High Energy

Coastal Processes

on Mixed Sand

and Gravel Beaches

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ABSTRACT

The role of high energy events in determining beach morphology on mixed sand and gravel barrier beaches is examined. Analysis of the beach response to high energy events contributes to the understanding of the significance of these events in determining the general and long term function of mixed sand and gravel beach systems. Issues concerned with the contribution of events of differing sizes to the geomorphic character of landforms are an ongoing area of debate in geomorphology. The concepts of magnitude and frequency of events, and thresholds or turning points in the behaviour of geomorphological systems have not been extensively studied in respect of coastal science. These concepts are an underlying theme of the study.

The morphological adjustments of seven beach profile sites along the Wainono Lowland Coast in South Canterbury are analysed using data from repeated profile surveys during a four year period. Excursion distance analysis was carried out on the survey data, and used to examine temporal and spatial variations in response between the study sites.

There were fewer storms during the study period than were expected after consideration of documented historical event occurrence for the area. From an examination of the beach response to the seven storm events that occurred during the study, a semi-quantitative characterisation of high energy events is advanced. Due to the lack of quantitative data describing the oceanographic components of each event, this characterisation was based on the beach response. Three classifications of high energy beach response were adopted. These are 'Destructive' events, which result in overtopping or barrier crest lowering; 'Damaging/ Erosive' events, which change the status of the beach by reducing its ability to dissipate wave energy and protect the coastal hinterland; and 'Damaging/Constructive events, which result in changes to the foreshore form by net accretion to the profile.

It is proposed that episodes with breaking wave heights in excess of 2.5 metres can be considered as high energy events. Waves of this magnitude produce run-up that affects over half of the beach profile. Damaging events during the study period had wave run-up to at least 4.5 m AMSL. The main differences between damaging and destructive events are in the storm water levels and the storm duration. Higher storm water level set-up occurs for destructive events than ... damaging events. Long duration storms (over 20 hours) will result in destructive beach adjustments.

Four factors were noted from this study as being important to the way the beach responds to high energy events. These are the slope of the foreshore, the presence and dimensions of intermediate berms, the pre-storm volume of beach sediment seaward of the barrier crest, and the sediment composition and structure within the foreshore. Most of the foreshore adjustment occurs in the middle and upper foreshore during high energy events. The antecedent condition of the foreshore, especially the sediment volume content, is an important control on the type of

beach response. It was found that profiles with foreshore volumes over 130 $m^3.m^{-1}$ of beach, and foreshore widths greater than 35 metres sustained less damage to the barrier crest than those with lesser dimensions.

A spatial analysis of the field data showed both alongshore and across-shore variations in morphology and morphological adjustments between profile surveys. A quasi-stationary 'slug', or collective unit of sediment was identified in the field area. The 'crest' of the slug is represented by the region of greatest seaward protrusion, and a foreshore volume in excess of the mean volume over time. The slug 'trough' is the area between crests, which has less than the mean volume over time. The average difference between the slug 'crest' and 'troughs' was 101$m^3.m^{-1}$ of beach. The difference between the foreshore width at the crest and trough was approximately 20 metres. Movement of the slug of sediment alongshore is a result of the longshore sediment transport processes at work on the mixed sand and gravel beach. The predominant longshore drift for the study area is northwards. Storms generally approach from the south or south east. Due to the low incidence of storms during the study period, there was no evidence of a net northwards passage of the slug through the field area.

The presence of a slug at a site on the coast plays an important role in determining the antecedent morphology of the profile and its ability to dissipate wave energy and protect the coastal hinterland. A site adjacent to a slug crest will present a 'healthier' protection against wave attack than a site adjacent to the trough because there is more sediment available during episodes of erosion, and more beach surface area between the breaking wave and the barrier crest to absorb or dissipate swash energy, therefore reducing the risk of crest erosion or overtopping.

Across-shore variations in process response and sediment shape characteristics were determined from field evidence. The beach profile was divided into six zones. These zones are the 'Backshore', the 'Barrier Crest', the 'Upper Foreshore', the Intermediate Berm', the Interberm Nadir', and the 'Lower Foreshore'. It was noted that no general model of across-shore zonation of sediment shape characteristics exists for mixed sand and gravel beaches. This lack of an applicable model has hindered the effective description and comparison of mixed sediment beaches from different parts of the world. Sediment shape data from this study were used to develop such a model. Materials from each zone possess a unique sediment shape signature, which is represented by a frequency histogram of sediment shapes. The model provides a baseline against which other mixed sand and gravel beaches can be compared.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

CHAPTER ONE
INTRODUCTION

1.1 Thesis Statement

This thesis considers the role of high energy events in determining beach morphology and other responses to processes on a mixed sand and gravel beach. A dynamic mixed sand and gravel barrier beach system in South Canterbury, New Zealand will be examined. The study beach is subject to high energy coastal events resulting in environmental problems such as beach erosion and saltwater flooding of low lying hinterland.

The impetus of this study arises from a situation in which a dynamic coastal environment undergoing long term erosion is encroaching on a human use system. With intensification of use of land near the coast for farming, industrial, recreational and residential applications, the performance of beaches as protection from sea attack has become vital. Coastal flooding and beach erosion in South Canterbury has been economically and socially expensive. The extent of this problem was evident during July 1985, when 500 hectares of agricultural hinterland in the Wainono Lagoon area were flooded with sea water, resulting in a loss of productive use of the land for approximately three years. This occurred after the crest height of a 1.2 kilometre stretch of barrier beach was lowered by erosion, an average of 1.6 metres, allowing storm wave run-up to overtop the crest. Three kilometres south of this overtopping, two breaches resulted from storm initiated washover lobes which enlarged to become deep channels through the beach.

The consequences of this storm and other individual events have been attributed to oceanographic features of the storm and to the morphological character of this section of the coast (Kirk 1987a). However, the specific contributions of waves and water levels, and of beach composition and morphology to the incidence of overtopping and breaching along the South Canterbury Coast are unknown. Also not well known is the significance of high energy events such as that of July 1985 in determining the general and long term form and function of the beach system.

At a more fundamental level, issues concerned with the contribution to geomorphic character attributable to events of differing sizes are an ongoing area of debate in the science of geomorphology. The concept of magnitude and frequency of forces in landform development was put forward by Wolman and Miller (1960). In contrast, the concept of thresholds or turning points in the behaviour of a geomorphological system

was elaborated by Schumm (1979). These ideas have not been extensively examined in respect to coastal processes and are an important facet of this study. It is the aim of this thesis to improve upon the state of understanding in regard to the above matters, both in application to processes in the South Canterbury coastal environment and more generally to the development of coastal process theory.

The function of mixed sand and gravel beaches and consequently the causative processes of physical hazards in coastal environments of this type are inadequately explained in the scientific literature. Kirk (1980) notes that mixed sand and gravel beaches as found in New Zealand are comparatively rare on the world scale, and only a small body of coastal geomorphologists have come into contact with this type of beach in the field. The lack of knowledge and understanding of mixed sand and gravel beach adjustment and response to the sea is also pointed out by Kirk. He states that at that time (1980), the literature on this type of beach was limited and that neither the typical morphologies nor the apparently complex dynamics were widely known or understood.

During the 1980's a number of further studies were carried out on New Zealand mixed sand and gravel beaches. Notably however, they have been either specific problem solving or technical reports (such as Kirk and Weaver 1985; Kirk 1984, and in press (a) and (b)), internal publications by the South Canterbury Catchment Board - now due to Local Government restructuring in 1989, a part of the Canterbury Regional Council - (Kirk 1987a; Todd 1988), or University Masterate and Doctoral theses in the Geography Department, University of Canterbury (Hastie 1983; Pfahlert 1984; Siemelink 1984; Single 1985; Neale 1987; Benn 1987). The information they hold is not readily available to the international scientific community, and has not prompted a wide discussion of this beach type. For example, Carter (1988) refers to a 'plea' made by Kirk for the consideration of mixed sand and gravel beaches as distinctive forms. He goes on to say that,

> "Certainly there is a case for this as the response of strongly bimodal sediments is likely to be "hybridized". One example is that the bed may alternate, spatially and temporally, between rough gravel and smooth sand, causing great differences in wave run-up."
>
> (Carter 1988, p 132)

Work has been carried out examining wave run-up on mixed sand and gravel beaches, notably by Kirk (1970 and 1975). These and later works have highlighted the truly mixed nature of the beach sediments and the consequently unique process-response regime. However, the results gained from these studies are still not widely appreciated, neither is the development of an understanding of mixed sand and gravel beaches.

New Zealand studies of mixed sand and gravel beaches have increased the understanding of the function of this beach type in a number of ways. The areas covered include processes in the swash zone incorporating sediment entrainment, transport and deposition by swash and backwash (Kirk 1970), concentrated studies of historical data on erosion magnitudes and rates (Benn 1987; Kirk 1987a), beach renourishment as an option to inhibit coastal erosion (Kirk and Weaver 1985), and processes of longshore sediment transport (Neale 1987). High energy events have been acknowledged as important in causing short term morphological fluctuations but no one has specifically investigated their overall long and short term effects. This thesis will supplement existing knowledge of the operation of mixed sand and gravel beaches through examining short-term morphological adjustments to the beach in relation to the wave environment. A number of specific questions will be addressed, including:

What are 'high energy' events, and how can they be characterised?

What are the short term effects of high energy events on a mixed sediment barrier beach?

What is the role of high energy events in determining the processes of long term coastal retreat occurring on the study coast?

What is the significance of high energy events to the beach sediment budget?

How does beach crest lowering occur?

How is breaching initiated, and what conditions pre-dispose its occurrence?

As well as increasing our understanding of these environments, answers to the last two questions can also be applied to understanding and resolving site-specific environmental problems such as erosion, overtopping, breaching and saltwater flooding.

1.2 The South Canterbury Coast

The general area under study for this thesis is the South Canterbury Coast. This coast has been the subject of research by members of the University of Canterbury Geography Department for over twenty years, and has proved to be a useful environmental laboratory for researching the dynamics of mixed sand and gravel beach systems. It is centred on the town of Timaru, 160 kilometres south of Christchurch, and extends north to Banks Peninsula, and south past the Waitaki River to Cape Wanbrow. Figure 1.1 sites the area under study and locates place names discussed in the text.
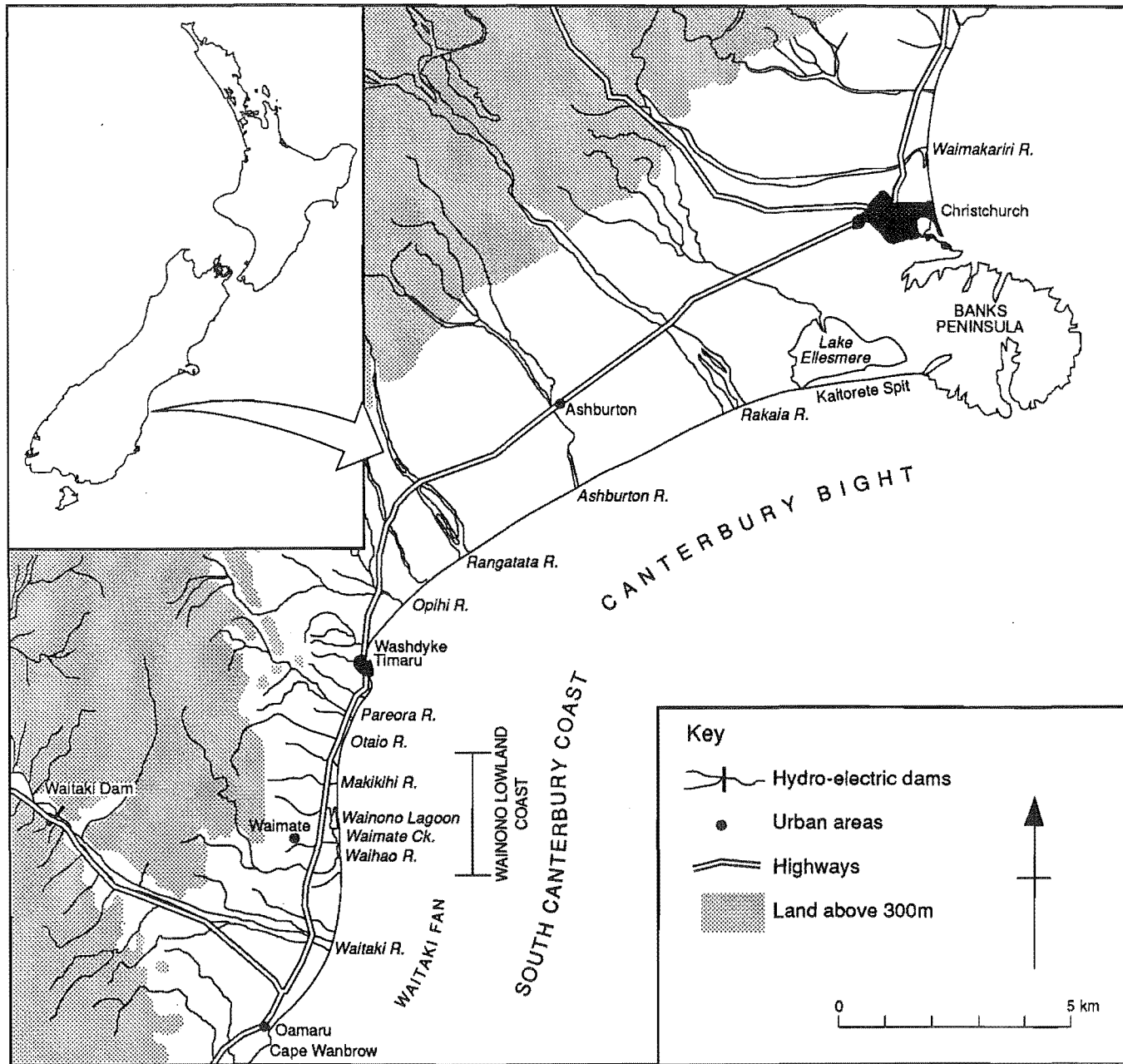
Figure 1.1 Location map of study area and place names from the text.

Todd (1988) categorises the southern component from Cape Wanbrow, Oamaru to the Port of Timaru, convex in plan view about the Waitaki River, as a single coastal system, and refers to it as the Waitaki Fan (Figure 1.1). The section of the Waitaki Fan north of the Waitaki River has been divided by Todd into three morphological units. The most southerly unit is 14 kilometres of alluvial cliffs comprised of glacial outwash gravels and loess deposits. The cliffing is the result of truncation of the Waitaki Fan by coastal erosion due to post-glacial sea-level rise. Travelling north, the next unit is a 28 kilometre stretch of sand and gravel beach ridge fronting low-lying hinterlands. The final unit from the Otaio River to the Port of Timaru, is composed of sand and gravel beaches backed by loess cliffs dissected by small rivers and creeks. The northernmost 4 kilometres encompasses beaches on a bay and headland coast associated with the basalt cliffs of Patiti Point, and Southbeach, an aggradational feature directly attributable to the building of the Timaru Harbour breakwater starting in 1878 (Tierney 1977; Neale 1987; Todd 1988).

The main study area for the thesis is part of the 28 kilometre stretch of coast from the Waihao Box to the Otaio River mouth. In particular it is that section from Waimate Creek to Hook Beach known here as the "Wainono Lowland Coast" (Figure 1.1) after Kirk (1987). It should be noted that this is not an official name recognised by the Geographic Place Names Board. This section of coast is subject to long term beach erosion, and to breaching caused by storm waves. South Canterbury Catchment Board established a network of beach profiles in this area and measured them at varying time intervals since 1977. The Board was concerned with determining the causes and possible remedies for past and future coastal hazards. The storm history of the region has been documented anecdotally and incidents of hazardous events have also been recorded. Previous studies of mixed sand and gravel beaches have been carried out on beaches of a similar nature to those of the study area, and studies of the geological history, sediment budgets and the nature of longshore transport through it have been made. The area is accessible throughout the year by Four Wheel Drive, and beach profiling can be carried out from a number of benchmarks and position-fixed steel 'waratah' standards along the backshore.

The beach sediments are derived from greywacke outwash gravels and sands. The beach is backed by Pleistocene and Holocene alluvial plains and fans often crossed by major rivers, streams, and artificial drainage channels. The alluvial fan sands and gravels are poorly consolidated and extend more than 50 kilometres out to sea to the edge of the continental shelf. In the nearshore they are covered by a thin layer of modern sands. The offshore sea-bed slopes gradually, with the gradient being

as low as one in five hundred. Rapid inundation of the continental shelf during the last post-glacial rise in sea-level caused extensive erosion of the outwash fans. From seaward extrapolation of the Waitaki River fan surface, Hewson (1977) argued that as much as 4.5 kilometres of retreat has occurred in the last four to six thousand years. This coast is still almost entirely erosional, with long term rates of shoreline retreat in the range of 0.5 to 4.0 metres per year or greater.

Wainono Lagoon is a major feature in the hinterland of the Wainono Lowland Coast. On average it covers an area of 325 hectares with a water level 1 metre above mean sea level. When in this state it is 2.8 kilometres long and 1.7 kilometres wide, its longest axis running parallel and directly adjacent to the beach (see Figure 1.1). A low-lying coastal wetland of largely undrained marshes covering a further 140 hectares to the north, west and south acts as a buffer between the lagoon and drained productive farmland (Pemberton 1980).

Kirk (1980) has summarised the principal morphological, sediment and process characteristics of mixed sand and gravel beaches as found in South Canterbury. The basic morphology and zonation of this beach type is also discussed by Kirk, and is shown in Figure 1.2. In the study area, the zonation is clearly defined except in instances of overwash. The narrow barrier beach of the Wainono Lowland Coast averages between 50 metres and 100 metres in width and the crest height ranges from 5 metres to 7 metres above mean sea level. The foreshore is stepped with remnant storm berms having steep seaward faces (from approximately 25° to 45°) being separated by near horizontal surfaces reflecting the last highest, and lower but more recent limits of wave run-up. The nearshore face and breakpoint is a narrow zone in which all wave breaking occurs. The tide pattern is semi-diurnal and is meso-tidal, with the spring tide range as predicted for Timaru Harbour being 1.7 metres, and the neap range 1.3 metres (New Zealand Nautical Almanac 1991/1992). However, because of the steep foreshore there is little horizontal translation across the profile of the position of the breaking wave and the nearshore face is never exposed by the retreating tide. The backshore consists of a washover slope encroaching upon adjacent low-lying farmland, or into drainage channels and Wainono Lagoon.

