0.0	0.4	-0.1
Aorangi Rd	0.2	0.2	0.0
Nth Aorangi	-0.6	0.1	0.2
Seaforth Rd	-0.2	-0.6	0.0
Kings	0.0	0.2	0.7
Kereta Rd	0.0	-0.5	0.1
Trounces	0.4	0.4	-0.3
Beach Rd	-0.1	0.3	-0.3
Horseshoe Lagoon	0.6	0.4	0.0
Connolly's Rd	0.5	0.4	-
Opihi 01S000	0.3	0.2	0.5 (L.M.C., -0.3)

Appendix 3.5

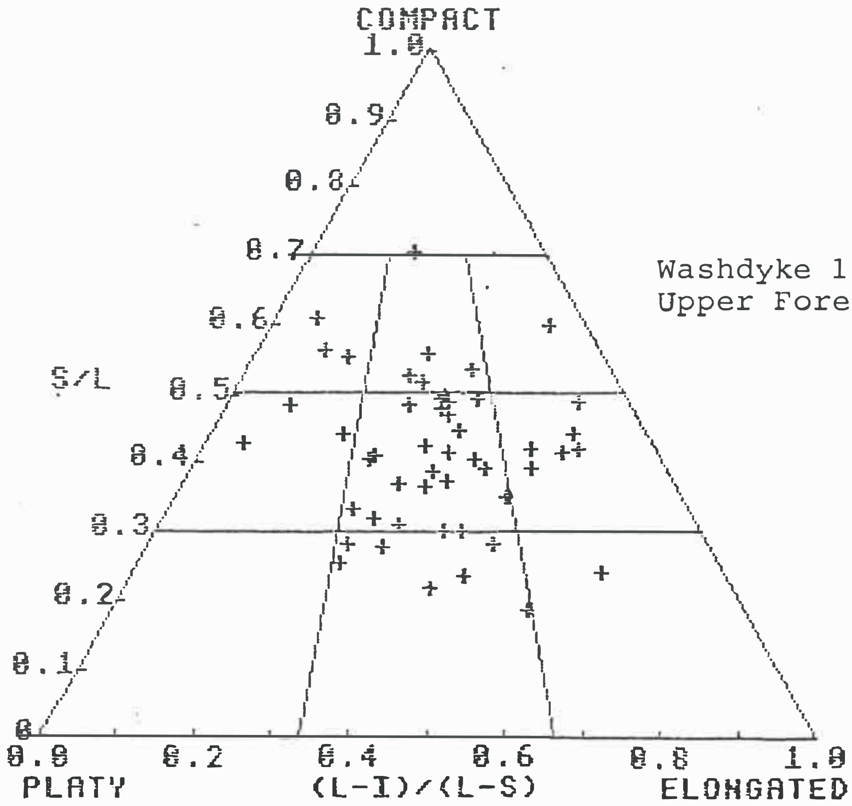
Kurtosis Values (K)

Profile	Lower Foreshore	Upper Foreshore	Backshore
Smithfield 06S1225	0.8	-	0.9
Washdyke 400	1.5	0.7	3.1
Washdyke 600	2.3	1.0	2.5
Washdyke 800	1.8	0.8	0.6
Washdyke 1100	1.2	0.7	0.6
Washdyke 1400	0.9	0.5	1.0
Washdyke 1500	1.4	0.7	1.0
Washdyke 1600	5.2	0.9 (crest 5.0)	0.6
Washdyke 1800	1.8	2.3	1.0
Washdyke 2000	0.8	1.0	0.5
Washdyke 2302	0.8	0.6	0.7
Aorangi Rd	0.8	0.8	0.7
Nth Aorangi	0.7	1.0	0.8
Seaforth Rd	1.0	0.6	0.6
Kings	2.8	1.1	2.4
Kereta Rd	1.0	0.5	2.0
Trounces	1.2	0.7	0.5
Beach Rd	0.6	1.0	1.6
Horseshoe Lagoon	0.5	1.1	0.9
Connolly's Rd	1.0	1.0	-
Opihi 01S000	1.1	0.9	2.5 (L.M.C., 0.7)

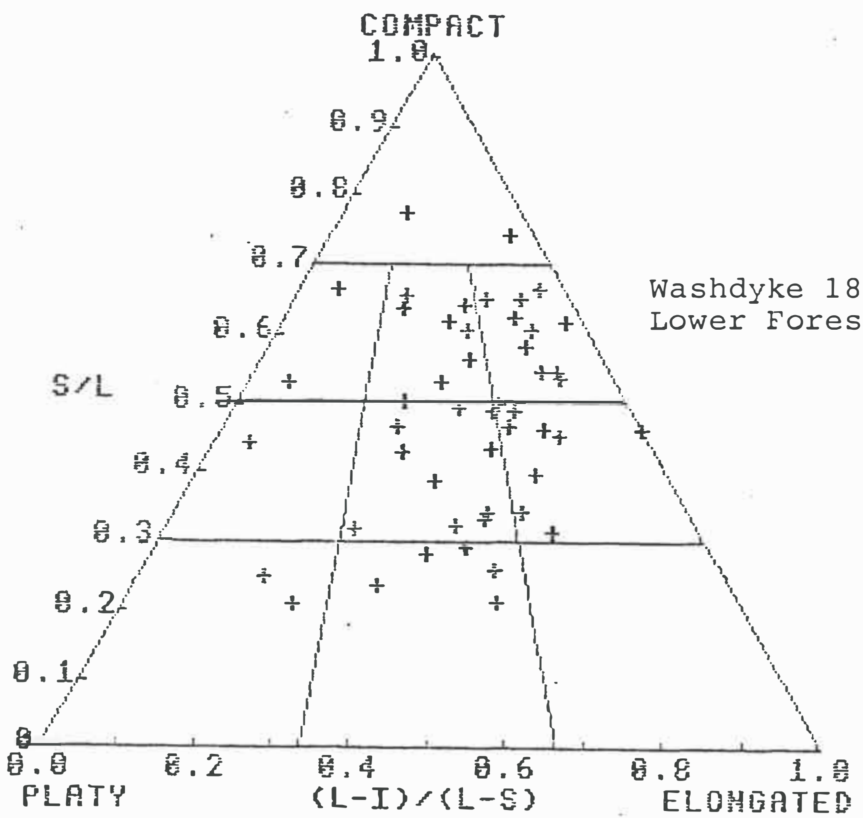
APPENDIX 3.6

Examples of Shape Triangles

(After Sneed and Folk, 1958)