Davies (1964) has categorised all of the east coast of the South Island as an 'East Coast Swell Environment'. The wave fetch is extensive, from the South to the North-east and long period swells arrive from storm centres up to thousands of kilometres from the coast. Large storms also generate locally, producing short period steeper waves at the coast. Mixed sea states commonly occur, incorporating long period swell
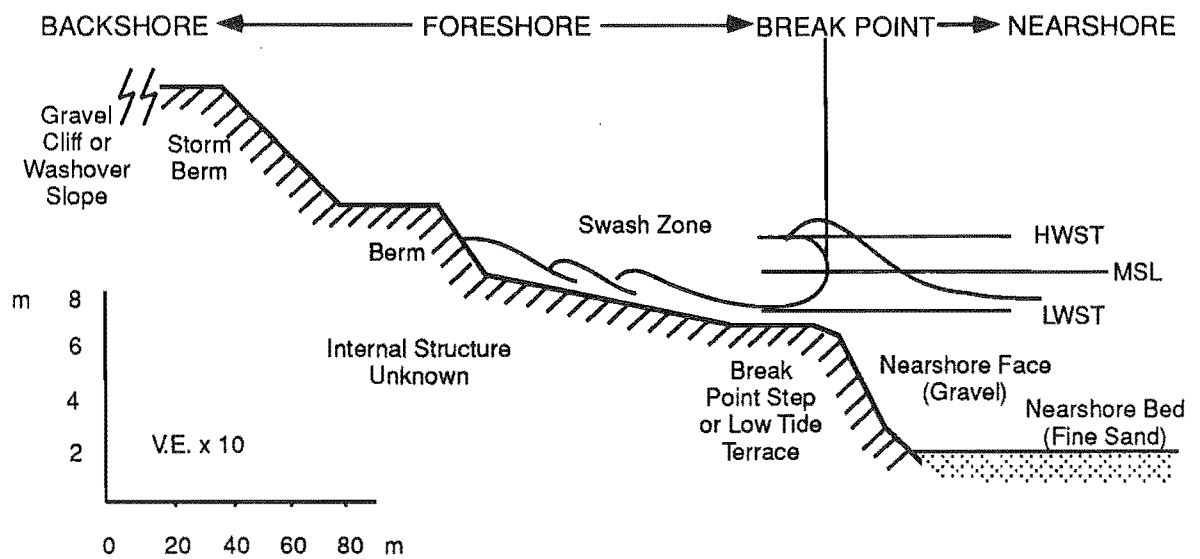
Figure 1.2 Typical morphology and zonation of mixed sand and gravel beach profiles (after Kirk 1980, Figure 2).

waves superimposed on short period storm and local wind generated waves. Mixed states also occur whereby swell waves of differing heights, periods and approach directions arrive at the coast from more than one remote storm. The average incidence of storm waves on this coast is ten to fifteen times per year and in the long term there appears to be no pronounced seasonality of storm incidence. However, Hastie (1985) measuring waves at Timaru in 1981-82 found that winter months displayed a greater range of wave conditions with higher significant wave heights and longer significant periods.

Table 1.1 displays details of wave data collection for South Canterbury. The methods of collection and the time periods covered are variable, with the most continuous record being Hastie's 1981-82 study. Table 1.1 also illustrates the range of wave heights and periods measured in this region.

The high incidence of waves of different heights and periods approaching the coast from different directions causes a complex wave environment at the shore. Hastie (1985), using wave data recorded 2 kilometres offshore from Timaru Harbour, from October 1981 to October 1982, found that the significant wave height ranged from 0.32 to 3.33 metres. The significant wave period ranged between 5 and 17 seconds. The mean values were 0.97 metres for height and 10 seconds for period. The maximum wave height recorded was 6.30 metres. The most recent period of wave data collection was carried out for Neale, with waves recorded by beach observation at South Beach, Timaru, from January to May 1987. He found that significant wave heights ranged from 0.3 to 1.8 metres, and periods ranged between 3.5 and 12.5 seconds (Neale 1987). He also noted a lack of storms during his study period. Kirk (1987a) states that breaking waves can be as high as 3 to 5 metres. There is a single surf line under most conditions and breakers are of a plunging type, collapsing as the wave broaches the nearshore step. During storms, long period waves can spill across the low gradient inner continental shelf and nearshore, then quickly rise in height and plunge at the nearshore face.

There is a large incident wave breaking angle for most storm conditions. Typically for a Southerly, the angle of incidence adjacent to Wainono Lagoon is 23°, and for a South-easterly it is 9° (Hewson 1977). This generates a strong longshore energy flux (Neale 1987). Net sediment transport is northward and is known to be of the order of 60,000 $m^3.yr^{-1}$, as measured by build up of material against the Timaru Harbour breakwater at Southbeach (Tierney 1977). The longshore sediment transport is of a dual nature. Gravels and coarse sand are confined to the foreshore and the steep

a) Data collected offshore

Source	Location	Measurement Period	Method of Measurement	Height (m) Min	Max	Mean	Breakdown	Period (secs) Min	Max	Mean	Median	Dominant	Direction
Hewson, 1977	Sedco 135F Oil Rig, 8km off Waitaki, water depth 50m	Oct-Dec 1966 112 obs.	wave rider bouy and visual	0.5	5.5	1.8	<1m:24% 1-2m:62% 2-3m:10% >3m:3%	2	11	7	7	6-8s:74%	N-NE:40% S-SE:26% S-SW:31%
Carter and Herzer, 1979 Pickrill and Mitchell, 1979	Sedco 135F Oil Rig, 20km off SE Oamaru, water depth 39m	Oct-Dec 1970 106 obs.	wave rider bouy and visual	-	4.5	1.77	<1m:1% 1-2m:46% 2-3m:45% >3m:8%	5	11	7.4	8	7-9s:62%	N-ENE:45% SE:20% S-SW:30%
Carter and Herzer, 1979 Pickrill and Mitchell, 1979	Tasman Glomodill ship 45km off Ellesmere coast, water depth 74m	Jul-Aug 1975 63 obs.	visual	-	6.0	2.38	<1m:15% 1-2m:22% 2-3m:35% >3m:28%	No period data collected					N-NE:20% E-SE:10% S-SW:65%
SCCB record	Benreoch Oil Rig, 60km off Waitaki coast, water depth 300m	Mar-Jun 1984 491 obs.	visual	0.0	7.0	2.68	<1m:2% 1-2m:40% 2-3m:34% >3m:24%	3	12	8	8	7-9s:74%	N-ENE:28% E-SE:4% SSE-S:43% SSW-SW:25%
MWD	9.5km off Rakaia water depth 30m	1983-1985	wave rider bouy	Record not available									

b) Data collected nearshore

Source	Location	Measurement Period	Method of Measurement	Height (m) Min	Max	Mean	Breakdown	Period (secs) Min	Max	Mean	Median	Dominant	Direction
THB	0.8km off Timaru break-water	Jul-Dec 1968 118 obs.	Echo sounder visual	0.5	5.8	1.24	<1m:48% 1-2m:44% 2-3m:7% >3m:1%	4	15	9.5	10.01	8-12s:82%	NE-ENE:9% E-SE:78% SSE-S:13%
Hewson 1977	0.8km off Timaru break-water	1967-1969 809 obs.	Echo sounder visual	0.4	3.66	1.28	<1m:37% 1-2m:51% 2-3m:11% >3m:1%	4	20	10.4	10	8-12s:68%	ENE:1% E-SE:98
Hastie 1983	2.5km off Timaru Harbour, water depth 12m	Oct-Oct 1981-1982 3728 obs.	Bottom-mounted wave recorder	Hs: 0.32 Hm: 0.22	Hs: 3.33 Hm: 2.33 Rec. 6.30	Hs: 0.97 Hm: 0.64	<1m:61% 1-2m:36% 2-3m:3%	Ts: 5 Tm: 7	Ts: 17 Tm: 17	Ts: 10 Tm: 11	Ts: 10	8-12s:85%	NE-ENE:25% E-SE:50% SSE:25%

c) Data collected onshore

Source	Location	Measurement Period	Method of Measurement	Height (m) Min	Max	Mean	Breakdown	Period (secs) Min	Max	Mean	Median	Dominant	Direction
Kirk 1967	Canterbury Bight various	Dec-Jul 1966-1967	visual		3.65								SE:Dominant E-NE:Secondar
Kelk 1974	Ashburton River	Dec-Jul 1973-1974	visual				<1m:75% 1-2m:25%	5.5	12		10.0	7-10s:80%	E-SE:95%
Hewson 1977	Waitaki Fan various	Dec-Apr 1976-1977 126 obs.	visual	0.3	3.0	1.07	<1m:58% 1-2m:37% 2-3m:5%	4	12	8.8	9	7-10s:75%	ENE:16% E-SE:79% SSE:5%
Kirk 1981	Washdyke	1980-1981 231 obs.	visual	0.3	2.0	0.59	<1m:75% 1-2m:25%	3	19	-	5.9	7-11s:70%	
Todd 1983	Opihi River	Dec-Mar 1982 1983 78 obs.	visual	0.2	2.5	0.75	<1m:75% 1-2m:21% 2-3m:4%	5	16	8.8	8	7-10s:55%	NE-ENE:30% E-SE:66% SSE:4%
SCCB	Various	1984-1986 186 obs.	visual	0.25	3.5	1.25	<1m:48% 1-2m:40% 2-3m:10% >3m:2%	3	18	10.1	9	8-11s:65%	NE-ENE:5% E-SE:88% SSE-S:7%
Neale 1987	South Beach	Jan-Apr 1987 78 obs.	visual	0.3	1.8	0.8	<1m:87% 1-2m:13%	4	13	6.5	6	4-7s:75%	

Table 1.1 South Canterbury regional swell and wave records (from Todd 1988, Table 9.1).

nearshore face, and are transported by swash and backwash processes of breaking waves. Seaward of the nearshore step a separate transport system also moves fine sands net northwards (Hastie 1983).

It was intended that wave and water level data collection would be carried out for this study to enable direct and comparative analysis of waves observed with measured morphological changes on the Wainono Lowland Coast. However, this could not be completed as during the first recovery operation of a submersible bottom mounted recorder (an OSK 3239 Direct Wave Height Recorder, Pressure Type A, moored in 12.2 metres of water on a large "Sarus Tower" marking the end of Timaru Harbour entrance channel), it was lost from the recovery vessel enroute to the shore. Subsequent searches by echo sounder and metal detectors proved fruitless, and were probably frustrated by the coincidence of dredge operations in the area just prior to the loss of the recorder. So, for this study, storm monitoring summaries collected by the South Canterbury Catchment Board have provided information on wave heights, periods, and direction, and storm durations, for events which were considered to be storm conditions by the Coastal Investigations Officer, Derek Todd.

The onset of storms on this coast is very rapid. Warnings of large swell waves from distant storms can be made after consultation of New Zealand Meteorological Service coastal swell forecasts, but on occasion the first warning of large waves at the coast received by the Canterbury Regional Council can be a telephone call from a coastal resident (D. Todd, Canterbury Regional Council, Timaru 1990, pers. com.). Storms on this coast seldom last longer than 48 hours, with overtopping usually limited to two or three consecutive tides. For example, a warning of the storm of July 1985 was received on the 27th of July. The majority of overtopping on the Wainono Lowland Coast occurred with high tides at 2310 hours on the 27th and 1140 hours on the 28th. Wave heights recorded by a Ministry of Works wave rider buoy situated offshore from the Rakaia River mouth exceeded 2.5 metres from 2100 hours on the 27th to 0600 hours on the 29th, giving a storm duration of 33 hours (S.C.C.B. 1985).

1.3 High Energy Coastal Events

1.3.1 Problems of definition

There have been many studies examining the impact of extreme events on coasts, including an extensive coverage of storm effects on barrier islands of the east coast of the United States of America. For example, Balsillie (1986) examined the effect of extreme events on the East Florida Coast U.S.A. for the purpose of deriving predictive

methodology to determine beach and coast erosion after storms and hurricanes. Leatherman, Williams and Fisher (1977) examined the effects of a large-scale northeasterly storm on coastal islands of Maryland U.S.A. Individual storm events have also been examined, such as Hurricane Eloise, detailed by Burdin (1977), and Chiu (1977). In New Zealand, studies of high energy events have concentrated on the general incidence of storms at specific locations and the impacts on the coast, especially erosion, in relation to human modifications. These appear mainly as technical reports. For example Kirk (1978), reported on coastal erosion at Omaha, Northland, as a hazard to residential developments near the coast.

More recently, Todd (SCCB 1985; CRC 1990) has produced reports for the South Canterbury Catchment Board and the Canterbury Regional Council on specific storm events. This follows an increased appreciation of the importance of storms as geomorphic agents on the South Canterbury Coast, and a desire for preparedness against possible hazard events such as sea water flooding. It also reflects an appreciation of the deficiency in knowledge about the nature of storm or high energy events and the nature of the impacts on the beach, and the need for a better understanding of what high energy or storm events constitute on the South Canterbury coast.

Defining a coastal event as "high energy" or not is a complex process. Classification of an event at the coast in the past has been either subjective or dependent on the physical consequences at the beach or both. Events on the South Canterbury Coast considered to be high energy are generally associated with some storm event at sea caused either by intensive atmospheric depressions generating storm waves up to thousands of kilometres from the shore, or more locally generated waves associated with smaller scale weather systems such as southerly fronts moving northwards along the coast.

When considering the nature of high energy events on the study coast, Kirk (1987a) has given some guidelines as to what constitute "storm conditions". He defined storm wave systems as those having maximum wave heights equal to or greater than 3 metres. Using data from Hastie (1985), Kirk abstracted monthly occurrences of events with wave heights equal to or greater than 3 metres. These are presented in Table 1.2. He found seventy five occurrences of daily maximum wave heights greater than 3 metres, an average of one every 4.8 days. It is worth noting here that this indicates that storm conditions as defined by Kirk are not rare events.

a)	Monthly Occurrences			
	January	2	July	8
	February	9	August	8
	March	6	September	3
	April	10	October	1
	May	6	November	7
	June	11	December	4

b)	Occurrences of wave heights in stated intervals			
	H max	6m		1
6m	H max	5m		4
5m	H max	4m		12
4m	H max	3m		58
				—
	Total			75

Table 1.2 Occurrences of daily maximum wave heights greater than or equal to 3 metres, October 1981 to October 1982 (from Kirk 1987, Table 6; derived from the data in Hastie 1985).

Table 1.3 is a collection of flooding and overtopping reports of events affecting the lowland South Canterbury coast since 1962. The record has been kept in a comprehensive fashion only since 1984. Thus minor and moderate events prior to 1984 have not been recorded. Looking at this information in conjunction with Table 1.2, it can be seen that although there were many incidents of "storm conditions", only one event, that of June 28th 1982, led to a report of damage on the coast.

For the purposes of this study whether Kirks' definition of storm conditions is appropriate or not comes under question. Coastal storm events are generally considered to be rare occurrences that result in significant changes to the beach morphology. It has been shown that when measured by consideration of a wave height greater than 3 metres then storm conditions on this coast are not rare. However they are events containing processes involving high energy, and do cause changes to the beach morphology. It is important to determine whether these changes can be considered significant or extraordinary to the beach character, or if the classification of this coast as high energy is truly appropriate. If this is so, what do these events contribute to long term (tens to hundreds of years) trends in the beach behaviour?

Year/Date	Class	Event Description
1962 (16/4)	s	60 chains of bank between Opihi River and Orari demolished. Flooding of low lying land at mouths of creeks and rivers. 450 acres flooded at Orari Lagoon, over 1 000 acres south of Timaru. Damage to Waihao and Saltwater Creek "Boxes".
1968 (12/4)	s	"Wahine Storm". Combined with high rainfall. Damage to concrete block protection at the mouth of the Orari River. 500 acres flooded from Opihi River to 2 miles north of Orari River.
1969 (/4)	s	Waihao Dead Arm blocked. Beach crest lowered and 4 complete breaches. Estimates by TL Fancourt suggest that up to 650 acres (2/3 croppable) in the Seadown-Washdyke area can be flooded; 500 acres at Otaio-Makikihi; and 370 acres in spots from Makikihi to Morven (excluding Waihao Lagoon). Another 60 acres around Normanby and Pig Hunting Creek.
1974 (17/8)	s	Flooding of Milford Lagoon and 40 hecters of adjacent land. Overtopping of stopbanks. Extensive flooding in the Makikihi area, as far inland as SH1, partly by water backing up through culverts.
1974 (20-21/6)	s	Flooding: 60 ha South bank of Orari River; 50 ha South of Opihi River 500 ha South of Otaio River, including 55 ha at Waihao, Dead Arm. Some 560 ha of farmland underwater. 1700 ha of the Wainono Drainage Area (Makikihi River to Waihao River) has experienced serious interference with main drains adjacent to the coast because of erosion and infilling of the drains.
1977 (17-24/4)	s	Approximately 10 year return period event. 2 coastal breaches in stopbanks Opihi River to Washdyke. Waves H - 5m, T - 15 seconds.
1977 (2-5/7)	s	Severe overtopping into 210 ha, Opihi River to Washdyke; 194 ha of this landward of the stopbank. Aorangi Road area severely flooded. Erosion at Rangitata Huts (map available).
1978 (14/6)	s	Stopbanks overtopped in 9 places, Opihi River to Connollys Road for 6 consecutive tides over three days.
1978 (25-26/6)	s	Stopbanks from Opihi River to Washdyke overtopped on 4 consecutive high tides.
1980 (7/11)	mo	Two episodes of overtopping at Washdyke Beach re-nourishment trial site.
1981(/8)	mo	Runup onto crest of re-nourishment trial at Washdyke. H - 3.5 to 4.0 m.
1982 (28/6)	s	136 ha farmland flooded landward of stopbank from Washdyke to Opihi River. Aorangi Road area flooded. (map available)
1984 (18/1)	m	Overtopping at Washdyke during spring tides and a southerly storm.
1984 (1/5)	m	Minor overtopping at Washdyke on a surge with a heavy swell.
1984 (30/5)	m	Minor overtopping at Washdyke.
1984 (14/6)	mo	Moderate overtopping at Smithfield to Aorangi Road for one tide. Breaching of the old stopbank at Aorangi Road.
1984 (6/8)	m	Minor overtopping at Washdyke.
1984 (30/11)	m	Minor overtopping at Washdyke.
1985 (22-23/4)	mo/s	Aorangi Road area flooded. Minor - moderate overtopping on the first high tide, and moderate - significant on the next tide.
1985 (13/5)	mo	Moderate overtopping over two tides. Pareora River mouth overtopped. Breaching at Wainono Lagoon and Waihao Box.
1985 (27-28/7)	s	505 ha in total flooded in Otaio-Sinclairs Creek area. 3 coastal breaches at Waimate creek. Extensive beach crest lowering at Ruddeklau's , Wainono. Hs = 4.09 m; Tav = 7 sec at MOWD wave recorder off Rakaia River Mouth.
1985 (21/8)	mo	Moderate overtopping at Washdyke.
1985 (25/10)	m	Minor overtopping at Washdyke.
1986 (25/2)	m	Minor overtopping at Washdyke.
1986 (3/4)	m	Minor overtopping at Washdyke.
1986 (22/6)	mo	Overtopping at Washdyke - Seadown. Local storm sea and surge.
1986 (30/6-3/7)	mo	Moderate overtopping at Washdyke. A week of high seas due to a depression centered near the Chatham Islands.
1986 (8/8)	m	Minor overtopping at Washdyke.
1986 (23/8)	mo	Moderate overtopping at Washdyke - Seadown.

Notes:

[m] "Minor" events reach the beach crest and may wash over to the landward slope of the beach.

[mo] "Moderate" events may overtop the beach for a few hours of a tidal cycle.

[s] "Significant" events yeild sustained overtopping and occur for two or more high tides (12 hours plus)

Table 1.3   Coastal flooding events in South Canterbury from 1962 to 1986 (from Kirk 1987, Table 8).

1.3.2 Magnitude and Frequency of Geomorphic Processes

In general coastal theory, it is considered that there are two dynamic responses to wave conditions. Davies (1964) referred to "prevailing" and "dominant" events to distinguish the 'normal' or most prevalent wave environment, from storm waves. By analogy, this suggests that the normal conditions are not storm conditions. Most often the distinction is between 'swell', and 'storm' waves, or using North American terminology, 'summer' and 'winter' wave conditions, that are differentiated by wave shape. Swell waves are low in height in relation to the distance between crests, and therefore less steep than storm waves which are higher in relation to the distance between wave crests.

The Shore Protection Manual (C.E.R.C. 1984) states that:

> "The subtle changes in the beach which occur during normal conditions
> are nearly imperceptible to the untrained observer, but the beach's
> defence mechanisms become obvious when storms attack. Storms do
> not occur often, but their effects are often devastating in terms of
> shoreline erosion." (p1-10)

Experiences on New Zealand mixed sand and gravel beaches also lead to the hypothesis that much of the geomorphic work done on this beach type occurs during infrequent short duration high magnitude events. This is reflected in the resulting morphology and trends in beach behaviour, such as rapid erosion, longshore transport and across shore displacement of coarse material during southerly storm events. Comparatively, it is considered that the work performed during swell conditions occurs for a greater duration but is of a lesser strength and is therefore less important to the long term function of the beach.

Wolman and Miller (1960) discussed the relative importance of extreme or catastrophic events and more frequent events of smaller magnitude in geomorphic processes. Their basic premise is concerned with the geomorphic effectiveness of events in moving material on a feature and modifying the surface form. They state that:

> "Available evidence indicates that evaluation of the effectiveness of a
> specific mechanism and of the relative importance of different
> geomorphic processes in molding specific forms involves the frequency
> of occurrence as well as the magnitude of individual events."

They go on to say:

> "The relative amount of "work" done during different events is not
> necessarily synonymous with the relative importance of these events in

forming a landscape or a particular feature of the landscape. The effectiveness of an event of a given frequency in terms of its performance of work is measurable both by its magnitude and by the frequency with which it recurs." (p55)

Wolman and Miller argued that beaches have an equilibrium profile around which rapid fluctuations or adjustments occur depending on variations in the conditions controlling the form of the profile. They considered the beach profile to be a function of grain size and wave steepness, and used wind speed - as a partial controlling factor of wave steepness - to illustrate changes in frequency and magnitude of force in relation to the changes in beach profile. They concluded from their example that the equilibrium beach profile was related to moderately strong winds and therefore moderate storms rather than winds resulting in infrequent catastrophic storms. They acknowledged that some types of work can only be done by high magnitude events. However Wolman and Miller do not allow for a distinction between the form and position of the beach when considering a beach equilibrium.

Most beaches are considered to be dynamic in that they constantly respond and adjust to dissipate incoming wave energy. This results in a change in form of the beach, and in some cases changes to the position of the beach in space. Changes in the form of the beach can be observed by monitoring changes to the beach profile after events of different magnitudes and over different time periods. A number of observations of a profile over a period of differing process environments can be contained by a profile envelope as shown in Figure 1.3. Overnourished beaches are often found to have large envelope changes in profile as the beach progrades. Beaches that are sufficiently nourished have large profile envelopes but in the long term neither prograde nor retreat landwards. Eroding beaches typically have small profile envelopes but the beach as a whole retreats landwards (R.M. Kirk, University of Canterbury 1991, pers. com.). The profile envelope can be thought of as a result of events of all sizes, including both prevailing and dominant conditions, while the shape of the profile at any one time reflects the antecedent conditions. The position of the beach in space is solely a function of high energy events that affect the whole beach profile and drive the beach landward.

Kirk (1967) considers the mixed sand and gravel beaches of the Canterbury Bight to be in a state of dynamic 'sub-' equilibrium, whereby the beach is constantly adjusting in profile to ongoing wave conditions and maintaining a near constant shape and beach volume in the short term, but is migrating landward as a response to reduced sediment supply over a longer time scale.

a)

b)
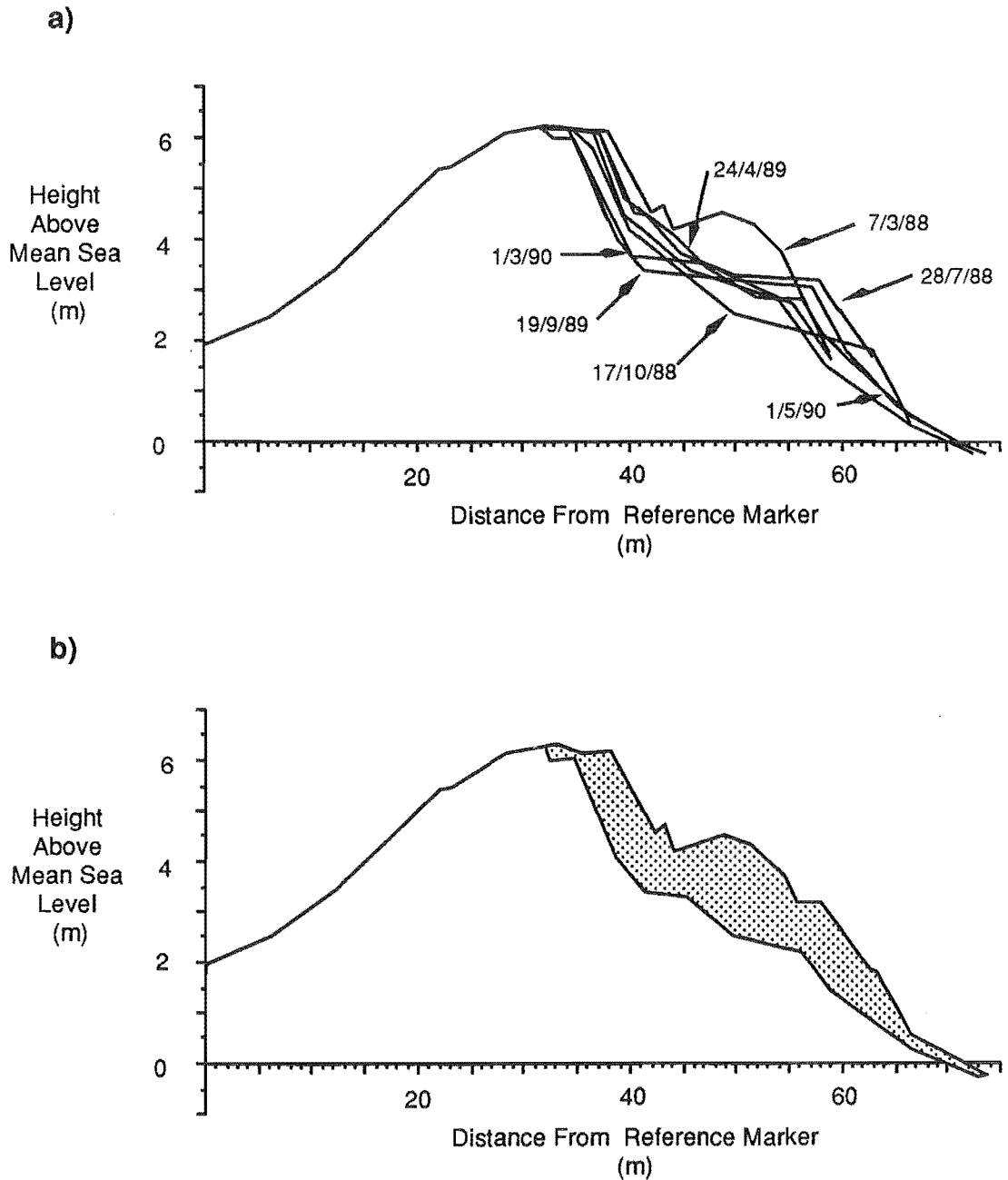
Figure 1.3 Beach profile showing envelope containing short term changes.

a) A selection of profile surveys (from Profile 7 of this study).

b) Shaded area is the envelope of change between the first and last survey dates of a) above (7/3/88 and 1/5/90).

Warnke (1967), investigated a low energy coastal environment in the Gulf of Mexico, that is subjected to infrequent but high magnitude storm surge due to the passage of hurricanes. He found that the conclusions of Wolman and Miller were only partially applicable to his study area. Only the shape and location of the beach profile within the profile envelope was determined by prevailing to moderate processes, while the location of the beach envelope in reference to a fixed system of coordinates representing the position of the beach, was determined by hurricane surge. Warnke also stated that although hurricane surges could be considered infrequent or unusual, catastrophic events, they nevertheless occur approximately twice a year and cannot be called infrequent or unusual in a geological sense and are "part and parcel of the Gulf-coastal environment" (Warnke 1967, p58).

Dramatic events or turning points in a system have also been considered in terms of a geomorphic threshold, although the concept has not often been applied to coastal environments. Schumm (1979) offers two definitions for the geomorphic threshold. His first definition is that the threshold is inherent in the manner of the landform change, developed within the geomorphic system by changes in the morphology of the landform itself. The landform will not cross it's threshold until it has evolved to a critical stage. This definition utilises the concept on an intrinsic threshold, where processes remain relatively constant, but change the structure of the landform until a stage is reached where failure will occur.

Schumm's second definition involves a change in an external variable. This change could be progressive over time or relatively instantaneous. For example, climatic change or changes in sea-level are long term variables, whereas change in water elevation through a tidal cycle is a short term variable and a change in wave energy with a storm event occurs in a few hours. Changes to the pattern of sediment availability can be external or intrinsic to the system. For example, damming of the Waitaki River for hydro-electric power generation caused a marked interference to the sediment output of the river. This has become an important factor in the availability of sediment at the coast. In turn, this disruption in sediment supply is transferred downdrift along the coast as an intrinsic factor of the beach morphology. These changes cause a disruption to the shape of the landform or in its function.

The onset of a storm therefore fits with Schumm's second definition of threshold exceedence, whereby the change in process from 'normal' to storm conditions causes a change in the way the beach functions. This could take the form of shoreline erosion, or there could be transport alongshore with a net loss of beach volume at a specific

location. Changes to the shape of the beach profile without loss of material can also result from storm waves. With the resumption of non-storm conditions, the beach usually presents a different character to wave action than that presented prior to the storm. The net long term consequences of subsequent stormy and non-stormy conditions can be examined in light of Schumm's first definition of the geomorphic threshold. It is in light of this definition that the antecedent condition of the beach and the progressive change in beach morphology becomes important in determining the response to a particular high energy event.

Speculation on the principles of magnitude and frequency, and thresholds is an important conceptual step in the study of coastal geomorphology. It is useful in that it provides a basis for examining an interaction of coastal processes with geomorphic responses at differing spatial and temporal scales by including the beach as a constantly adjusting system responding to, and affecting the nearshore wave and run-up environment.

This thesis will examine these concepts in an attempt to state some general principles that have not previously been fully elaborated in coastal science and specifically in relation to South Canterbury mixed sand and gravel beaches. Two questions can be put forward for consideration.

> Does the magnitude and frequency concept apply to the South Canterbury coast, if so how, and if not why not?

> What thresholds exist in the function of a mixed sand and gravel beach system?

1.4 Beach Function

Beach response has been discussed so far, purely as some change in morphology due to oceanographic processes. However, this response is implicit to the way the beach functions, it is the "...natural dynamic response to the sea" (C.E.R.C. 1984 p1-9). The beach profile adjusts to best dissipate wave energy, and in doing so, the beach becomes protection for the coastal hinterland. Therefore, the function of the beach is of vital importance to human use of the greater coastal environment, and the long term functional performance of the beach is a measure of success in protecting the hinterland.

New Zealand mixed sand and gravel barrier beaches are generally erosional features. As the sea cuts back into highly erodible fan gravels adjusting the coast in plan view, the beach migrates landward maintaining its shape and volume to some

degree. Volume is lost however, due to abrasion and impact of pebbles, and by net losses out of the active beach from longshore transport and overwash. The shape in profile changes in the short term in relation to wave conditions and the availability of sediments in the active swash zone. In the long term, maintenance of profile shape is dependent on inputs of beach material to offset losses. This material has three main natural sources. Either it is injected into an area by longshore transport of material from 'updrift', or it comes from the eroding hinterland, cliffs or gravel fans, or coarse sediment carried to the sea by rivers enters the beach system at river mouths.

The Wainono Lowland Coast works in this way, except the supply of sediment to the coast is less than losses from the beach. Mean historical rates of erosion along this section of coast are generally less than 1.0 metre per year, although in the nine years from 1977, landward displacement of the beach crest at Wainono Lagoon averaged 6.7 metres per year. As protection for the low lying farmland and wetlands, the barrier beach absorbs and dissipates wave energy. Severe storms can cause dramatic erosion, but can also inject material into the beach system (Kirk 1987a, p86). This material comes from the low gravel cliffs south of Wainono, and from the Waitaki River mouth system.

Neale (1987) introduced the idea of 'slugs' of material moving along the coast. His work is reviewed in Section 2.7. Passage of these slugs alongshore was thought to be a source of irregularities in beach morphology. Material is injected into the system during stormy periods as a result of cliff and beach erosion or due to the input of sediments caused by flooding down the Waitaki River. The injection of material therefore is neither uniform over time nor in particle size. Neale considered these slugs to move northwards alongshore at an average rate of 1.4 km.yr^{-1} (in the direction of net longshore transport) as discrete units progressing past any given site in a wave-like form. This can be seen in terms of changes to the average volume of the beach. An excess in the average beach volume can be likened to the crest of the slug wave while a volume less than the average is the trough. The passage of slugs at a specific site is a controlling factor on the amount of beach material available in the adjustment of the beach profile in response to the wave environment. This is especially important in the case of sites where a slug 'trough' is present during a storm event. The presence of a slug 'crest' can also present a projection in the plan aspect to incoming waves, causing localised concentration of wave energy at the extremities of the slug. These are important pre-disposing "antecedent" conditions for a site and it is necessary to study the concept further, specifically by examining:

What are the mechanics and component variables of the passage of slugs, how big are they, what drives them and how fast do they move along the coast?

How does the passage of slugs affect the response of the beach to high energy events at different sites along the coast and at particular sites over time as the slugs pass through?

1.5 Thesis Rationale

Most coastal theory has been devised in consideration of sand beaches, while most knowledge of the workings of mixed sand and gravel beaches has been adapted from existing theory to fit specific environmental conditions (for example Neale 1987). Examining the relative importance of events of varying magnitude in determining beach morphology and function for this study requires an understanding of how the mixed sand and gravel barrier beach system adjusts and responds to high energy events, and how these responses contribute to long term changes of the beach. The approach taken here has exposed a dearth of knowledge as to how mixed sand and gravel beaches function and to how the concepts of magnitude and frequency apply to these beaches. In resolving these deficiencies in knowledge it is necessary to examine the nature of the prevalent high energy coastal events, and the impact of these and low energy events on the beach morphology.

Any coastal event must be considered in relation to magnitude and temporal scales, both of the event and of the consequences onshore. The energy component of the main operative process comes from the wave environment. The impact on the beaches is dependent on where the distribution of the work on the beach profile occurs, the duration of an event, and how often such an event occurs. The consequences of an event will also depend on the character and 'health' of the beach under wave attack directly prior to the event. The hypothesis is that a 'healthy' beach, one well supplied with sediment or holding sediment available to dissipate wave energy, will respond to an event differently to a beach in sediment deficit . For these reasons, the antecedent conditions are important in predetermining the effects of a storm event at a given time.

The impacts of high energy coastal storms on the South Canterbury Coast are by nature difficult to observe or measure during the event. Coastal storms moving northwards along the coast are often associated with cold southerly frontal systems and are accompanied by rapid drops in temperature, strong winds and driving rain. Figure 1.4 shows the extreme physical nature of the storm events, which create difficulties in field observations and measurements. Because the barrier type beach is very narrow

Figure 1.4 Overtopping and flooding of the barrier beach at Waimate Creek between Wainono Lagoon and Waihao River (source, D. Todd Canterbury Regional Council).
a) Looking across the Waihao Dead Arm drainage channel to the backshore, June 1974.
b) Looking south along the backshore from the beach crest, July 1985.

and the seaward side is very steep, wave run-up and steep plunging breakers pose a threat to the safety of anyone attempting to closely monitor beach changes during the event. This includes wave height and period observations, as associated with the close proximity of the breaking waves, there is also a possibility of the beach being overtopped or breached, possibly stranding the observer in a highly dangerous situation. Therefore, a quantitative assessment of the oceanographic variables and breaking wave processes is extremely difficult to obtain.