Washdyke 1800
Upper Foreshore



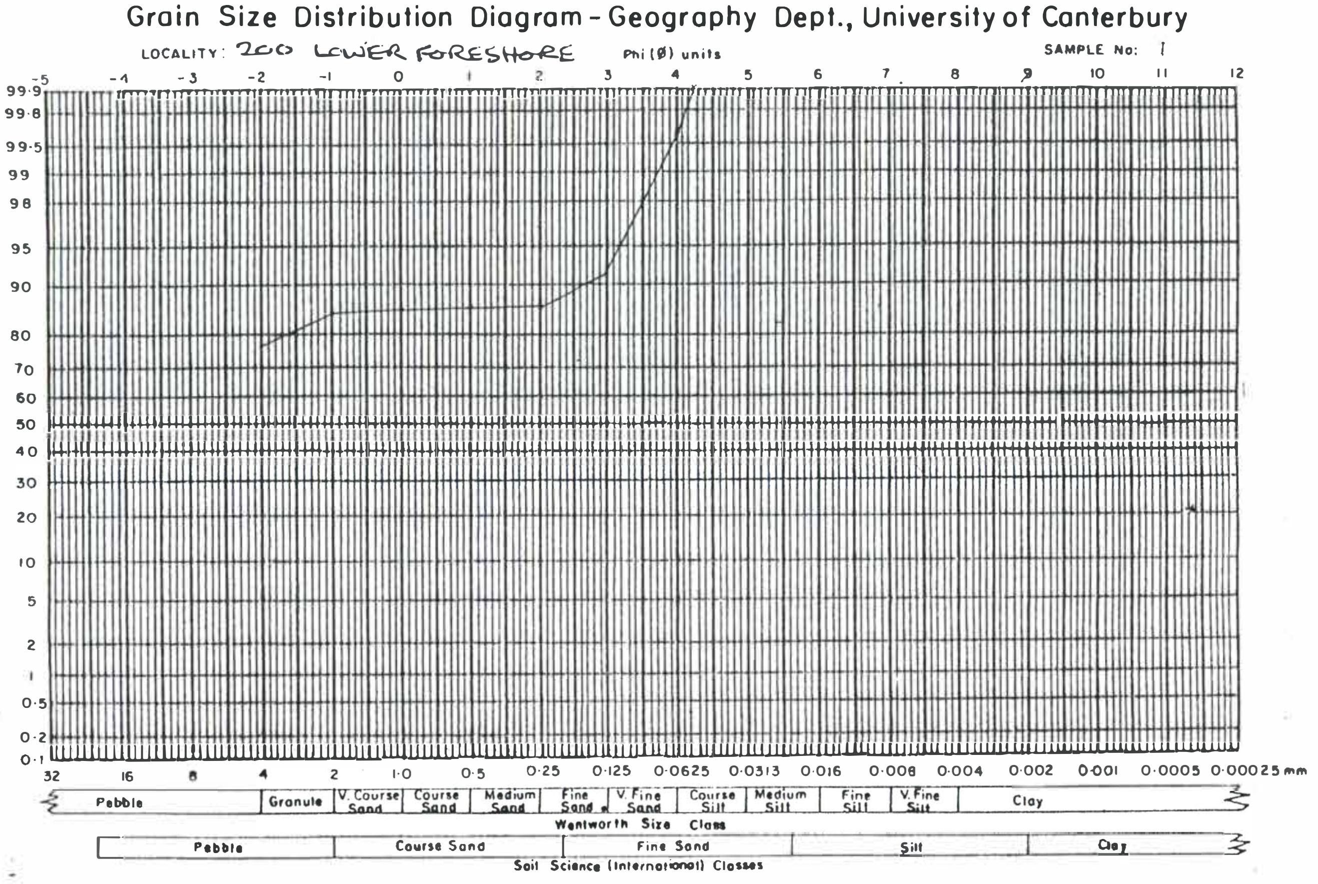
Washdyke 1800
Lower Foreshore

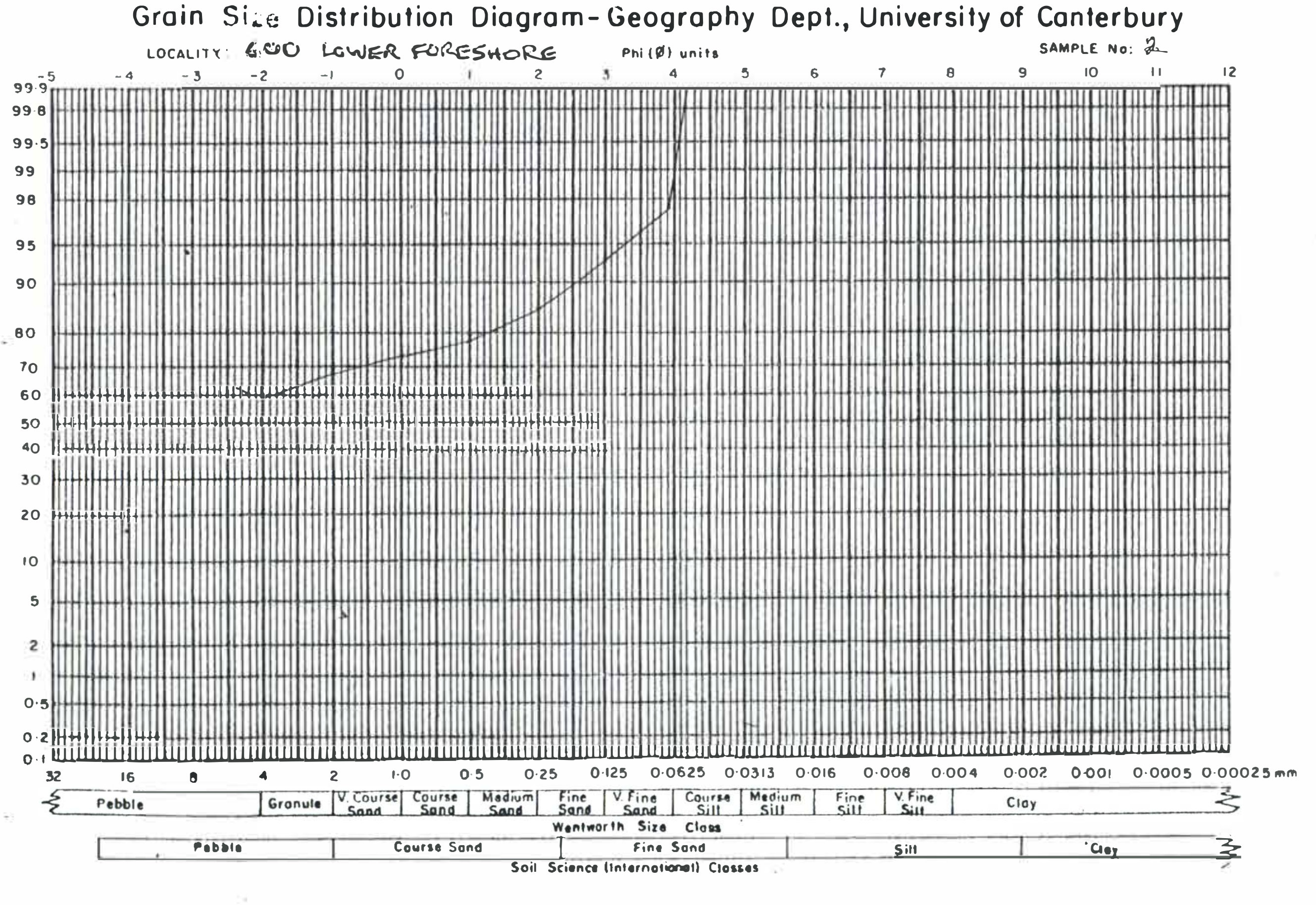
Appendix 3.7

Nominal Diameter Values (ϕ)

Profile	Lower Foreshore	Upper Foreshore	Backshore
Smithfield Reef 06S1225	-2.656	-	-2.743
Washdyke 400	-2.463	-2.654	-2.595
Washdyke 600	-2.933	-2.607	-2.667
Washdyke 800	-2.745	-2.818	-2.944
Washdyke 1100	-2.637	-2.852	-2.843
Washdyke 1400	-2.534	-2.88	-2.735
Washdyke 1500	-2.678	-2.823	-
Washdyke 1600	-2.579	-3.001	-2.758
Washdyke 1800	-2.710	-3.118	-3.255
Washdyke 2000	-2.411	-3.13	-3.018
Washdyke 2302	-2.853	-3.181	-3.190
Aorangi Rd	-2.807	-4.401	-2.833
Nth Aorangi	-2.806	-3.306	-3.018
Seaforth Rd	-2.66	-3.221	-3.221
Kings	-2.735	-3.192	-2.849
Kereta Rd	-2.372	-3.364	-1.899
Trounces	-3.433	-3.433	-3.113
Beach Rd	-2.632	-4.443	-2.825
Horseshoe Lagoon	-2.825	-4.969	-4.480
Connolly's Rd	-2.442	-4.525	-
Opihi 01S000	-2.499	-2.868	-2.47

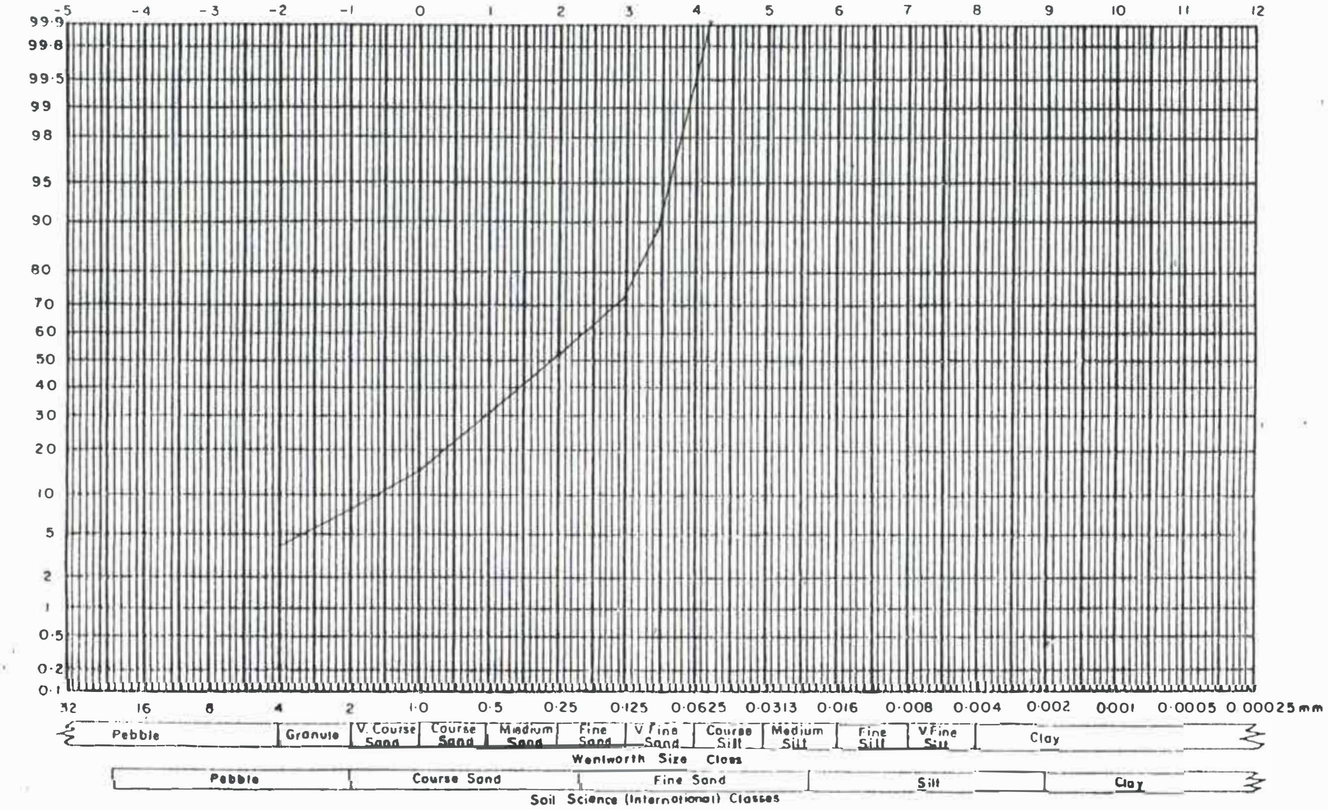
APPENDIX 5.1 Grain Size Distribution Curves





Grain Size Distribution Diagram - Geography Dept., University of Canterbury

LOCALITY: 1000 BACKSHORE Phi (Ø) units SAMPLE No: 3



Grain Size Distribution Diagram - Geography Dept., University of Canterbury

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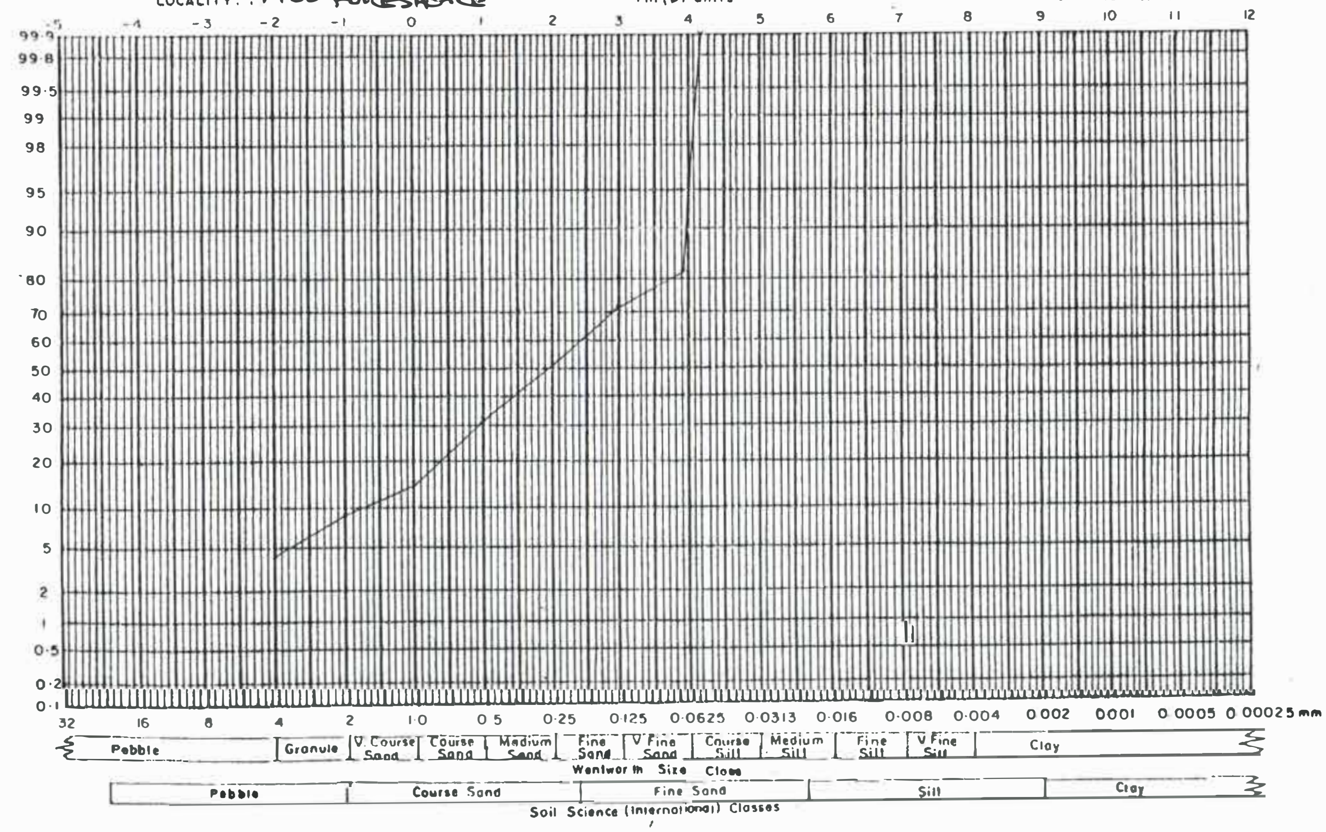
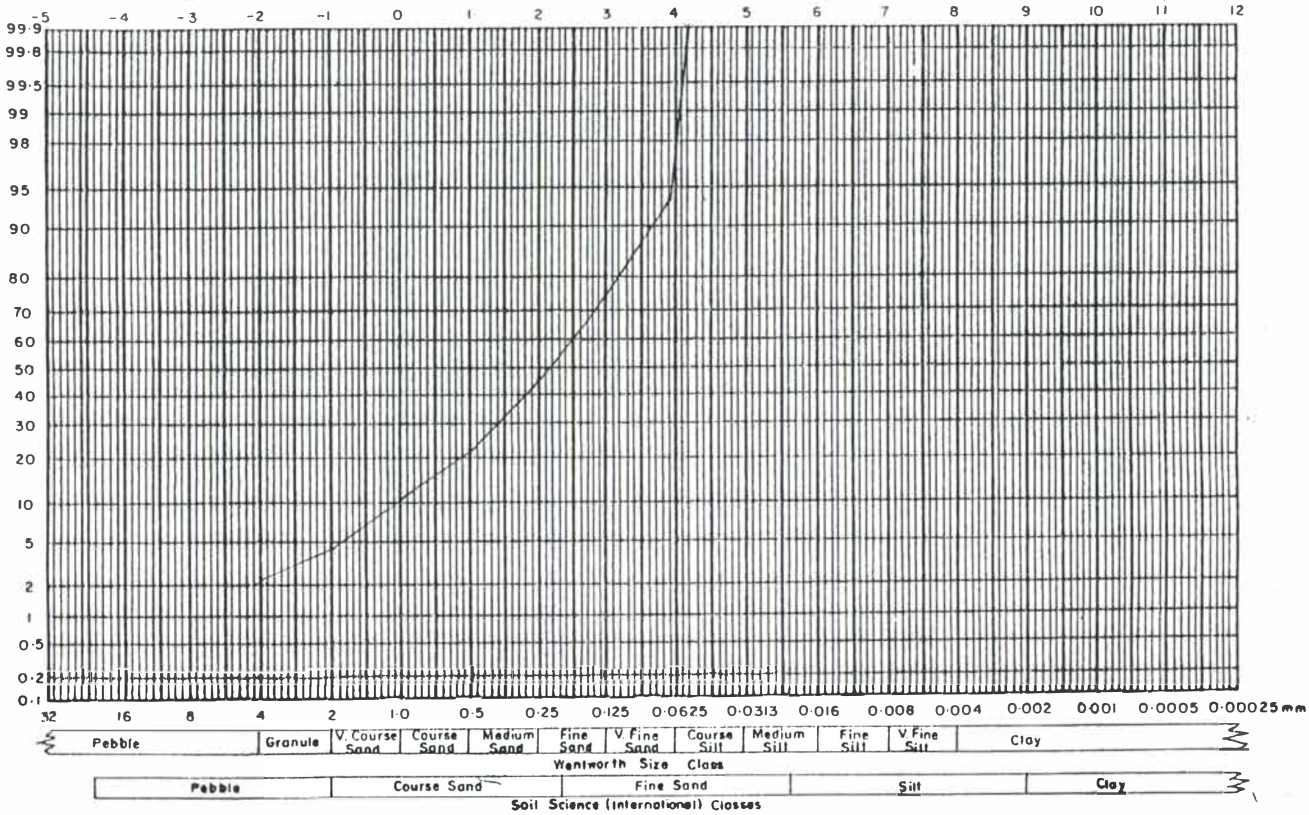