The coastline in the study area is isolated from major urban areas and is sparsely populated. The South Canterbury Catchment Board (now the Canterbury Regional Council) has arranged for wave observations to be made by coastal land-owners during major storms, or when the board has received storm wave warnings from the New Zealand Meteorological Service. These observations have provided estimates of wave heights, periods, and directions of approach for specific events, and also contribute to the record of wave data for the South Canterbury region.

Apart from short term sediment changes, the morphological character of the beach is more readily assessed quantitatively. Owing to the rapid onset and short duration of the majority of storm events on the South Canterbury Coast, an examination of morphological change over a short period including a storm event is more viable than a study of processes and beach response during the event. For the above reasons, measurable changes in beach volume, shape and horizontal position of the shoreline in relation to a fixed datum, were examined for a number of profile sites along the study coast, to provide an insight as to the short and long term adjustments of the beach in response to the wave environment.

The major focus of the thesis is therefore a morphological examination of beach change to identify the role of high energy events in determining the long term form and function of mixed sand and gravel barrier beaches, including catastrophic responses, rather than an intensive study of the work done by successive individual high energy waves during an event.

1.6 Thesis Outline

In summary, this chapter has introduced a need for further understanding regarding mixed sand and gravel beaches. An hypothesis has been advanced stating that much of the geomorphic work done on mixed sand and gravel beaches is done during short duration high magnitude events, while a series of specific questions have been identified to guide the research. The magnitude and frequency discussion of

Wolman and Miller, and Schumm's contentions of threshold exceedence and catastrophic events have been introduced in relation to high energy coastal events and beach adjustment. The practicalities of studying high energy events at work have also been discussed. The remainder of this thesis assesses the above hypothesis in relation to high energy events on the Wainono Lowland Coast.

Initially it is necessary to synthesise what is known about mixed sand and gravel beaches, and the South Canterbury Coast. To this end a synopsis of the major findings of some of the studies carried out by staff and students of the Department of Geography, University of Canterbury, will follow in Chapter Two, especially relevant post-graduate theses. The Wainono Lowland study area will be described and put into context in relation to the larger South Canterbury coastal system in Chapter Three. This includes a detailed description of the morphological character of the study area, incorporating information gathered during this thesis with that from past studies.

A discussion of beach profile adjustment over the study period is presented in Chapter Four as a means of determining morphological change in the study area between September 1987 and July 1991. Beach cross-sectional profiles were surveyed by the author and by a team from the Canterbury Regional Council at seven sites along the coast over different time intervals through the study period. Analysis of the resulting plotted profiles is combined with excursion distance analysis of contours at different elevations on the foreshore, and with volumetric change of the profile to address the questions raised in this chapter concerning the role of high energy events in determining the long term morphological character of the coast, particularly in respect to sustained long term coastal retreat and to the sediment budget.

Specific examples of high energy storm events are examined in Chapter Five. The weather situations from which the storms developed and the resulting impacts on the beach are discussed. The short term effects of storm or high energy events on the South Canterbury coast are considered, as are the more specific questions concerning the processes of beach crest lowering and breaching. The important issue of defining the characteristics of high energy events for this area is also discussed at this stage.

The longshore component of the Wainono Lowland beaches is an important aspect of the three-dimensional interaction of the study sites. It also sets up the linkages of this section of coast within the larger South Canterbury mixed sand and gravel beach system. Longshore aspects of the study area are discussed in Chapter Six in respect to a spatial analysis of beach adjustments during the study period. Neale's notion of the passage of 'slugs' of sediment moving along the coast is

discussed in light of the field evidence from this study. Across-shore zonation of the profile and variations in sedimentary characteristics are also investigated.

Conclusions from the study are presented in Chapter Seven as are some possible directions of future research concerning the workings of mixed sand and gravel beaches and the South Canterbury coast.

CHAPTER TWO

MIXED SAND AND GRAVEL BEACHES

2.1 Introduction

Zenkovich (1967, p 271) stated that mixed sand and gravel beach systems have 'the most complicated' dynamics of all beach types. Methodology developed for pure sand or pure gravel beaches cannot be directly applied to the mixed beach. Therefore, because of the predominance of mixed beaches on the east coast of New Zealand, and the pressures of human use on these coastal environments, new methodologies and theories have had to be developed to enable coastal scientists to understand the processes at work. These developments in New Zealand coastal studies have been made mainly by university scientists and their research students.

Since the 1960's, studies of New Zealand east coast beaches have been carried out by a number of staff and students of Canterbury University Geography Department, initially under the supervision of Dr R. F. McLean, and then Dr R. M. Kirk. Research and teaching of the Coastal Studies courses are aimed at extending the spatial coverage of studies on New Zealand coasts, elaborating on problems encountered in previous studies, and investigating coastal processes and environments in attempting to provide and apply answers to practical problems (Kirk 1987b). Many Masterate and Doctoral theses have also been written by students under the supervision of Dr R.M. Kirk, regarding the dynamics of mixed sand and gravel beaches. These theses are held in the Map Library of the Department of Geography, and so are not readily accessible to the international scientific community. A number of papers have been produced within the department that have relevance to this study - as background to the study of mixed sand and gravel environments, and to understanding the processes at work.

It is the intention of the Canterbury Coastal Studies Group to pursue coastal questions from many scientific premises using previous studies as a basis for expansion of knowledge whether by extension from or elaboration of important findings. This has led to a holistic approach to research and to the teaching of coastal studies, and is especially significant in developing an appreciation of the interconnectedness of processes, sediments, morphology and human intervention.

A review and summary of some of the mainly unpublished work and investigations concerning mixed sand and gravel beaches is presented in this chapter. This review includes studies carried out for "pure" research, undertaken to gain advanced university

degrees, and applied studies prepared as consultative work for local bodies and engineering concerns. The purpose of this review is to place this study in a scientific context and to provide background information on mixed sand and gravel beach processes and morphologies. No overview of the present state of knowledge regarding this beach type has been published since 1980 (Kirk 1980).

2.2 General Characteristics of Mixed Sand and Gravel Beaches

2.2.1 Overview

By 1980, New Zealand studies of mixed sand and gravel beaches had progressed mainly within masterate theses and through applied problem solving for local bodies in the South Canterbury region. Some papers had been published on aspects of the New Zealand beaches such as those by Pickrill (1977), Kirk et al. (1977) Kirk and Hewson (1978) and Kirk (1980). Kirk (1980) is probably the most well known of these papers, and covers the basic notions of mixed sand and gravel beaches. In it Kirk outlines the morphologies, sediment characteristics and processes at work on mixed beaches using New Zealand open coast studies as examples. He also details the context of studies carried out to 1980.

McLean (1970) introduced four common features of New Zealand mixed sand and gravel beaches as listed below.

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.

4. They are exposed to the high energy waves of an East Coast Swell Environment (Davies 1964). (McLean 1970, p142)

These features are common to both North Island and South Island mixed sand and gravel beaches.

2.2.2 Beach morphology and sediments of the Canterbury Bight

Kirk (1967) investigated the Canterbury Bight in overview for his Masters thesis in Geography. The aims were to describe the sediments and variations of morphology in relation to the active processes over short term, seasonal and longer time periods. The beaches of the Canterbury Bight are exposed to a considerable variation of wave sizes and rapid changes in approach directions. They are potentially well supplied in beach

material from rivers and eroding cliffs. The Canterbury Plains are a 40 kilometres wide Pleistocene fluvio-glacial outwash plain. The gravels are known to be more than 700 metres thick and extend 50 kilometres seaward of the present coast (Kirk 1969, 1987a). They are composed mainly of Mesozoic greywacke, argillite and chlorite zone quartzo-feldspathic schist (Herzer 1981). Greywacke, the dominant rock type of mixed sand and gravel beaches is defined by the Chambers Dictionary of Science and Technology as a sandstone containing silt, clay, and rock fragments in addition to quartz grains. It is more poorly sorted than other sandstones. It often occurs as beds which show gradation in grain size from fine at the top to coarse at the bottom (Collocott and Dobson 1974). Coastal adjustment due to post glacial sea level rise has caused erosion of the seaward edge of the outwash fans and a northward drift of sand and gravel to form Kaitorete Spit. Retreat of the cliffs has resulted in offshore bathymetric contours running approximately parallel with the present day coastline.

Kirk's methods of data collection included measuring twenty four beach transverse profiles four times from December 1966 to June 1967. Profiles were surveyed using an Abney level and tape measure. Although only accurate to half a degree in vertical angle, errors were minimised through consistent application of the technique. Sediment samples were taken from the swash zone at mid-tide level and from the backshore. Wave observations of height, period and direction were made daily from Timaru Harbour and in conjunction with beach profile surveys.

Kirk (1967) found that the surf zone in the Canterbury Bight is very narrow and there was little seaward or shoreward translation of breakers during the tidal cycle. He also found that a low tide step existed at which waves break at all stages of the tide. Wave energy dissipation is confined to this narrow break zone and the lower foreshore is subject to high turbulence. The beach profile is therefore dominated by swash and backwash. Kirk (1970) examines the swash zone processes more fully and findings are presented subsequently in Section 2.4.3 However, basic principles are introduced in his masterate study.

Kirk (1967) noted that some of the measured profiles exhibited pronounced tiers of berms related to erosion and deposition episodes due to waves of different magnitudes. The highest waves were noted to have the largest swash, and produced the highest berms. During the formation of these berms, lower berms are removed or modified. However, movement of individual prisms of gravel onshore to the limit of the high tide swash occurs progressively during the tidal cycle so the beach profile is undergoing constant change in the short term which is masked by large changes due to storm episodes.

Seasonal changes were found by Kirk to be generally small with erosion and deposition occurring all year round. There was some indication of a change from net deposition in summer to net erosion in winter, but the magnitudes were small especially in consideration of measurement inaccuracies in his profile survey technique.

In his discussion of changes in beach morphology, Kirk distinguished between short term adjustments - a function of incidence and distribution of wave energy on the profile - and long term adjustments - changes in size, shape and position of the profile in relation to a fixed set of coordinates, as a function of the incidence of supply and loss of materials to the littoral zone.

Kirk calculated that the Canterbury Bight beach profiles were retrograding in the long term. This was thought by Kirk and McLean to be at odds to the fact that the coast was supplied by sediment from several big active rivers (Dr R. M. Kirk, Dept of Geography, University of Canterbury, 1991 pers. com.). There is an abundant total sediment supply from the rivers, but a comparative deficiency of coarse sizes that can be contained within the beach system. There is therefore an imbalance due to the excess of wave energy over the availability of material that can be moved by the wave environment, so the long term consequence is coastal erosion. The beach was considered to be in "sub-equilibrium" as it appeared to be in short term equilibrium but eroding in the long term. In plan form, the Canterbury Bight is generally orientated to face the prevailing South-easterly swell direction. The northern section of Kaitorete Spit is the downdrift terminus of the Canterbury Bight and is depositional. It is also the only section of the Bight orientated towards the dominant southerly storm waves. As such, the Bight is still adjusting to post-glacial sea-level fluctuations, and to spatial and temporal variations in sediment supply.

Kirk (1969) presents the development of Canterbury Bight in relation to equilibrium theories of beach development. Much of the information presented in this paper was gathered and discussed in his Masters thesis. He described the Canterbury Bight as a high energy shore, exposed to highly variable wave action. He divided the shoreline into elements which included the retreating cliffed margin of the combined alluvial fans of the major rivers, the present river mouths and lagoons, and wave built barrier beach ridges. Field observations and analysis of beach profile changes and plan-form characteristics are discussed. Variations in beach profiles are presented volumetrically and as isopleth diagrams showing movements of selected beach contours from a fixed base point. The latter presentation for four profiles as presented by Kirk, is shown in Figure 2.1. Profiles 7 and 11 represent cliff backed sections while profile 13 is situated
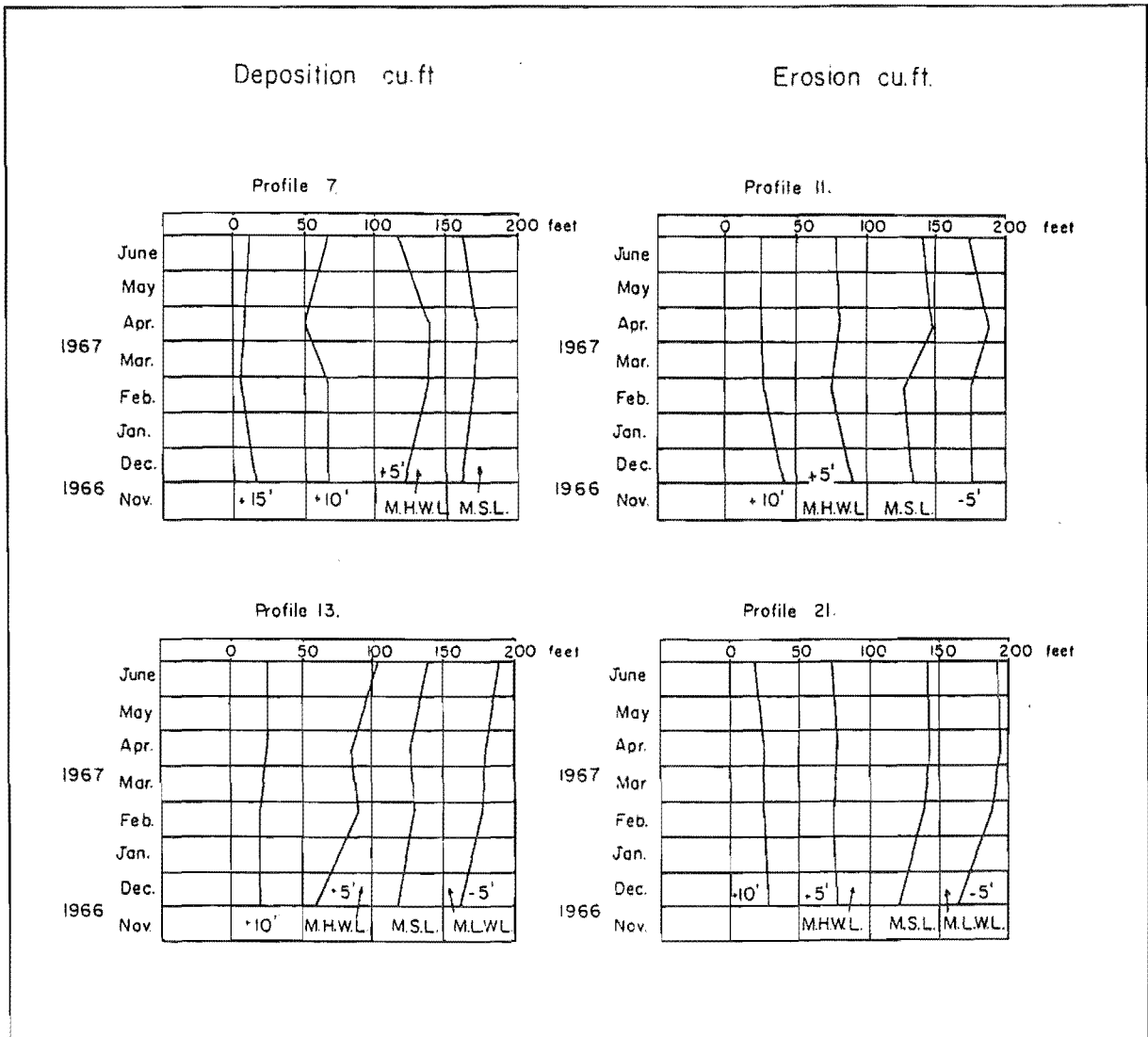
Figure 2.1 Isopleth diagrams showing the seasonal movements of selected beach contours at four stations (from Kirk 1969, Figure 2).

near the Ashburton River lagoon barrier. Profile 21, sited south of the Opihi River is a barrier ridge beach adjacent to low elevation cliffs formed in loess deposits. Kirk used this data to demonstrate a low order of profile variation, suggesting a short term erosional equilibrium related to storm action.

Profile slopes were explained in relation to swash action during swell and storm episodes. Building, removal and subsequent rebuilding of berms by swell swash and storm swash was said to be confined to the lower third of the profile. Low planar slopes above High Water Level were attributed to an adjustment to long turbulent swashes associated with southerly storm waves. Kirk considered that a long term trend of pronounced coastal erosion would tend to make the beach become wider and flatter as erosion proceeds. A deficiency in the approach is that no consideration was made of water level variations in conjunction with storm conditions such as storm surge and wave set up.

Kirk (1967) concluded that mixed sand and gravel beaches display a considerable complexity of form and process. He attributed this to the mixing and range of sediment sizes, and the differing responses to wave energy. He also suggested that there is a close correspondence between morphological indices of beach development and textural characteristics of the beach deposits. This effectively characterises the beach and he suggested that it could be used to compare the stages of development between different beaches.

Kirk (1969) concluded that the Canterbury Bight is in a subequilibrium stage of development. There exists a short term erosional equilibrium in relation to the prevailing southeasterly swells and the incidence of southerly storms. Fluctuations around this equilibrium form appear to be minor but over the long term the small amplitude envelopes containing short term changes, are shifting landward. In this case Kirk emphasised the important distinction between form and position of the profile relative to a fixed set of coordinates.

2.2.3 Plan shape and orientation of beaches along the East coast, South Island

McLean (1967) wrote an essentially descriptive report of equilibrium plan shape of 86 beaches situated along the east coast of the South Island. He noted deviations from the simplest geometrical model of the time, a circular arc, obtaining the theoretical radius of curvature for each beach by measuring the chord length between end points of the beach, C, and the length of a perpendicular line drawn through the midpoint of the chord to the shore, P. Using C and P, the radius of curvature, R, was calculated by the

formula $R = (C^2 + 4P^2) / 8P$. Beach orientation was also obtained by measuring the orientation of the line, P, in degrees from north. Deviations from main directions were described and a condition of equilibrium was considered using criteria from Hoyle and King (1958), such that the beach must be supported at both ends, it must have a curved shape representing the arc of a circle with the angle subtended at the centre by the radii of the beach ends of 0.25 radians, and it must be orientated perpendicular to the dominant waves. A fourth condition, that the slope of the beach profile must be in equilibrium, was excluded by assuming a state of dynamic equilibrium for the foreshore slope of all beaches as they continually adjust to changes in energy and material factors. McLean regarded planimetric shape and orientation of beaches to be the result of a complex set of process elements, including energy factors (waves, tides, currents and winds), material factors (grain size, mineral composition, shape and availability) and shore geometry (straight, indented or convex seawards).