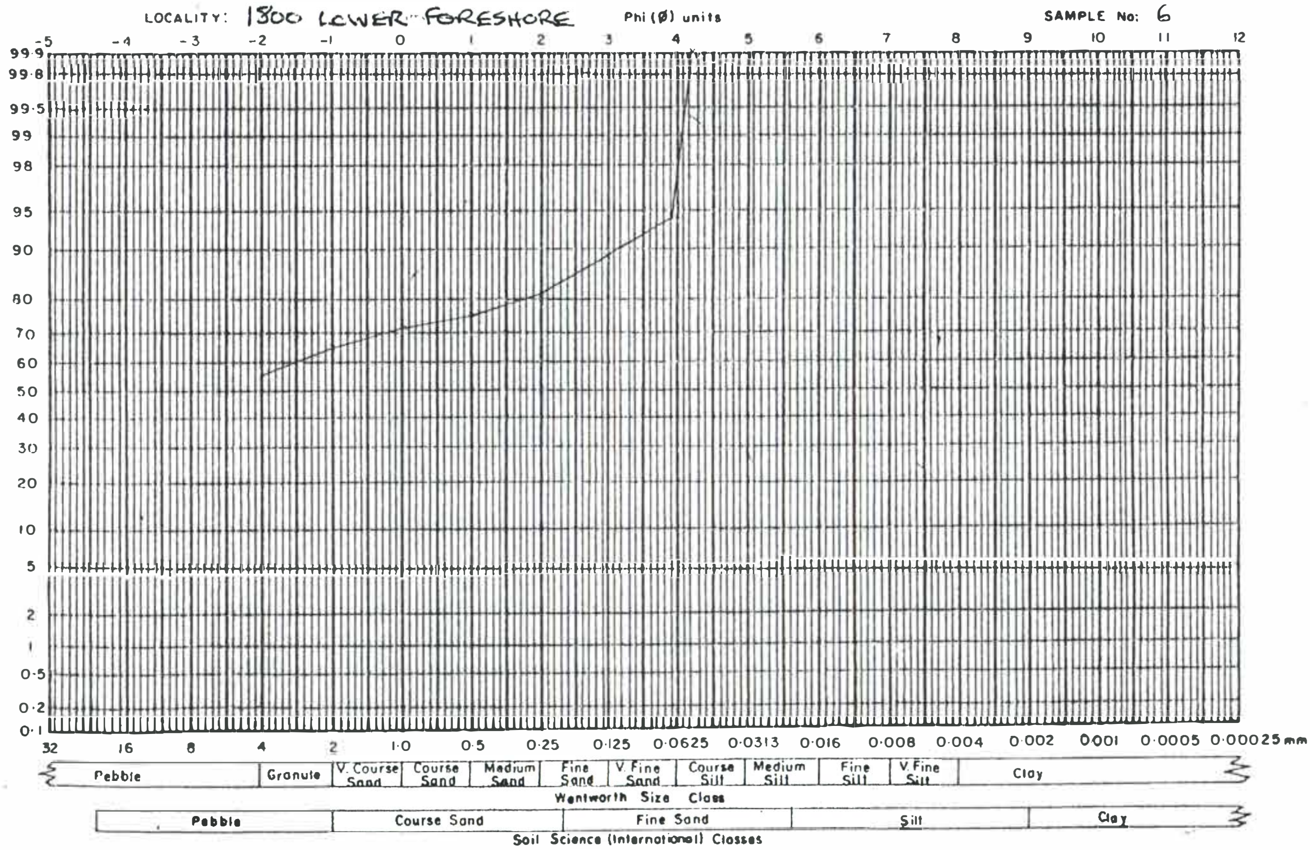
Grain Size Distribution Diagram - Geography Dept., University of Canterbury

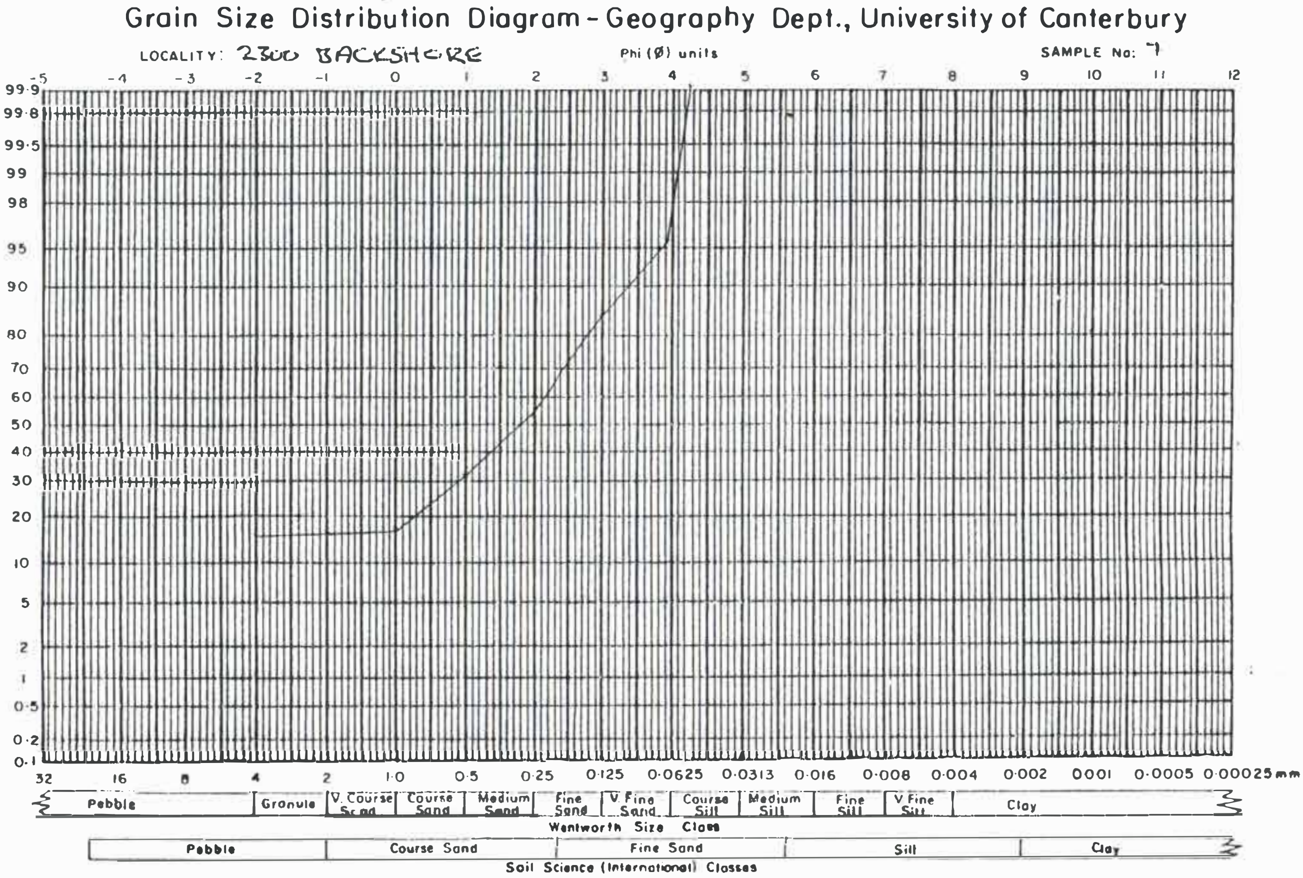
LOCALITY: 1400 BACKSHORE   Phi (Ø) units   SAMPLE No: 4

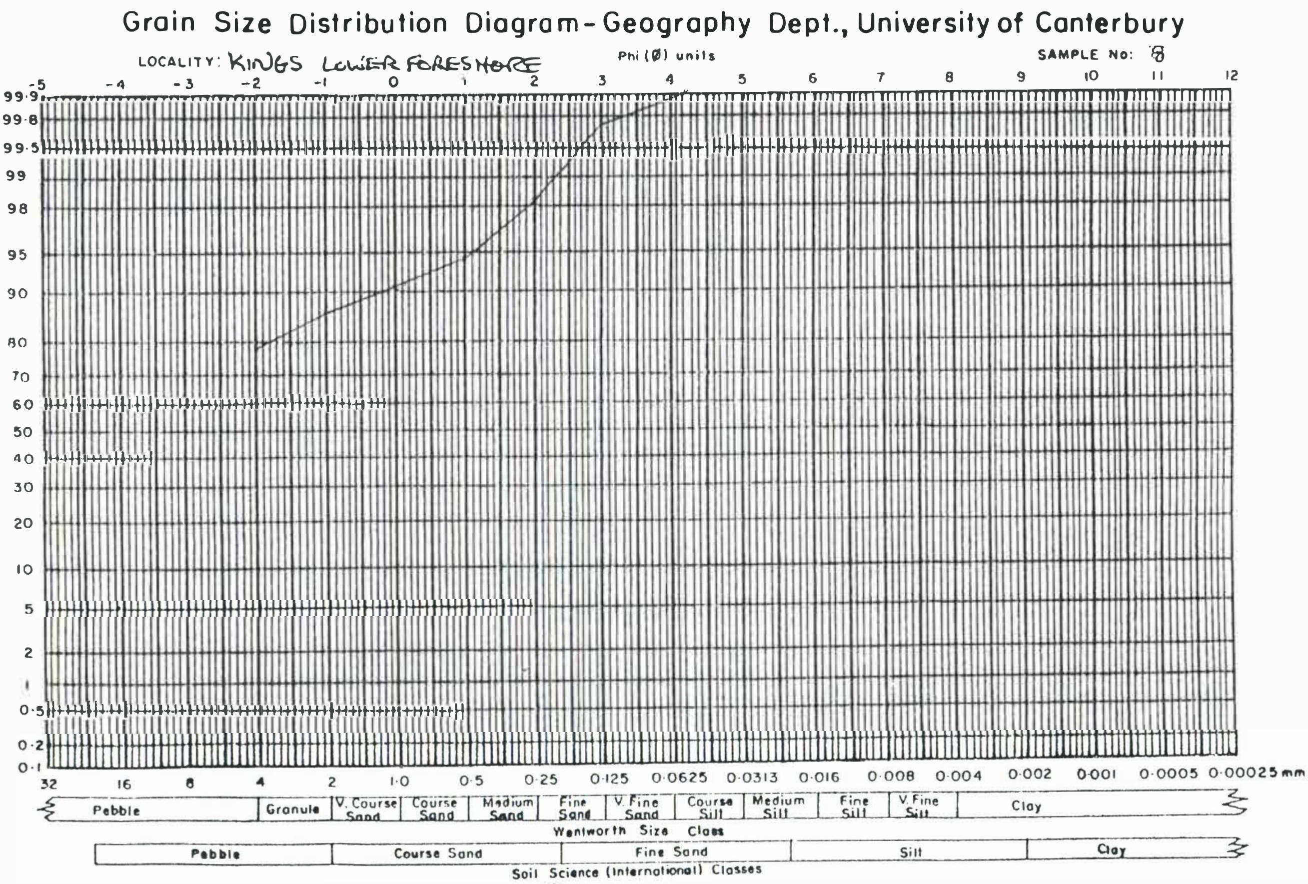


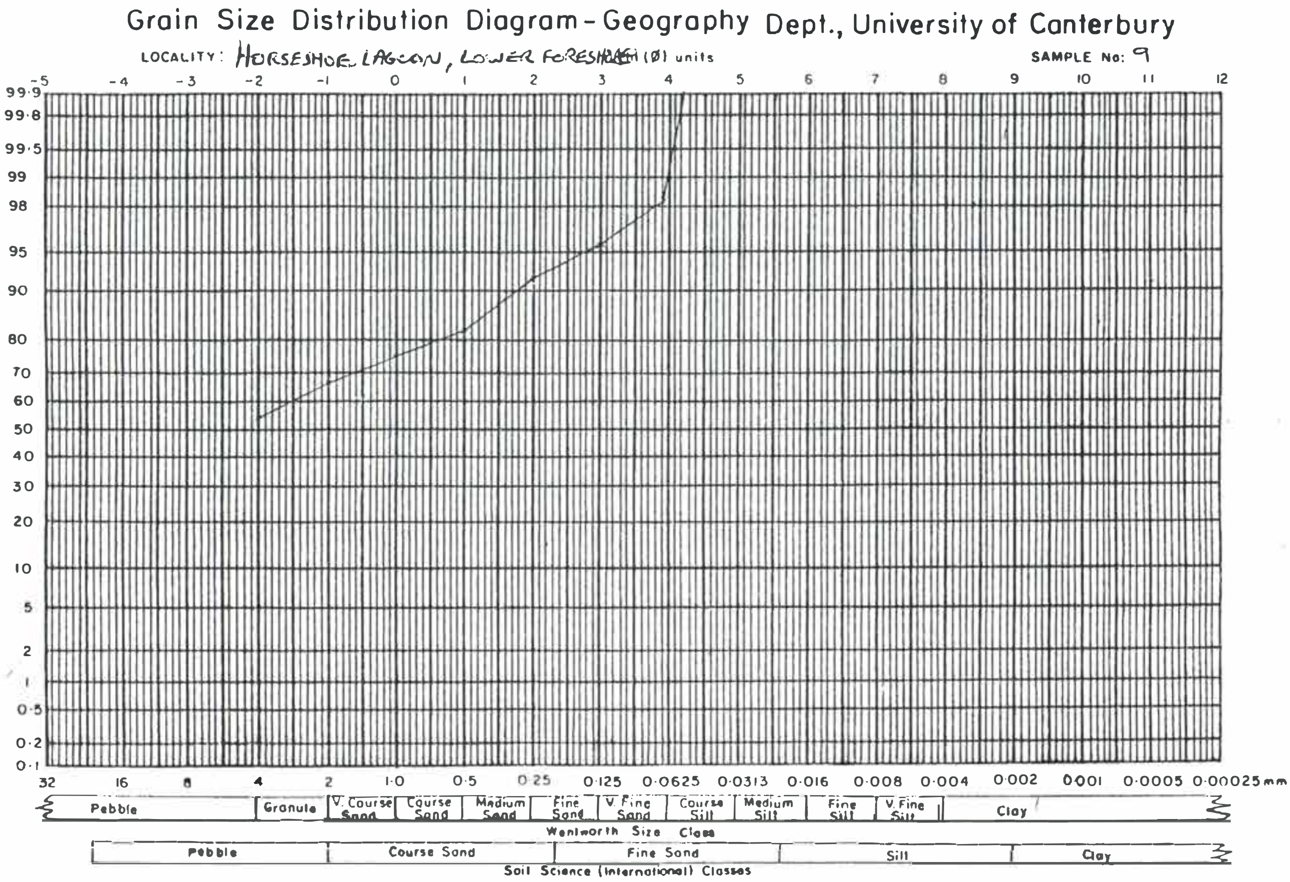
Grain Size Distribution Diagram - Geography Dept., University of Canterbury