Figure 2.2 shows the curvature of a selection of the studied beaches. It was found that most curvatures are concave seaward with two notable exceptions. The deltas of the Clarence and Waitaki Rivers are convex seawards. The Waitaki shore curve was seen to approximate a circular arc, being the reflected image of the bays adjacent to the north and south. It was not known whether this shape represented an equilibrium or subequilibrium.

The dominant direction in which the beaches are oriented is East-south-east to South-east. This suggests that the dominant swell reaching this coast comes from the East-south-east to South-east, this being confirmed by observations made off Otago, and subsequent to McLean's study, from Timaru. McLean stated that although not all of the beaches are orientated to the dominant deep water wave swell direction, the deviations can be explained by topographic effects and may reflect shallow water swell which has undergone refraction.

Only one beach, Tahakopa Bay beach, Southland, satisfied all the criteria of equilibrium. Most of the beaches are supported by headlands at each end, and many approach the circular arc shape. However McLean found there was a great deviation in the subtended angles, with only a few beaches approaching the prescribed angle of 0.25 radians, and only Tahakopa Bay beach has a circular form. He concluded that although the study beaches varied greatly in morphological and sedimentological character, they displayed common attributes in plan shape and orientation. His results also showed that many of the east coast, South Island beaches satisfy some of the criteria for equilibrium beaches, with many beaches approaching a circular arc curvature, and 40 percent facing the main deep water swell direction.
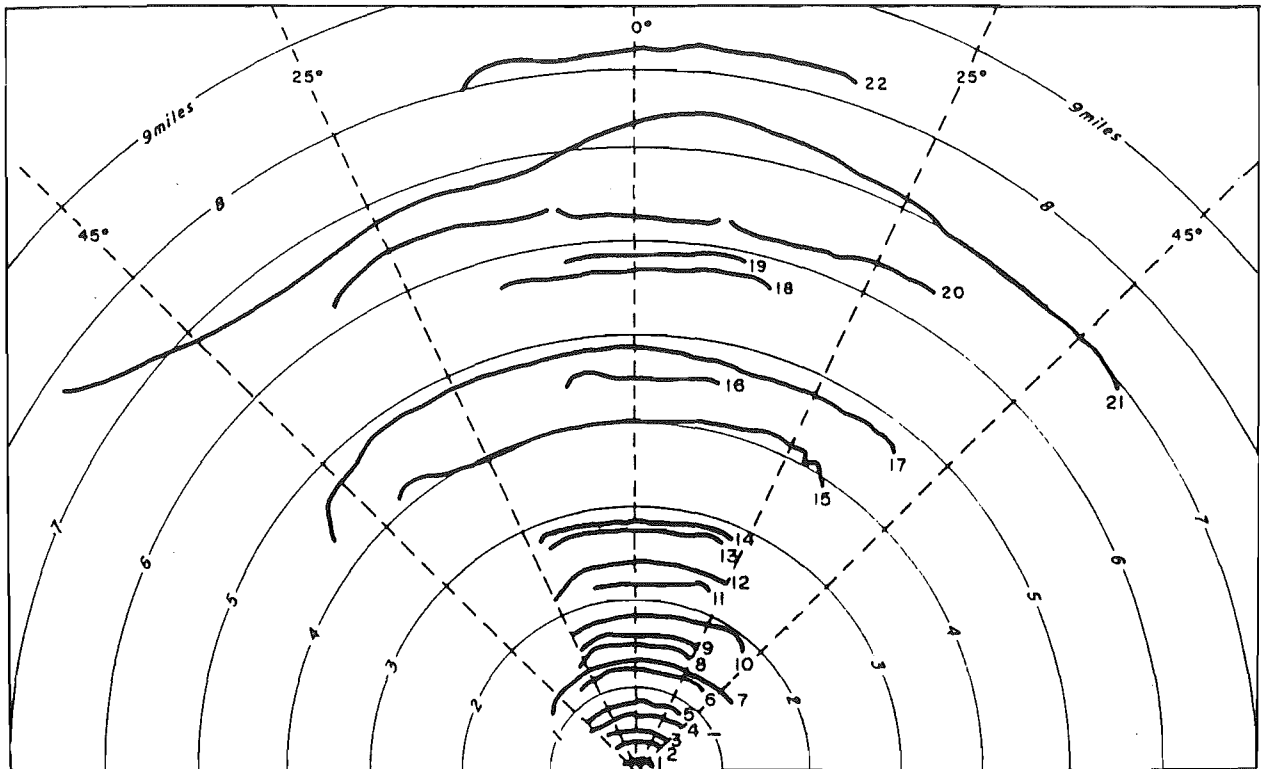
Figure 2.2 Curvature of selected beaches along the east coast, South Island.
Shoreline outline according to topographic maps on scale of 1:63,360 and
1:25,000. The arc of circular curvature is shown in brackets (from McLean
1967, Figure 1).

1- Kaitiki beach (110°); 2- Caroline Bay (90°); 3- Puketeraki beach (85°); 4- Saltwater Creek beach,
south of Timaru (90°) 5- Oaro beach (80°); 6- Spit beach, Otago (75°); 7- Waikouaiti beach (95°);
8- Long Bay beach (55°); 9- Kakanui beach (50°); 10- Victory Beach, Wickliffe Bay (65°);
11- Warrington Beach (35°); 12- Moeraki beach (50°); 13- Gore Bay beach (40°); 14- Tahakopa Bay
beach (45°); 15- Katiki beach (75°); 16- Waiau River beach (20°); 17- beach north of Kaikoura (95°);
18- beach between Cape Wanbrow and Kakanui Point (30°); 19- St Clair - St Kilda beach (20°);
20- Clutha River mouth beach (65°); 21- Cloudy Bay beach (105°); 22- beach between Kaikoura
Peninsula and Kahutara River (30°).

2.2.4 Profile shape

The typical morphology of the mixed beach in profile is presented diagrammatically in Figure 2.3. Kirk (1980) put forward the basic morphological characteristics of the mixed sand and gravel beach and described the typical profile form. This form has been discussed in Chapter One with regard to the beaches of the Wainono Lowland Coast study area.

The beach profile is generally narrow in width, steep and convex in shape, as shown in Figure 2.3. It is characterised by four morphological and process zones. The nearshore zone contains a distinct separation between the fine sand nearshore seabed, and the coarse gravel nearshore face. The lower foreshore is moderately steep (5-12°) and wave breaking occurs in this zone at all stages of the tide, and wave energy is highly turbulent. The typical mixed sand and gravel beach profile contains 150-250 m³ of sediment per metre of shoreline above the nearshore breakpoint (Kirk 1980). The upper foreshore is steep and extends from the wave breakpoint to the uppermost berm or cliff base. It is dominated by swash and backwash processes and is the zone where most changes take place. Kirk (1980) described this zone as the 'engine room' of the beach. It can contain a number of swash berms reflecting the limit of wave run-up for smaller wave environments than that which created the uppermost berm. These intermediate berms are obliterated or highly modified by larger events. The backshore zone is generally one of two types. It is landward of the limit of storm wave swash and is either the base of eroding cliffs or is of a barrier form, sloping from the top of the uppermost berm down to the lower hinterland. In the case of the latter the beach is subject to overwash or barrier breaching.

Neale (1987) represented the mixed sediment foreshore as having six subsystems or 'subzones' as shown in Table 2.1. Neale's subzones are similar to those put forward by Kirk (1980). However there are two 'extra' zones. The Swash Berm and the Storm Face are inclusive in Kirk's Upper Foreshore zone, but Neale distinguished them as having distinct process characteristics. Although Neale referred to them as zones they could also be considered as features that are situated within an area designated as a zone on the beach profile. These zones (or features within a zone) are event-dependent in their positioning horizontally on the beach, and may include remnant features of the last highest storm event. According to Neale, the subsystems are determined and linked by inputs from, or changes in the process environment. Changes in or between subsystems are initiated and linked by changes in processes. For example, successively higher waves will move the swash berm higher up (or landward on) the beach profile. Episodes of erosion or accretion will alter the geometry
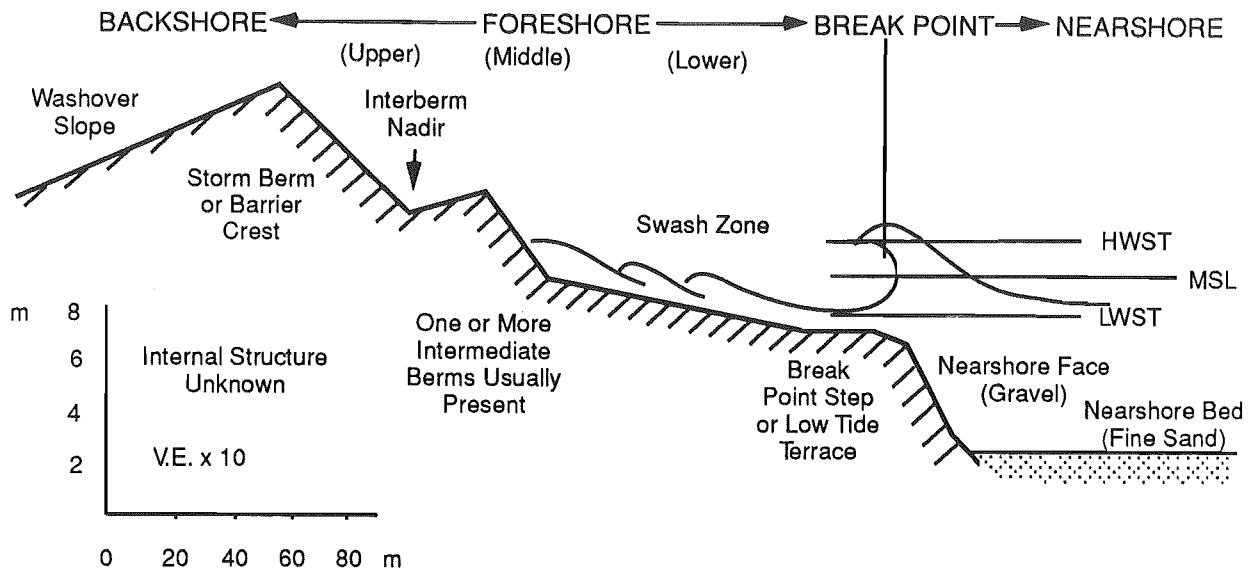
Figure 2.3 Morphology and zonation of mixed sand and gravel barrier beach profiles (after Kirk 1980, Figure 2).

Subzone	Geometry	Materials	Energy Flux
Nearshore Face (breaker zone)	steep	coarse gravels, high settling velocity, low mobility	high, very turbulent, mostly shore-normal dissipation and reflection
Foreshore Face (swash zone)	moderately steep (5-12°), concave, changeable	gravels and coarse sand, high mobility, well sorted	high, turbulent, increasingly shore-parallel, highly bi-directional
Swash Berm (upper swash)	convex, variable size, shape, and position	coarse gravels, high entrainment velocity, low settling velocity, low mobility	sharp drop in swash velocity, low potential, mostly shore-parallel, some vertical
Storm Face (storm swash)	less steep (5-7°)	coarse gravels, moderately sorted	intermittently high, moderate obliqueness, some vertical
Storm Berm, Washover Slope (upper storm swash or overwash)	near horizontal, reverse slope	coarse gravels, poorly sorted	intermittently moderate, mostly shore-normal and vertical

Table 2.1 Process-response subsystems of a mixed sand and gravel foreshore (after Neale 1987, Table 3.2).

or materials of the Nearshore and Foreshore Faces at least, and may affect the total beach profile. It follows from this that no subsystem is independent of any contiguous subsystem. However zones that differ by geometry, sediment materials or process regime can be distinguished

Episodes of erosion produce a concave foreshore with a steep scour face landward of the breakpoint, and a low flatter terrace to seaward. The beach profile is subjected to fluctuating erosion rates over a long time period depending on wave conditions. Long term reductions to berm heights occur with prolonged erosion events. This leads to increased occurrences of overtopping and coastal retreat of coastal cliffs.

2.3 Sediment Characteristics

2.3.1 Abrasion of beach gravels

Marshall (1927, 1929), recognised that many New Zealand beaches were of a different nature to those of Britain and the United States. The focus of his studies was the processes involved in the abrasion of New Zealand beach gravels. His discussion is primarily orientated towards abrasion of gravels in laboratory situations. He examined beach sediments travelling in an "iron cycline", or Deval Machine, using local gravels from beaches near Napier, on the east coast of the North Island, New Zealand. These beaches were supplied by gravels in a "mixed state with coarse and fine material together" (Marshall 1929, p333). The gravel material consisted of hard uniform greywacke showing little or no bedding and was strongly resistant to fracturing. Experiments were carried out on gravel reduction by abrasion, impact and grinding-crushing of small grains by relatively large pebbles. The gravels used ranged in size from 0.27 mm to 4.44 mm. Marshall found that practically no sand resulted from abrasion, with the end product being silt and mud. He also concluded from his tests that coarse gravel if constantly exposed to movement on the beach, will reduce in size much faster than finer gravels and sand. Impact caused by definite blows of relatively large pebbles onto smaller ones where the large pebbles were ten times larger than the small ones, produced losses up to sixteen times more rapid than abrasion on the smaller particles. The resulting sediment was found to be medium fine sand. Grinding-crushing of small grains was the most rapid reduction process, with sand formed by impact being quickly ground to silt. Marshall (1927) concluded from these experiments that if greywacke gravel is moving on a beach, then sand is quickly eliminated by abrasion, impact and grinding.

By 1929, and after further experiments he concluded that the time taken for reduction of size classes increased as the grain size decreased, as shown in Table 2.2. He went on to describe the sands and gravels of two Hawke Bay beaches. His field examinations confirmed the experimental results concerning gravel abrasion and the elimination of greywacke sands due to grinding.

Grade	Time required to the next grade	Time required to reduce grades by 50 per cent	
(mm to mm)	(days)	(mm to mm)	days
44.4 - 31.7	14	44.4 - 22.2	42
31.7 - 22.2	28		
22.2 - 15.8	43	22.2 - 11.1	106
15.8 - 9.5	89	11.1 - 5.5	157
9.5 - 4.7	186	5.5 - 2.7	354
4.7 - 2.7	300		
2.7 - 1.0	632	2.7 - 1.35	441
1.0 - 0.71	865	1.35 - 0.67	1200
0.71 - 0.50	1102	0.67 - 0.33	2827
0.50 - 0.36	1750		
0.36 - 0.27	3000		
	Total 8009		

Table 2.2   Relative rates of gravel reduction (from Marshall 1929, Table 4).

Marshall also presented ideas on the nature of beach slope in relation to sediment size, noting that beaches composed of gravel are much steeper than those formed by sand. His observations showed that the grade of the beach material was the most important factor in determining the beach slope, which is then modified by the intensity of wave action. Listed below from Marshall, are some considerations he presented for comparing the flattening effect of rough seas on the beach, and the effect of the size of material on the beach slope.

1. A smaller proportion of the water of each wave sinks into the beach and the volume of the downwash is greater and its velocity also will be greater because friction retards the greater mass to less extent.

2. The transporting power of the backwash is greater because of the higher velocity and volume.

3. The velocity of the backwash is greater because the water has a greater distance to flow back down the beach.

4. The grade of the gravel relative to the movement is less and it can therefore be more freely moved.

The effect of the size of the mineral particles on the grade of the beach is suggested by Marshall to be as follows:-

1. The finer the material the less percolation into the beach and therefore the larger the volume and transporting effect of the backwash.

2. The backwash will move the beach material more easily and in greater quantity if it is finer.

3. The undertow below the level of wave action on the beach can transport very fine material some distance from the actual beach.

4. The angle of repose for fine material in water is lower than that of coarser grains. Actual tests showed that in still water the angle of repose of pebbles 3.4-2.0 mm is 30 degrees, of sand 0.25-0.15 mm it is 25 degrees, and a slight movement of the water makes the difference far greater. (Marshall 1929, p364)

The first list covers some basic ideas that are not clearly comprehensible. However these ideas hold for high energy conditions on mixed sediment beaches. Examining Marshall's considerations shows that he compared swash and backwash processes on the beach during storm conditions ("rough seas") with the same processes during low energy conditions. Marshall's basic premise in this case seems to be that the volume of water arriving on the beach in rapid succession during storms - such as from short period waves or large waves breaking offshore beyond the nearshore step and spilling onto the beach - is such that it exceeds the capacity for percolation into the beach, therefore there is more water on the surface of the beach when the energy for swash is less than the force of gravity, resulting in a large volume and greater depth of backwash that is not affected by friction with the beach surface. Point two follows directly from this premise. Point three is made assuming that the high energy swash flow travels further towards the crest than during lower energy events. Point four would perhaps be better stated that bigger material can be moved because of greater velocity. It should be noted here that these points would not necessarily hold if the crest of the beach was overtopped by wave run-up and that the percolation capacity of the beach and the arrival of water at the beach are important variables in determining the backwash. Both lists contain many of the basic concepts from which contemporary studies of mixed sand and gravel beaches have expanded.

2.3.2 Canterbury Bight sediments

Kirk (1967) carried out an examination of sediment samples to determine size and shape characteristics of the sediments of the Canterbury Bight beaches. The dominant sediment rock type was found to be greywacke. Mixtures of sand and gravel were found throughout, and Kirk considered the Bight to be one unit. Sizes ranged from medium sand (1.86ø, 0.3 mm) up to large pebbles and cobbles (-5.18ø, >32.0 mm). There was also a wide variation in sorting, skewness and kurtosis. Analysis of variance on mean sizes from different profiles showed that no single section of the beach had a variation in mean grain size greater than that along the total length of the Canterbury Bight. The variation across the shore was greater than along it. Kirk concluded from his analysis that sorting takes place in lanes that roughly parallel the shoreline. The backshore had more variable size and poorer sorting reflecting wave overtopping processes, while the foreshore was better sorted. Changes in grain size distribution alongshore over time were taken to indicate variations in wave activity.