LOCALITY: 1800 LOWER FORESHORE   Phi (Ø) units   SAMPLE No: 6



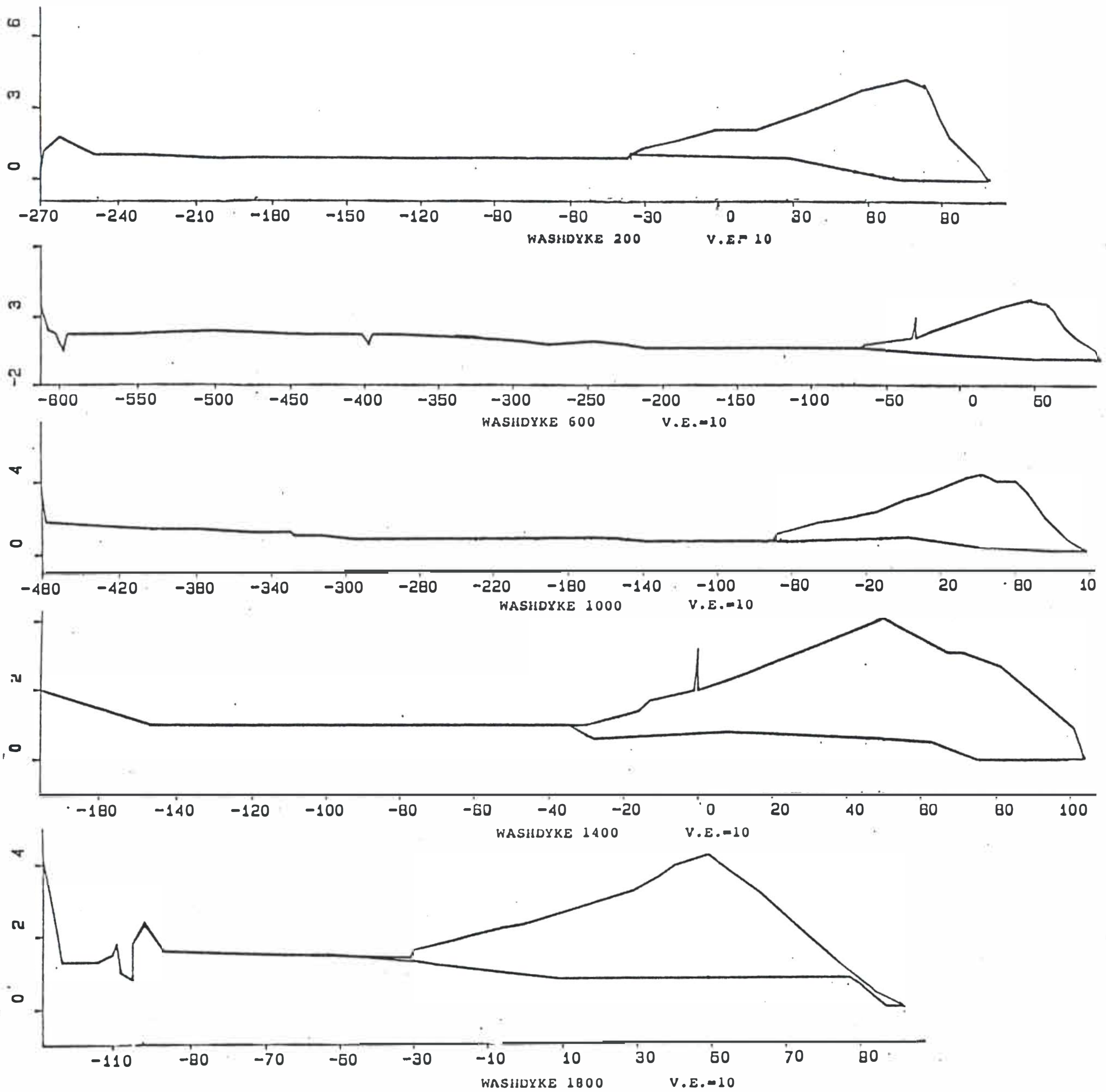

Grain Size Distribution Diagram - Geography Dept., University of Canterbury
LOCALITY: 2300 BACKSHORE
Phi (Ø) units
SAMPLE No: 7
Wentworth Size Class
Pebble
Granule
V. Course Sand
Course Sand
Medium Sand
Fine Sand
V. Fine Sand
Course Silt
Medium Silt
Fine Silt
V. Fine Silt
Clay
Soil Science (International) Classes
Pebble
Course Sand
Fine Sand
Silt
Clay

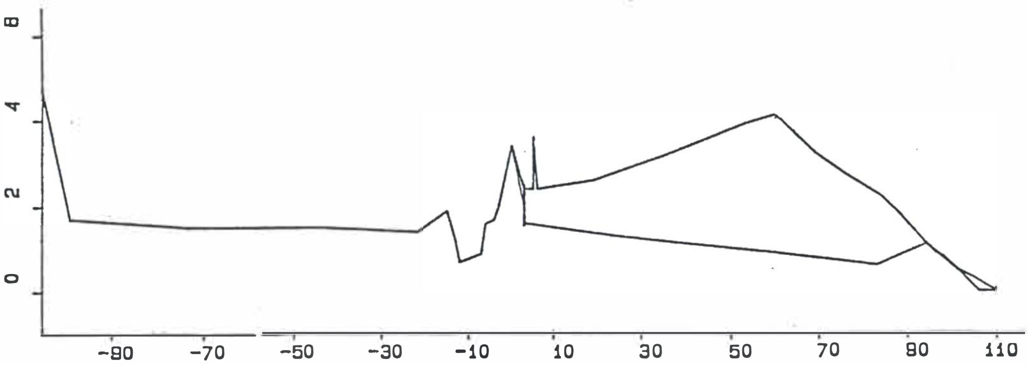

Grain Size Distribution Diagram - Geography Dept., University of Canterbury
LOCALITY: KINGS LOWER FORESHORE
Phi (Ø) units
SAMPLE No: 8
Wentworth Size Class
Pebble
Granule
V. Course Sand
Course Sand
Medium Sand
Fine Sand
V. Fine Sand
Course Silt
Medium Silt
Fine Silt
V. Fine Silt
Clay
Soil Science (International) Classes
Pebble
Course Sand
Fine Sand
Silt
Clay



Grain Size Distribution Diagram - Geography Dept., University of Canterbury
LOCALITY: HORSESHOE LAGOON, LOWER FORESHORE
(Ø) units
SAMPLE No: 9
-5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12
99·9 99·8 99·5 99 98 95 90 80 70 60 50 40 30 20 10 5 2 1 0·5 0·2 0·1
32 16 8 4 2 1·0 0·5 0·25 0·125 0·0625 0·0313 0·016 0·008 0·004 0·002 0·001 0·0005 0·00025 mm
Pebble
Granule
V. Course Sand
Course Sand
Medium Sand
Fine Sand
V. Fine Sand
Course Silt
Medium Silt
Fine Silt
V. Fine Silt
Clay
Wentworth Size Class
Pebble
Course Sand
Fine Sand
Silt
Clay
Soil Science (International) Classes

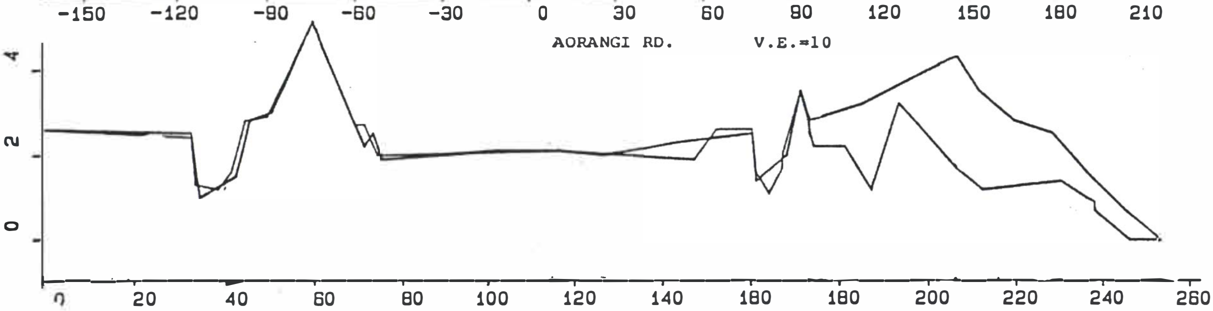
APPENDIX 5.2 Beach Surface and Stratum in Profile