Figure 2.4 (from Kirk) shows the relationship between grain size and sorting. The pattern displayed suggests two populations of sizes, a sand and a pebble population. The wide scatter of the mean sizes indicates the degree of mixing between the two "end member populations". Superimposed on the diagram is a third order polynomial curve fitted to the data. The significance of the shape of this curve will be shown later in the discussion of McLean (1970) and McLean and Kirk (1969).

Figure 2.5 shows the relationship between mean grain size and foreshore slope. Kirk found that sand and granule size classes produced slopes close to those proposed by Shepard (1963) as being the average relationship. However, pebble sizes produced a wider variety of slopes, consistently below Shepard's average or the optimum gradient. It was suggested that this indicates the beach is not in a stable equilibrium to the wave environment, but was responding to erosive conditions.

Kirk also found there was little trend in size and sorting distributions alongshore. The narrow surf zone and plunging surf were thought to cause shore normal movement of material with little of the classical zig zag motion of swash and backwash. Storm and swell conditions caused mixing and winnowing of grains. Storm derived lenses of sand and granules were seen to be worked by wind and waves to produce a diminishment of sand and resorting of the beach face into bands of sand and pebbles and mixtures of the two. Mixing was also thought to obscure movements of individual size classes.

It was also suggested that pebble shape was a very important control on the type of deposition. Samples were dominated by bladed shapes, with discs and rods making
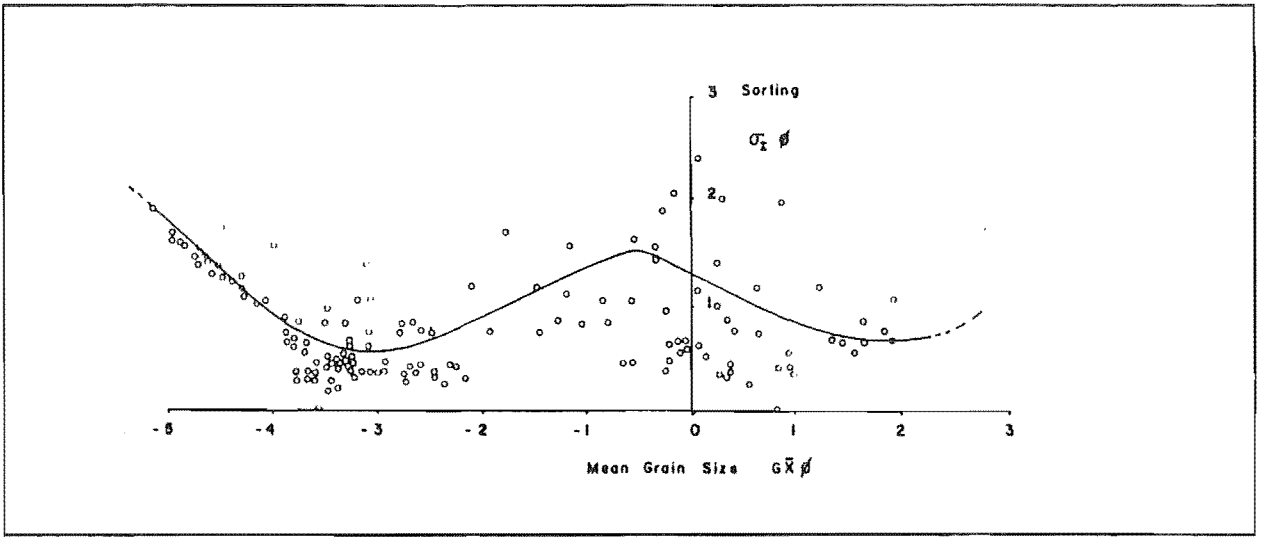
Figure 2.4 The relationship between mean grain size and sorting (from Kirk 1967, Figure 12).
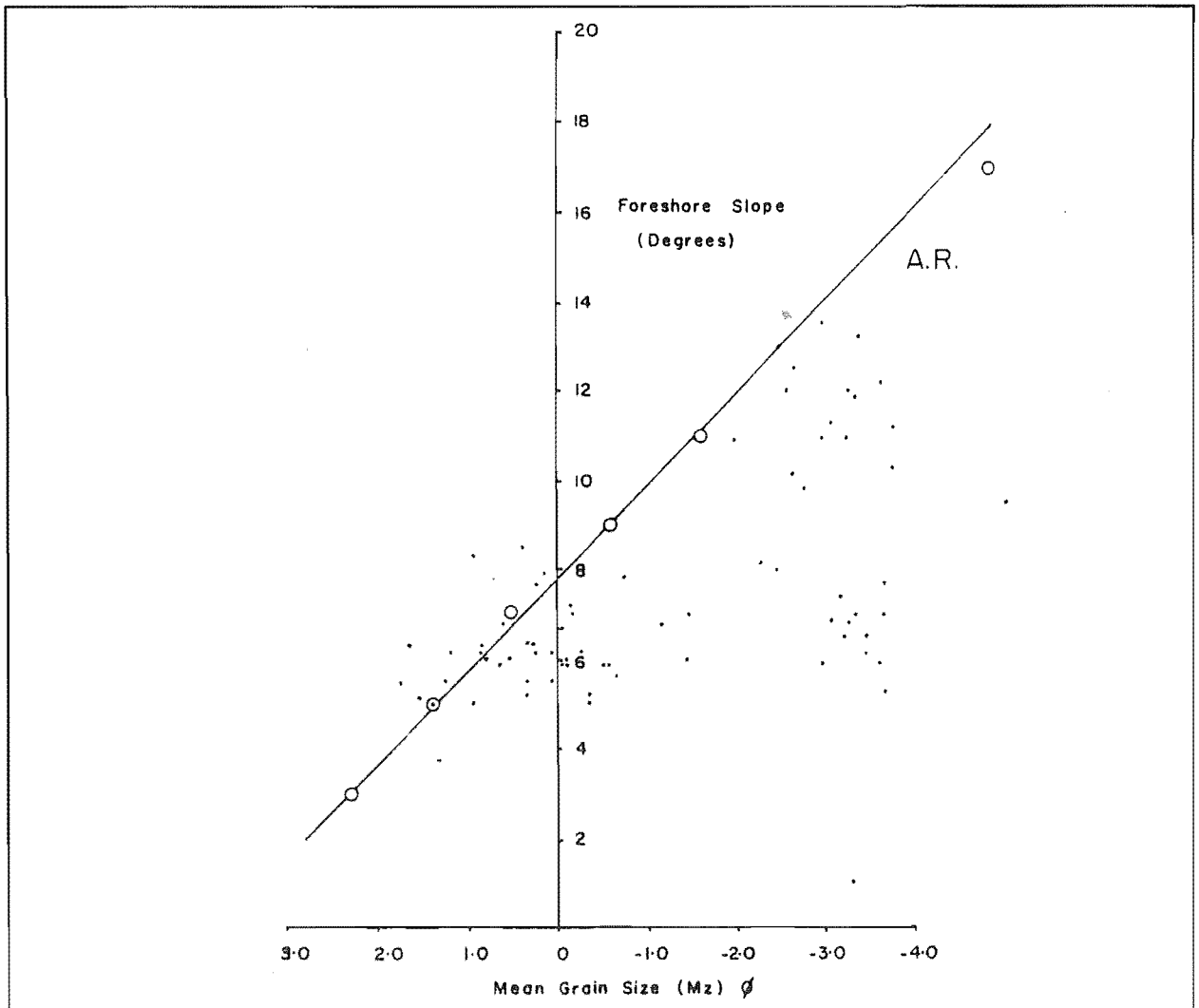
Figure 2.5 The relationship between mean grain size and foreshore slope (from Kirk 1967, Figure 16).

A.R. = The average relationship of Shepard (1963, page 171). Dots indicate samples taken from Kirk's 1967 investigation. r for samples = 0.487

up smaller sub-equal amounts of samples. This shows a preference for disaggregation of greywacke along the c-axis rather than selection for shape during transport. Sediment sorting is also well developed before the particles reach the coast indicating that there is not a wide range of abundant shapes upon which the waves can exert selective influences. However some shape distribution can be seen across the profile. Large flat particles are carried up on swash because of the lower settling velocity, and are stranded at swash limits and in areas on the backshore subject to overtopping. Rounded particles roll easily so are more susceptible to erosion.

Kirk proposed that a high concentration of sediment supply comes from the rivers, and examination of river and beach sediments showed there was little difference between the two. However, he found that the largest sediment supply to the beach was from the eroding cliffs. The cliff base is not "wave cut". Marine processes remove material that has accumulated at the toe of the slope due to subaerial processes, injecting it into the active beach environment and keeping the cliff face 'oversteep'. Kirk found that cliff erosion averaged about one metre of horizontal retreat per year. Wind velocities sufficient to transport medium and coarse sand on the beach reworks lenses of sand deposited by swash during storm conditions into sporadic stringers and bands along the backshore.

Kirk stated that transportation and sorting processes are close controls of beach morphology. Beach deposits reflect the combination of suspended and bedload transport of fines, and bedload transport of the coarse materials. A significant and observable result of the mixture of transport processes is the deposition of sand lenses at the same time as pebbles are being eroded during storms. Sand is trapped in the interstices between pebbles and by the percolation of swash and backwash as shown in Figure 2.6. Large pebbles and cobbles form lag deposits since they move onshore to higher berms by large swash associated with storms, and are stranded by the lowering of the wave environment.

2.3.3 Grain size and sorting on mixed sand and gravel beaches

Folk (1965) put forward an hypothesis that Nature produces different particle sizes in differing quantities. Sand and pebbles are 'end member' populations and are produced abundantly. He produced a mean size/sorting relationship curve as shown in Figure 2.7 by examining a wide range of mean sizes of samples. The curvilinear pattern shows good sorting in the end members and poor sorting for the populations in between which Folk considered to be mixtures of end member sizes. Shepard (1963) and Inman (1949) investigated the idea of hydraulic selection of sediments in the beach
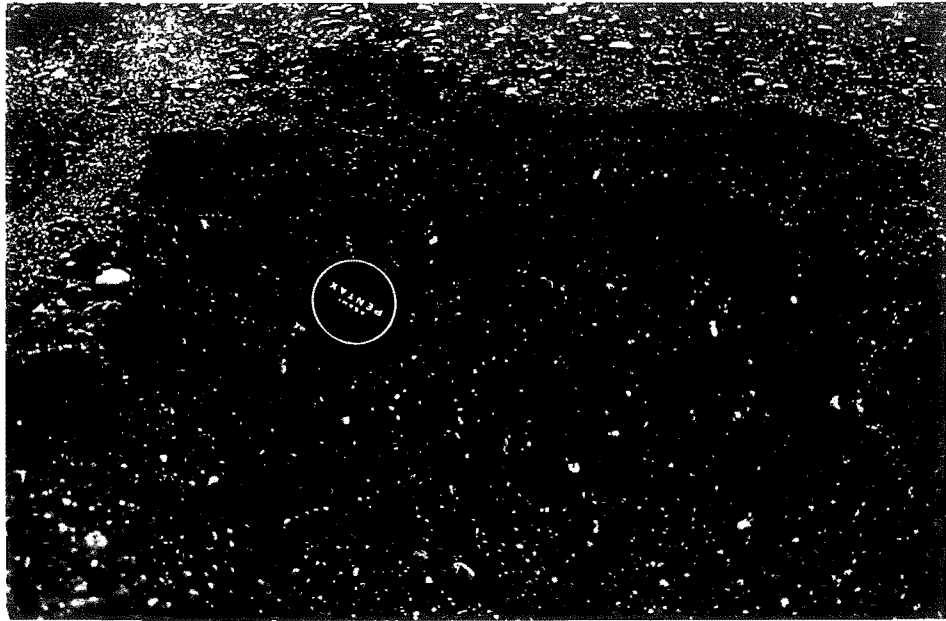
Figure 2.6 Storm swash deposited layer of sand over pebbles. Much sand has been trapped in the interstices between the pebbles and the more mobile small pebbles have remained on the surface. The lense-cap is 50 mm in diameter (from Kirk 1967, Plate 13).
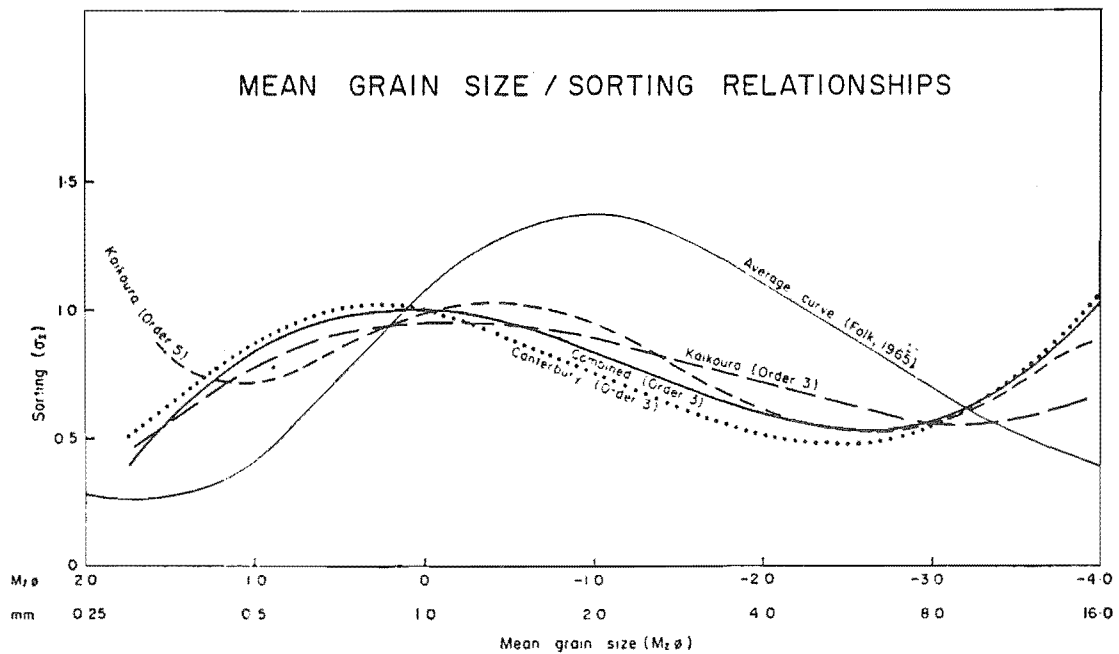
Figure 2.7 Order 3 polynomial curves relating grain size and sorting for Kaikoura, Canterbury Bight, and combined data. The Order 5 curve for Kaikoura and the average curve from Folk (1965, page 6) are also included (from McLean and Kirk 1969, Figure 5).

environment, and put forward a linear relationship between mean grain size and foreshore slope.

McLean and Kirk (1969) hypothesised that if Folk was correct then where a large range of sediment sizes is present with a characteristic curvilinear relationship between average grain size and size-sorting, it is reasonable to expect an equally characteristic relationship between grain size and foreshore slope. McLean and Kirk tested for the applicability or existence of this curvilinear relationship on New Zealand mixed sediment beaches. McLean and Kirk (1969) and McLean (1970) examined variations in grain size and sorting, and the relationship of size and sorting to beach foreshore slope on mixed sand and gravel beaches. The McLean and Kirk study describes and compares sediment characteristics on beaches from Kaikoura and the Canterbury Bight which are different in detail, but which they considered to be similar in general terms. Sampling methods followed those from Kirk (1967). For their sample beaches, McLean and Kirk found that Folk's premise of 'in between' populations being made up of mixtures of sand and pebbles (end member populations) was not entirely correct. For the sediment samples examined by McLean and Kirk, both unimodal and bimodal size frequency distributions were found. Unimodal sediments occurred over the whole range of particle sizes, while the bimodal samples contained two strong modal classes separated by a break between -2.5ø (6 mm) to 0.5ø (0.75 mm), the granule and very coarse sand ranges. Poorest sorting was found to occur in the size grades between medium-coarse sand and small-medium pebbles, and was interpreted as a result of the mixing of the sand and pebble fractions. However within the poorly sorted grades there was a cluster of very well sorted samples in the granule range distinguishing two groups, one a mixture of sand and pebbles, the other consisting of well sorted granules. The two types of sediment are distinguished by sorting rather than by mean size.

The concept of a linear increase in beach slope angles associated with increasing particle size implies that gravel beaches are steeper than sand beaches. This was tested by examining relationships between size and slope, and size and sorting. McLean and Kirk found that size, through permeability, exerts a primary control on slope. However, the degree of exposure to wave energy and whether the beach is eroding, accreting or stable is also important. Exposed beaches have less steep slopes than sheltered beaches, and erosion results in combing down the beach face while accretionary episodes result in steeper slopes. Therefore, fluctuations in hydraulic conditions represented in the variability in size/sorting values will in turn be reflected in size/foreshore slope variability.

Figure 2.8 shows frequency distributions of size, sorting and slope for the two study areas separately and combined, as presented by McLean and Kirk. From Figure 2.8a the differences in the ranges of grain sizes between the two beaches can be seen. Canterbury Bight samples are generally coarser than those from Kaikoura, although only mean grain sizes less than -4.0ø (16 mm) were considered. Median sorting values for each case lie in Folk's moderately well sorted category (Figure 2.8b). This does not reflect the marked differences in mean grain sizes. For both beaches there are two modal peaks in size and sorting. The well sorted mode (0.5ø units) relates to the medium sand and pebble fractions and the poorly sorted mode (1.5ø units) is grouped with the coarse sand and granule size grades. The authors concluded that although the two study areas exhibit significant differences in size distributions, they have a general correspondence in sorting values. This was considered to reflect the similarity in mineralogies and the high energy nature of the shores

The similarity in beach sediment properties is also reflected in the frequency distributions of foreshore slope, as shown in Figure 2.8c. The median slope for the Canterbury Bight foreshores was found to be 6°, and for Kaikoura the median slope was 5°. McLean and Kirk note the bimodal nature of the slope distributions. A secondary peak occurs for both regions between 10° and 12°. They concluded from this that there was a general correspondence between variations in sediment properties and foreshore geometry as gauged by slope.