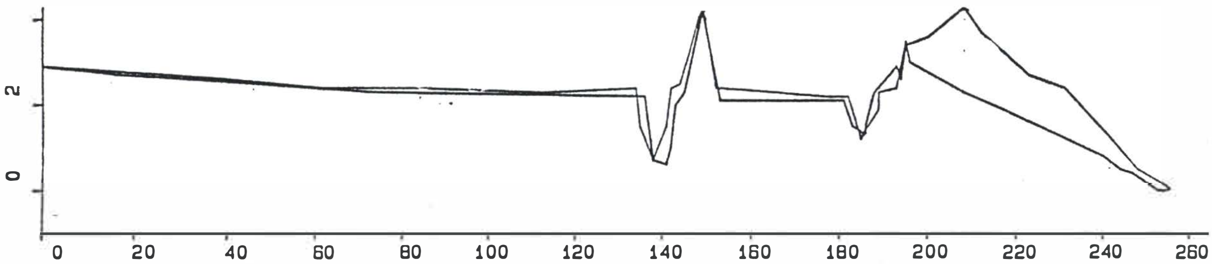


WASHDYKE 2302 V.E.=10

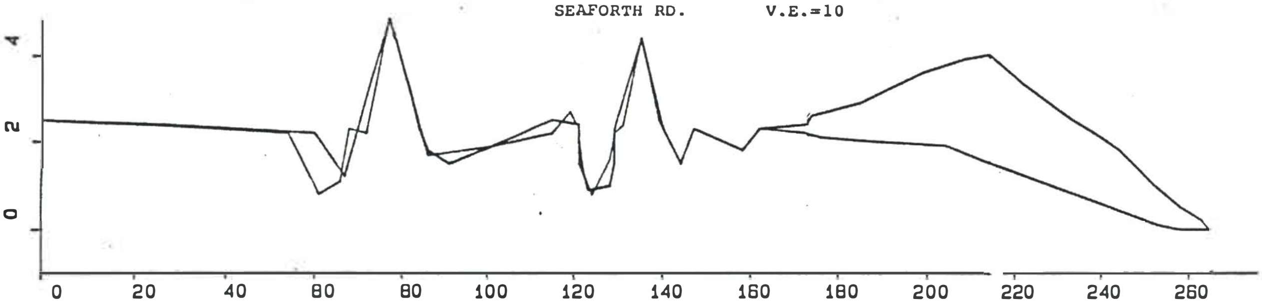
AORANGI RD. V.E.=10



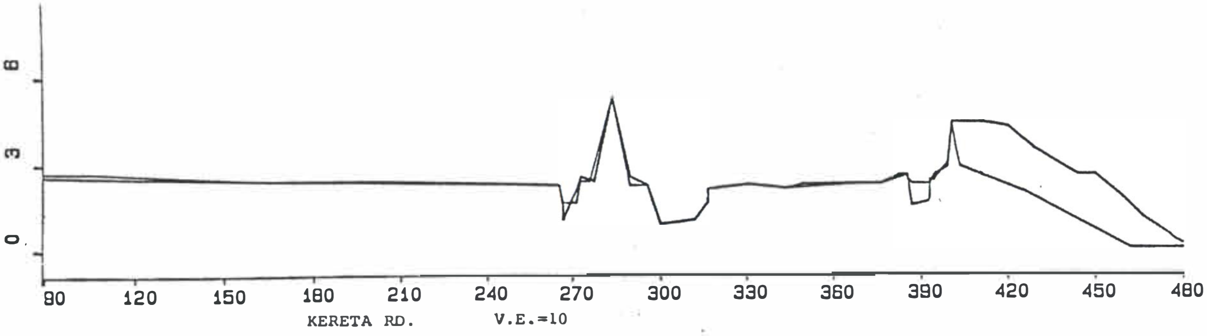
NTH AORANGI V.E.=10

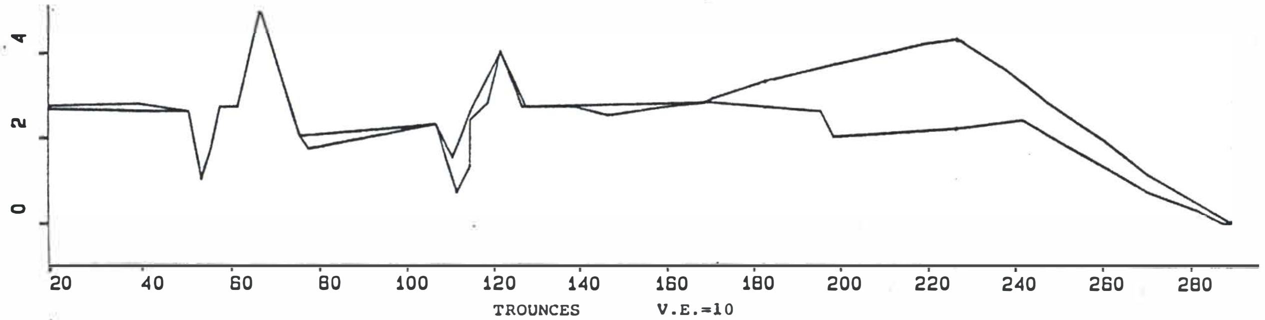


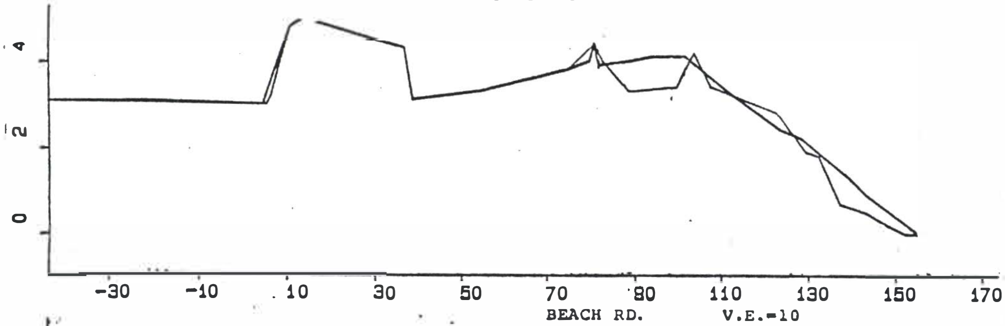
SEAFORTH RD. V.E.=10

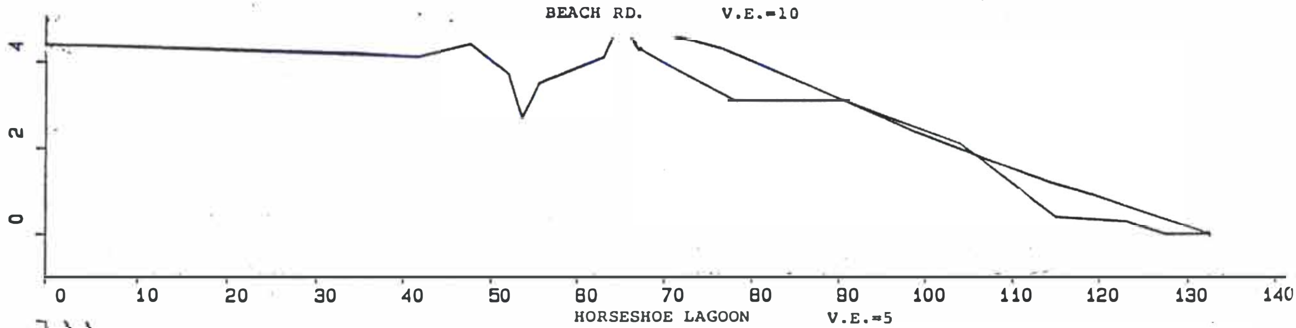


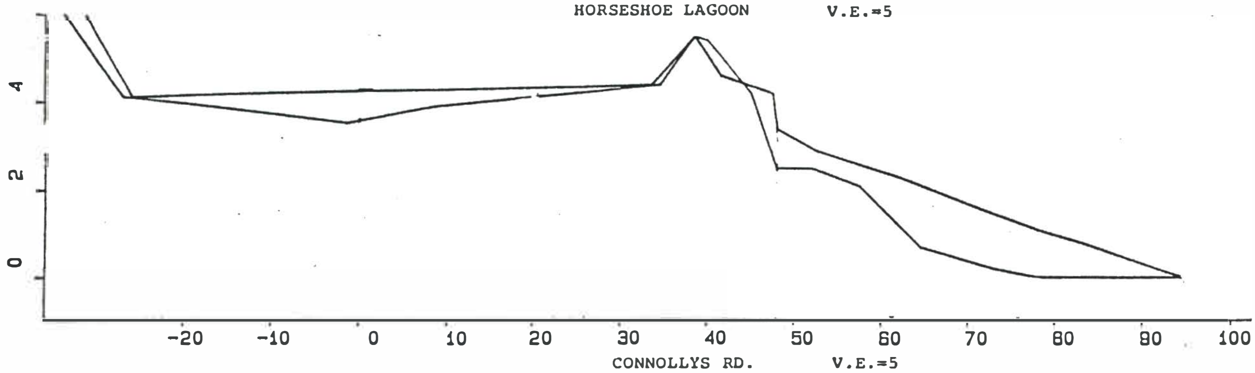
KINGS V.E.=10


6
3
0
90 120 150 180 210 240 270 300 330 360 390 420 450 480
KERETA RD. V.E.=10


4
2
0
20 40 60 80 100 120 140 160 180 200 220 240 260 280
TROUNCES V.E.=10


4
2
0
-30 -10 10 30 50 70 90 110 130 150 170
BEACH RD. V.E.=10


4
2
0
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140
HORSESHOE LAGOON V.E.=5


4
2
0
-20 -10 0 10 20 30 40 50 60 70 80 90 100
CONNOLLYS RD. V.E.=5

Appendix 6.1 Net Coastal Retreat

(m) for Four Time Intervals

Period		1865-1956	1956-1967	1967-1977	1977-1987
Profile					
Smithfield 06S1225		-172.0	- 2.0	-22.25	+ 8.4
Washdyke	200	-378.75	-29.0	-60.0	- 7.7
	400	-362.75	-28.75	-41.0	- 5.1
	600	-350.25	-20.0	-40.75	- 0.9
	800	-335.25	-21.25	-33.75	- 9.3
	1000	-318.75	-26.25	-41.25	-11.9
	1100	-307.25	-23.75	-42.25	-21.6
	1400	-280.25	-26.0	-49.25	- 6.0
	1500	-275.75	-30.5	-33.0	-20.3
	1600	-270.25	-31.25	-34.75	-11.2
	1800	-270.5	-37.0	-27.5	-28.0
	2000	-262.5	-33.5	-32.0	-23.5
	2100	-257.5	-35.25	-31.75	-29.3
	2302	-252.25	-30.25	-34.25	-28.2
Aorangi Road		-247.5	-26.0	-34.5	-27.2
North Aorangi		-238.5	-30.0	-34.5	+16.7
Seaford Road		-222.0	-32.5	-25.0	-13.1
Kings		-190.0	-40.0	-25.0	-15.5
Kereta Road		-186.0	-19.5	-24.5	-35.1
Trounces		-175.5	-24.5	-23.0	+ 1.6
Beach Road		-150.0	-19.0	-10.0	- 3.0
Horseshoe Lagoon		-111.5	-21.0	-10.0	-14.0
Connolly's Road		-118.5	- 7.0	-23.5	-14.7
Opihi 01S000					+26.4
Means					
Total 12.25 km		-249.28	-25.85	-31.90	-11.35
Washdyke Barrier		-292.42	-26.80	-37.41	-13.9
Seadown Coast		-182.16	-24.38	-23.33	- 7.79

Note: -ve = Erosion +ve = Accretion

Appendix 6.2 Erosion Rates ($m.yr^{-1}$) for

Four Time Intervals

Period	1865-1956	1956-1967	1967-1977	1977-1987
Profile				
Smithfield 06S1225	-1.89	-0.22	-2.22	+0.84
Washdyke 200	-4.16	-2.63	-6.0	-0.77
400	-3.93	-2.61	-4.10	-0.51
600	-3.84	-1.81	-4.07	-0.09
800	-3.68	-1.93	-3.37	-0.93
1000	-3.50	-2.38	-4.12	-1.19
1100	-3.37	-2.15	-4.22	-2.16
1400	-3.07	-2.36	-4.92	-0.6
1500	-3.02	-2.77	-3.30	-2.03
1600	-2.96	-2.84	-3.47	-1.12
1800	-2.97	-3.36	-2.75	-2.8
2000	-2.88	-3.04	-3.20	-2.35
2100	-2.82	-3.20	-3.17	-2.93
2302	-2.77	-2.75	-3.42	-2.82
Aorangi Road	-2.71	-2.36	-3.45	-2.72
North Aorangi	-2.62	-2.72	-3.45	+1.67
Seaforth Road	-2.43	-2.95	-2.50	-1.31
Kings	-2.08	-3.63	-2.50	-1.55
Kereta Road	-2.04	-1.77	-2.45	-3.51
Trounces	-1.92	-2.22	-2.30	+0.16
Beach Road	-1.64	-1.72	-1.0	-0.3
Horseshoe Lagoon	-1.22	-1.9	-1.0	-1.4
Connolly's Road	-1.30	-0.63	-2.35	-1.47
Opihi 01S000	-	-	-	+2.64
Means				
Total 12.25 km	-2.73	-2.34	-3.18	-1.13
Washdyke Barrier	-3.20	-2.43	-3.73	-1.39
Seadown Coast	-1.99	-2.21	-2.33	-0.77

Note: -ve = Erosion +ve = Accretion

Appendix 6.3 Linear Long Term Erosion 1865-1987.
Net Retreat and Average Erosion Rates

Profile		Net Retreat (m)	Erosion Rate ($m.yr^{-1}$)
Smithfield 06S1225		-244.5	-2.00
Washdyke	200	-440.0	-3.60
	400	-437.5	-3.58
	600	-412.5	-3.38
	800	-401.25	-3.28
	1000	-399.75	-3.27
	1100	-395.0	-3.23
	1400	-363.0	-2.97
	1500	-358.0	-2.93
	1600	-348.5	-2.85
	1800	-363.5	-2.97
	2000	-363.0	-2.97
	2100	-366.0	-3.0
	2302	-345.0	-2.82
Aorangi Road		-298.5	-2.44
North Aorangi		-300.0	-2.45
Seaforth Road		-291.0	-2.38
Kings		-270.0	-2.21
Kereta Road		-265.0	-2.17
Trounces		-222.5	-1.82
Beach Road		-185.0	-1.51
Horseshoe Lagoon		-157.5	-1.29
Connolly's Road		-157.5	-1.29
Total mean		-321.06	-2.62
Washdyke mean		-374.1	-3.06
Seadown mean		-238.55	-1.95