Further analysis was carried out on the relationships between size and sorting and size and slope. Sorting values were found to vary widely. It was also noted that data fell into two distinct groupings. A strong size/sorting mode occurred in the region -2.5ø to -4.0ø, but for grain sizes smaller than this, sorting was more variable. This was said to be consistent with the high energy nature of the beaches, reflecting the effect on smaller particles. Curve-fitting on the data produced curves similar in form to those postulated by Folk (1965). The data from Kaikoura indicated a more complex situation, and the data from Canterbury Bight showed a pronounced coarse tail. McLean and Kirk tested their data objectively and statistically to see whether Folk's proposed curve was evident. They did this by fitting up to 6th order polynomial curves to their data, selecting that curve which best explained most of the data variation at stated F-levels. Their results are displayed in Table 2.3 and Figure 2.7. Figure 2.7 shows that the curves although similar have marked differences to Folk's curve. The curves from McLean and Kirk's study have two regions of best sorting, and the amplitude of the mixed zone between the sand and pebble modes is low. It should be noted that the wide range of sorting from very well to very poorly sorted is most significant.
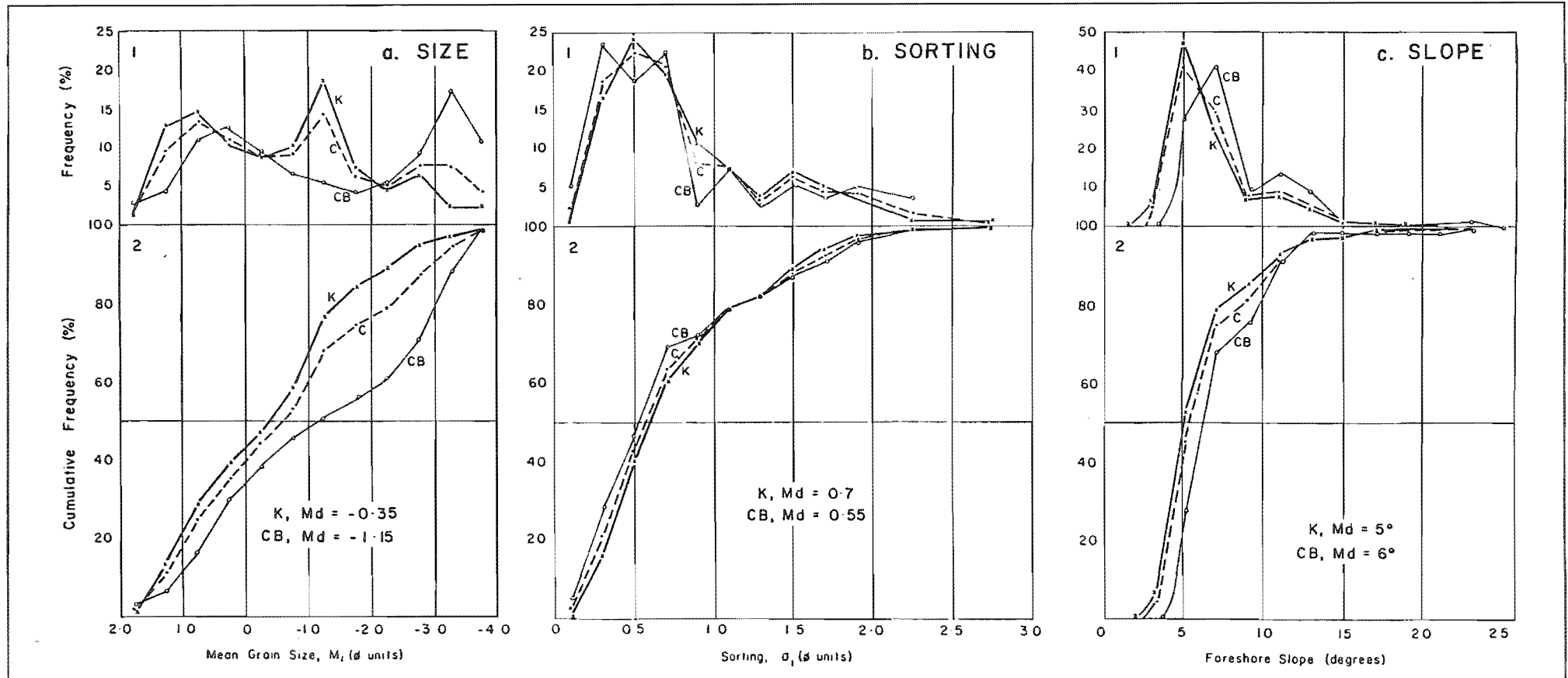
Figure 2.8 Grain size, sorting, and foreshore slope frequency distributions for Kaikoura (K) and Canterbury Bight (CB) beaches and combined data (C). 1- Frequency (%) polygons. 2- Cumulative frequency (%) a- Mean grain size frequency per 0.5 ø units. b- Sorting frequency per 0.2 ø units. c- Foreshore slope frequency per 2 ° (from McLean and Kirk 1969, Figure 3).

Data Set	Order of Polynomial	R (%explanation)	F-level	Remarks *
Kaikoura	1	0.01	0.98	NS
	2	0.70	2.38	NS
	3	2.30	5.57	S
	4	5.80	0.12	NS
	5	5.80	4.95	S
	6	8.90	1.07	NS
Canterbury Bight	1	0.01	1.75	NS
	2	1.30	6.97	NS
	3	6.00	10.83	S
	4	12.70	0.82	NS
	5	13.20	4.44	NS
	6	15.90	3.15	NS
Combined	1	0.01	1.63	NS
	2	0.06	6.32	NS
	3	2.70	25.32	S
	4	10.40	3.17	NS
	5	11.30	6.04	NS
	6	13.20	3.51	NS

* NS - Not Significant
  S - Significant at 95% confidence level
Note: The Order 3 curve demonstrates the strongest trend

Table 2.3   Results of curve fitting: Grain Size/Sorting (from McLean and Kirk 1969, Table 1).

Curve-fitting on a plot of foreshore slope against mean grain size is shown in Figure 2.9. A general tendency towards increasing slope angles with increasing mean grain size is apparent although the relationship is complex. The best-fit curves are considerably different to the linear curve fitted to Shepard's (1963) data of an average relationship. The authors attributed this difference to the nature of the sediment. Shepard's data is a result of using "pure" types of beach sediment, whereas the beach materials of the Canterbury Bight and Kaikoura are of a mixed nature. The low gradients found on the study beaches were thought to reflect both the greater variability in size-sorting of the mixed sediments, and the exposed nature of the beaches. McLean and Kirk made the point that "...each beach will have its own characteristic foreshore slopes, which result from the interplay of controls (source area characteristics and hydraulic factors), materials (size, sorting, skewness, shape, kurtosis and roundness) and processes" (McLean and Kirk 1969, p151).

In examining size/slope in relation to sorting it was found that where sorting improves over a range of grain sizes, such as between -1.0ø and -2.5ø (Figure 2.7), there is a steepening of the size/slope curve. This indicates that mixed sand and gravel beaches consist of two sediment populations, and therefore two kinds of slopes. This is
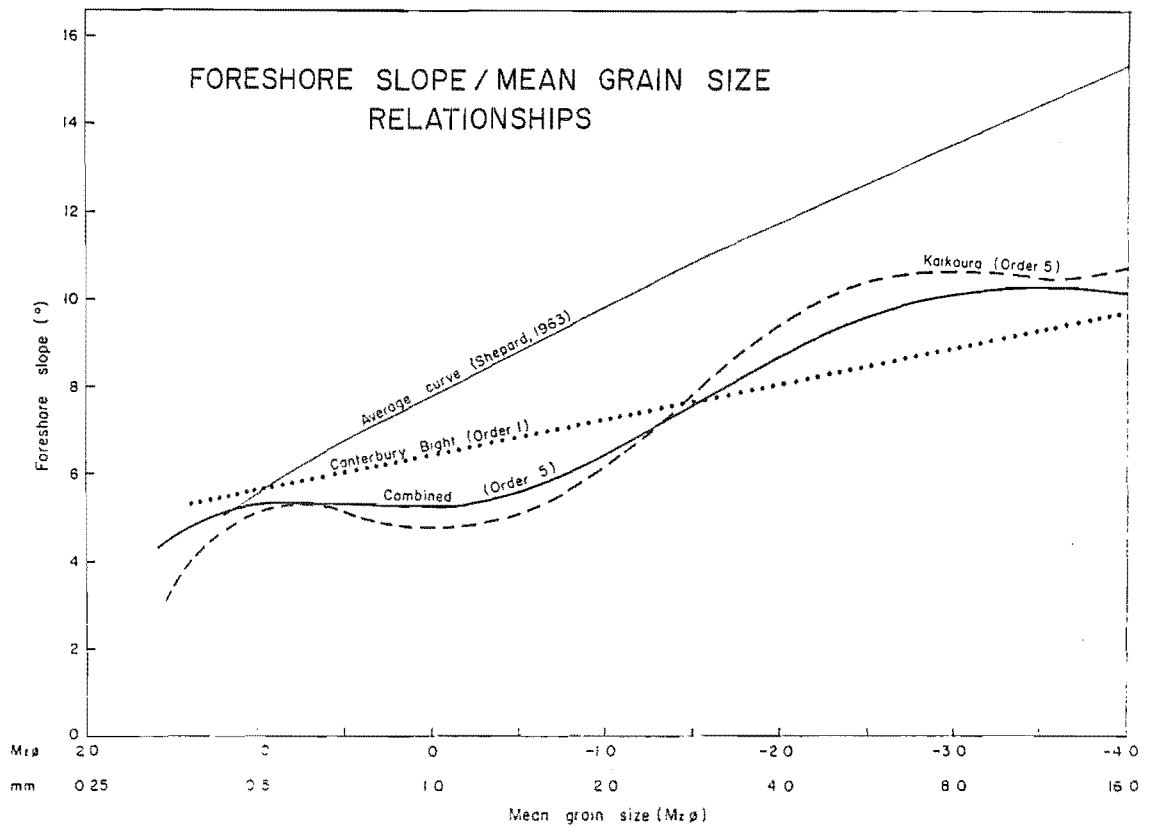
Figure 2.9 Order 5 polynomial curves relating grain size and foreshore slope for Kaikoura and combined data. The Order 1 curve for the Canterbury Bight and the average curve from Shepard (1963, Table 9) are also included (from McLean and Kirk 1969, Figure 7).

an important factor in determining the beach morphology. From Figure 2.7 it can also be seen that although there are two regions where slope is responsive to size, there are also two areas that are not responsive (the flatter sections of the curve). Depending on the grain-size mix, morphology may reflect or not reflect the sediment characteristics in a particular site, leading to distinct variations in morphology from site to site if there is a variation in the grain-size mix. This is not only applicable from site to site, as found by McLean (1970) at Kaikoura, but also morphology may vary over time if the grain size composition changes. Source area effects were considered to be the primary control of sorting on the beach, while hydraulic effects contribute to the variation in spread of the data.

Variations in sorting and grain size were found across the beach profile, and were stated to be a response to the zonation of hydrodynamic processes, and the characteristics of the available material. With large size ranges available on the profile, distinctive shore parallel textural zones could be found. However where available sediments are of a uniform size, grading would not occur and across beach variations in size and sorting would be minimal. McLean (1970) did not find well developed zonal arrangements across the beach. There were examples of both large and small mean sizes and good and poor sorting at all levels, from the lower foreshore to the upper backshore. He gave two reasons for this situation. Firstly, shore-normal variations are closely allied with gross longshore changes, and secondly, continual mixing occurs on the beach due to the highly turbulent swash and backwash processes.

Kirk (1980) reiterated that mixed sand and gravel sediments were notable for highly variable size and sorting patterns of sediments across the foreshore. Coarse pebbles are found on berm crests while the seaward facing slopes contain a mixture of sand and gravel. Kirk noted a close but complex relationship between grain size characteristics and foreshore morphology, including the existence of two marked populations of slope angles. He also noted the complexities in longshore patterns of size and sorting, and the difficulties in identifying longshore transport from sediments. However he stated that,

> "...grain size and sorting variations and their influences on shore
> morphology can usually be deciphered by careful consideration of
> source-area effects which act as primary controls on the gross patterns
> present, and by examination of variations in hydraulic factors which
> have a secondary effect in the spatial and temporal variability of textural
> properties."

(Kirk 1980, p207)

Kirk concluded that the most complex aspect of mixed beaches related to their sediment characteristics and the way in which they are worked on in the swash zone.

2.3.4 Washdyke-Seadown coastal erosion and internal beach structure

Benn (1987) examined severe coastal erosion phenomena at Washdyke, north of Timaru. This section of coast is comprised of 12.5 km of mixed sand and gravel barrier beach backed by low-lying farmland and a large lagoon separating the beach from a major industrial district. Erosion and seawater flooding in the area are a hazard to valuable assets, and as such have been the concern of the South Canterbury Catchment Board and the Timaru City Council for many years.

Benn's aims were to describe the historical erosion characteristics of the field area, and quantify and describe the sediments in the beach system and those comprising the hinterland. This was deemed important as it is considered that erosion in this area is the result of a deficit in the sediment budget from alongshore and sediment for maintaining the beach must come from the hinterland. It is therefore useful for future coastal management to understand the characteristics of this source of sediment. Washdyke lagoon is also an important geomorphological feature for the area. It provides a transition zone between intense wave energy on the beach and the low-lying hinterland, and as a coastal wetland is an important wildlife sanctuary.

With the assistance of the South Canterbury Catchment Board, Benn made a comprehensive sediment survey from the foreshore and backshore. He was also able to examine the internal structure of the beach using a large excavator. The sediments were mainly pebbly moderately-poorly to poorly sorted greywackes. Three types of sample were evident. These were mixed sand and gravel, pure sand and pure gravel. The graphic mean size ranged from $-6.2\emptyset$ to $0.7\emptyset$ (cobbles to coarse sand), with an overall mean of $-2.33\emptyset$ (pebble class). Bladed, very bladed and elongated sediment shapes were found to dominate. Benn found that no longshore trends for sedimentary parameters could be determined. This was a similar finding to Kirk (1967) and Hewson (1977).

He found four types of internal structure as shown in Figure 2.10. Where a thin sediment layer covered the underlying impermeable substratum, it was comprised of either gravel or sand. This was considered to be the result of finer particles being winnowed from the beach and deposited down drift due to the swash zone being mostly saturated, leaving the gravels as a lag deposit. Thicker deposits of beach sediments in the barrier beach, of up to 7 metres in depth, were characterised by either narrow
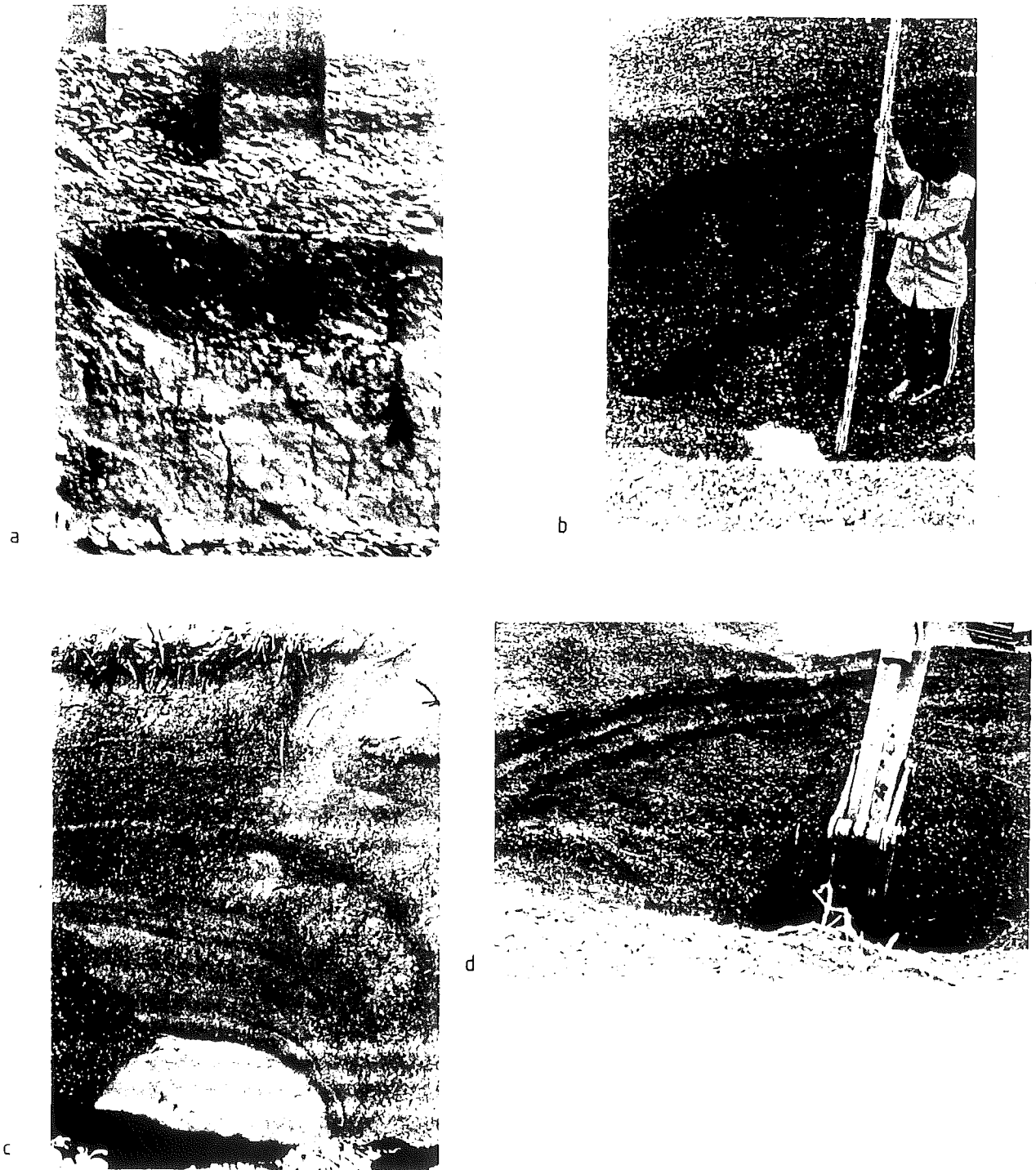
Figure 2.10 Internal structure of the beach. a) Thin cover of gravel, Seaforth Road
(source, D. Todd Canterbury Regional Council). b) Gravel concentrated on
the surface, and sand below, Opihi backshore. c) Beds of sand and
gravel, Washdyke upper foreshore. d) Beds of sand and gravel, Opihi
foreshore (from Benn 1987, Plate 2.3).

vertical laminations of gravel and sand or by wider gravel concentrations on the surface and sand below. Laminations were possibly caused by elutriation, where fine material is sieved through the pore spaces of larger particles, while thicker layers were possibly the result of changes in the process environment.

Using seismic profiling and excavation, Benn found that the sediments of the Washdyke Lagoon barrier beach were thicker than those of the beaches underlain by loess or basalt deposits. The thicknesses ranged from 7 metres for the barrier sediments in comparison to a thin veneer of beach material with the underlying loess exposed at the surface. The hinterland sediments were found to be fluvial in origin and varied from oxidised structually weak gravels, sands and clays to areas of soils with gravels, sands and clays underneath, over which the beach has migrated landward. Benn considered that the gravels of the hinterland, although of a comparable size to contemporary beach sediments, were likely to abrade rapidly because of their weathered character, and were therefore not a good long term source of beach material.

2.4 Wave Environment and Nearshore Processes

2.4.1 General process dynamics

The process regime of mixed sand and gravel beach environments can be considered to be distinctive, resulting from the combination of a number of factors (Kirk 1980). The pattern of wave breaking is concentrated onto a small area of the beach profile, and combined with a high energy wave environment and steep foreshore, high levels of flow energies per unit area of beach can result. The steep beach is also strongly reflective. Most of the active beach deposit lies above the low tide water level, with the energy component for movement of beach material coming from swash and backwash of broken waves.

Winds cause modification of the wave environment. The three major wind and swell directions found by Kirk (1967) were the same as those found by McLean (1967). South-easterlies were most frequent, while southerlies were the most dominant in as much as they were mainly storm waves, and east-north-easterlies predominated during the summer months. The waves arriving at the shore were mainly modified swell containing elements of two or more distinct sources. Local winds, often onshore, superimposed short period choppy waves onto the more regular swell wave-forms. The largest wave measured during Kirk's study period was approximately four metres high with a period of twenty seconds, while the average wave height measured was three

metres, with a period of fifteen seconds (Kirk 1967). Kirk noted turbidity offshore during most wave conditions, and considered that storm waves are influenced by the seabed at a depth of 22 metres which is approximately 10 kilometres offshore. He also noted that strong disturbance of the bed would only occur during vigorous storm conditions, and that at these times there would be potential for movement of pebbles in the nearshore.

Swash patterns explain much of the morphology of the mixed sand and gravel beach profile. The swash zone is the area of maximum bedload transport. Wave swash moves pebble and cobble sized materials landward of the surf zone causing a build-up or berm, at its limit. Also at the swash limit, the water both percolates into the beach gravels and starts to travel seaward as backwash. Thus backwash volumes and velocities are generally less than the swash. Kirk (1967) stated that under storm conditions the backwash is relatively more powerful than the swash due to permeability limitations of the beach gravels, and the large volume of water being delivered up the beach face. This is a similar conclusion to that found by Marshall (1929). This causes erosion of the profile as the backwash velocity is strong enough to transport material seaward or downslope. Kirk found a bimodal distribution of swash length. Short swash occurred most frequently, while larger swash was associated with storm waves. Therefore the central part of the beach profile was seldom affected by swash processes. He also noted that swash/backwash period is longer than wave periods, and that this also has an impact on the permeability of the beach face and hence erosion and deposition (Kirk 1967).

Kirk (1980) noted the difficulty in applying the notion of critical wave steepness to the New Zealand mixed beaches, and that variability of the wave system is very important. Storm waves arriving at the east coast of the South Island are not the classical short steep rough seas of the scientific literature. Being generated at a great distance from the coast they often have the appearance of large swells. Smaller prevailing wave systems responsible for berm building are variable in character. Kirk also discussed Kemp's ideas of swash phasing (Kemp 1960, 1963). The way in which swash and backwash interact with breakers during a wave sequence is important to the beach morphology.

2.4.2 Sediment transport in the nearshore marine environment

Hastie (1983) investigated nearshore bedload sediment transport offshore from Timaru. His main objectives were to obtain measurements of rates and directions of nearshore sediment transport at Timaru using artificial tracers; to define relationships

between wave parameters and transport rates so as to determine long term rates from wave records, and to investigate the practical application of artificial tracing techniques in studying the nearshore seabed. His study had an applied aspect for the Timaru Harbour Board in providing knowledge of sediment transport patterns for efficient disposal of channel and harbour dredgings.

The study was also descriptive of the two separate littoral transport systems at work in the mixed sand and gravel system. Coarser sediment is confined to the nearshore face and landward to the limit of wave and swash action, and finer sediment is confined to the seafloor. Hastie noted the significance of the construction of Timaru Harbour in altering the littoral transport systems of the beach and nearshore. While gravel accumulated on the south side, or down drift of the harbour, sand began accumulating within Caroline Bay in the lee of the harbour. The deficit in the gravel supply to the north of the harbour became apparent at Waimataitai and later at Washdyke. Gravel extraction from South Beach also modified the northward littoral drift of beach material. Very fine material was still transported predominantly northwards with an estimated 17% being trapped within the dredged harbour entrance channel.

Hastie also described in detail the nearshore bathymetry off Timaru and presented results of his studies of wave conditions (see Chapter One, Section 1.2, also Hastie 1985). In summary he found that the nearshore was mantled with a uniform layer of very fine sand with occasional patches of gravel. The area was characterised by intense sediment transport out to the 7 metre isobath and significant transport beyond to at least the 11 metre isobath. Calculated wave induced currents at the 7 metre isobath exceeded calculated thresholds for sediment entrainment for greater than 80% of the time for sand to coarse sand sizes, 56% of the time for very coarse sand, 28% of the time for granules and 6% of the time for pebbles. Depth of disturbance in this area was at least 0.11 metres.

From offshore tracer studies Hastie found that there was a net landward movement of all grain sizes with an increasing tendency for landward movement with increasing grain size. He also examined the transport of sediment from offshore as a possible source of beach material. Hastie observed the nearshore face of a mixed sand and gravel beach while diving, and noted that pebbles on the nearshore face were more spherical than those seen on the foreshore. The observation was confirmed by analysis of comparative samples from the nearshore face and the beach foreshore. The results are presented here in Table 2.4. He then used a 528 kg fluorescent dyed sample of sediment ranging in size from coarse sand to pebbles. This was released offshore from

Median Diameter (mm)	Shape								Krumbein Sphericity	
	Spheres		Discs		Rods		Blades			
	Fs	Nf	Fs	Nf	Fs	Nf	Fs	Nf	Fs	Nf
>9.5	1	11	36	26	0	8	13	5	0.64	0.71
8.0 - 9.5	4	16	28	19	4	9	14	6	0.63	0.71
6.7 - 8.0	4	23	28	18	7	6	11	3	0.64	0.74
5.6 - 6.7	10	29	25	13	7	7	8	1	0.68	0.75
Average Value Total Number	19	79	117	76	18	30	46	15	0.65	0.73
Percentage of Sample	9.5	39.5	58.5	38.0	9.0	15.0	23.0	7.5		

Table 2.4   Pebble shape on the foreshore and nearshore face at South Beach, Timaru (from Hastie 1983, Table 6.2). Fs = Foreshore, Nf = Nearshore face

Washdyke in 20 kg lots. Fifteen surface searches for pebbles were made over a period of two months along the foreshore opposite the dump site.

Only three tracer pebbles were found on the foreshore of the beach, two discs and a blade. However, this did show that it was possible for sediment to move from the shelf to the mixed sand and gravel beach. From wave data Hastie also concluded that there was a possibility of an offshore supply of sediment to the beach. Waves with an average significant height slightly greater than 1.0 metre and an average significant wave period ranging from 9 to 11 seconds are capable of moving pebbles up to 28 mm in diameter from the seafloor to the foreshore. These wave conditions were only slightly above the average from the full wave data set. Therefore onshore movement could be expected to occur for much of the year.

2.4.3 Swash zone processes

Kirk (1970) investigated the processes responsible for morphological and sedimentological changes that occur on the mixed sand and gravel sub-aerial beach face. His primary aims were to describe the nature of water movements in the swash zone, and to assess the relationships between swash and backwash flows and sediment transport. The study concentrated on a time mean basis of process and response as changes occur rapidly, but over various time scales. Measurement of flow speed and duration, pressures, depths and asymmetries was required, and an instrument system was designed and constructed to obtain these measurements in the swash zone. Kirk also measured responses to the flow regime by examining

adjustments to the grain size parameters of bed sediments, transport rates and vertical distributions of solids in the swash and backwash flows, and changes in bed elevation .

The study concentrated on four profiles on the mixed sand and gravel beaches near Kaikoura. Two were steep and composed of well sorted gravels, while two were flatter and comprised of more mixed sediments. All profiles were subject to highly turbulent swash and backwash, and over 3000 measurements of individual swash or backwash episodes were made under varying wave, tide and foreshore conditions.

Kirk (1975) described a typical form of a mixed sediment beach profile. It has a gentle nearshore gradient of 0.5° to 1.0°, being made up of fine sands and silts at depths of 6 to 10 metres. The beach face of gravels and cobbles rises abruptly for 5 to 8 metres from the nearshore bed. The surf zone is located at the upper limits of this slope and Kirk noted that significant reflection of energy occurs during storms (1975, p121). The foreshore has a wide planar or concave upward swash zone, with slopes from 5° to 12°. At the landward limit of swash, small berms are formed, although storm swash was observed at times to cover the whole beach. Storm berms of the study beaches were from 5 to 10 metres above mean sea level and were found to be up to 200 metres wide. The nature of the beach profile exerts a marked influence on the breaking of waves. On these steep beaches, most of the energy arriving at the shore is expended in breaking and swash processes. Breakers are of the plunging type, where the crest of the wave steepens, hollows until the face overhangs the trough, then collapses onto the beach. This creates considerable vertical accelerations of water and energy, both upward and downward. After breaking, a strong swash is initiated, with high energy being discharged into the swash zone. The backwash is also strong and affects the next breaker as it opposes the forward motion and enhances the next plunge. Neale (1987) suggested that the lower swash zone produces the greatest amount of longshore motion and has the greatest influence on the overall rate of littoral transport.

Kirk (1970) suggested that the state of flow on a beach determines the active forces, while the structure and form of the bed determine the reaction to the forces. In analysing the swash zone processes on the mixed beach, he first reviewed theories of laminar and turbulent fluid flow. He also reviewed studies of velocities for sediment entrainment, maintenance of motion and settling. Many of the theories derived from studies of rivers and streams (for example Sundborg 1956) and of hydraulic processes and sedimentary transport (such as Bagnold 1968) were found to be useful in describing the applications of forces necessary for energy dissipation on the mixed sand

and gravel foreshore. The significance of the studied swash zone flows was regarded in relation to sediment entrainment, transport and deposition. Kirk noted the phase properties of swash flows as put forward by Kemp (1960) as most important. The amount of water entering and leaving the swash zone is controlled by phase difference, the relationship between breaker period and swash period being such that if swash period is nearly equal to breaker period then the backwash of a wave collides with the next incoming wave.

Kirk's swash zone instrumentation was designed to measure many parametric requirements of fluid properties affecting the distributions of flow structure across the shore, such as pressures, times, depths, velocities and levels of turbulence, and shore response parameters, including vertical and lateral distributions of transported sediment at any one time, characteristics of available grains and variations in bed elevations resulting from entrainment, transport and deposition. A general framework was established by measuring breaker height, wave period, swash length, period and run-up height. A full explanation of the design, calibration and operation of his instruments appears in Kirk (1971, 1973).

Field measurements showed that the flow and sediment system was bounded by current speeds of 100 to 250 cm.sec^{-1} and by grain diameters of 1.0 mm to 50.0 mm. Figure 2.11 derived from Sundborg (1956) combines mean nominal diameter with mean maximum flow velocity. Kirk's measurements are also plotted, and from their position the character of the study beach can be inferred to be in a transitional or rough flow regime. Many of the grains undergo intermittent motion both in swash and backwash. They lie in the range between critical erosion velocity and cessation of motion (Figure 2.11). This is another indication of the complexity and morphological significance of mixed sand and gravel sediment motion due to swash and backwash processes. Conditions for the initiation of sediment movement are frequently and rapidly exceeded and particles of various sizes are transported at high rates. Tranquil and low energy flows result in truncation and mixing of the finer sediments. During high energy conditions the whole size range on the bed is transported although different size fractions may move at different rates and in net opposite directions. Bimodal distributions were found to be produced by backwash scour with removal of a mid-range fraction. Sorting is dependent on the net rate of transport of particles of different sizes within the flows, rather than on critical selection of size fractions from the bed. Shape sorting of pebbles does occur high on storm berms due to deposition at swash limits.
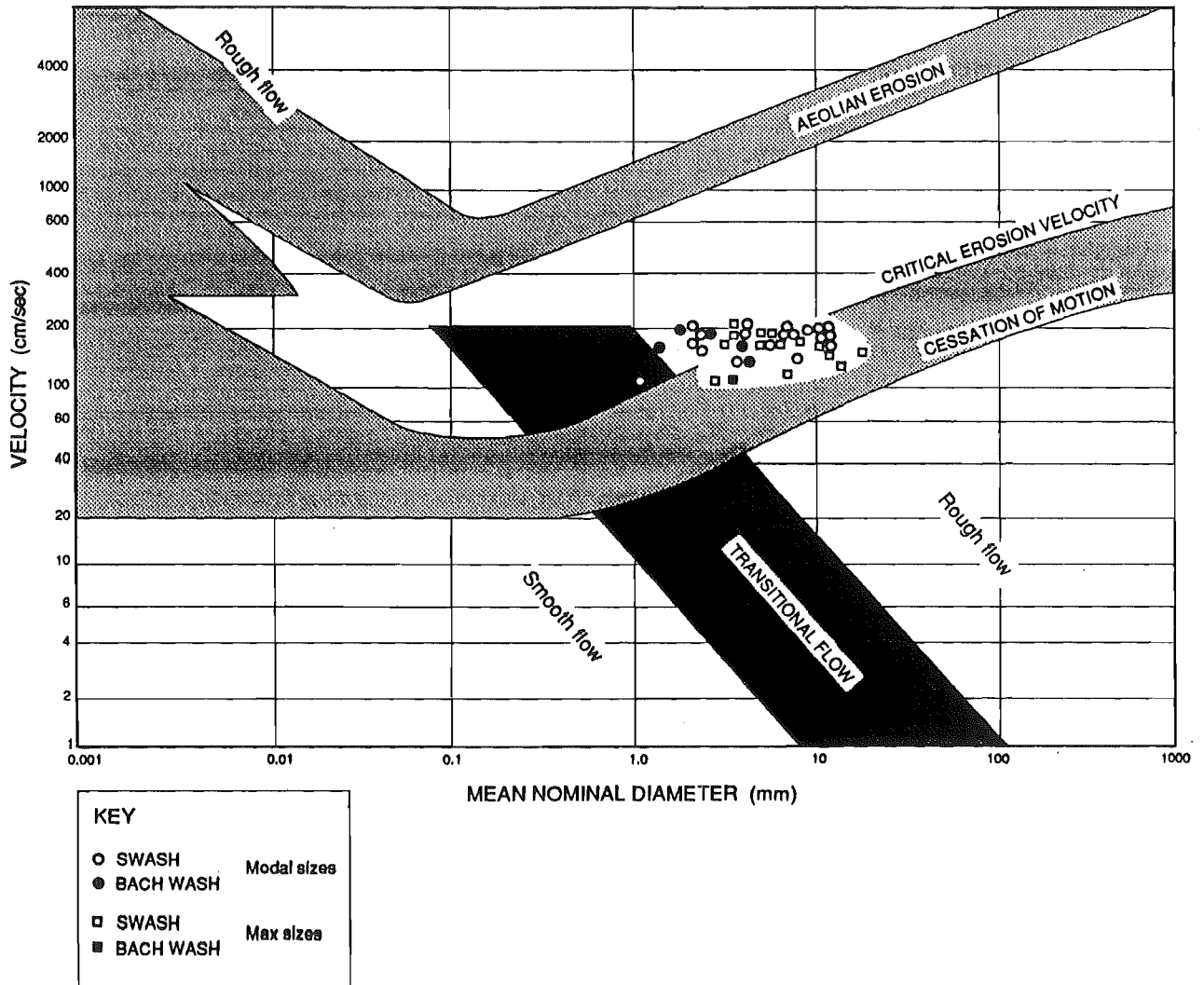
Figure 2.11 Particle sizes and flow speeds of swash zone sediments in relation to flow type. Curves are for uniform materials of density = 2.65 g.cm³ (from Sundborg 1956, Figure 13, in Kirk 1970, Figure 42).

The turbulent structure of flow is important in initiating sediment movement and in determining entrained sediment concentrations in the vertical profile of the water column. The relative intensity of turbulence increases landward from the breaking wave to the swash limit, and there is an increase in turbulence with an increase in breaker height. Kirk found that between 50% and 95% of the sediment load in both swash and backwash occurs in the lowest tenth of the water column. Motion was mainly in the form of sheet flow, though saltation was found to be locally important at the leading edge of swash.

Although energy levels rise with increasing wave height and period, Kirk considered that the chief determinant of flow structures is the phase ratio of swash period to wave period put forward by Kemp (1960). Wave steepness appeared to be of little direct influence as a predictive parameter of beach erosion, and the level of variability in the phase ratio for given wave trains arriving at the shore is more useful in describing observed foreshore response. Low values of the ratio, or low phase, where the swash flow has vacated the swash zone before the next wave and there is little difference between incoming and out going flows, are predominantly tranquil and enhance deposition on the foreshore. Medium phase differences provide "transitional" action, whereby scour is developed by the backwash owing to alterations in the flow structure during the downslope passage of the water. Kirk found that this offset swash deposition to some extent. High phase differences where interference between the incoming and outgoing flows is continual, were noted by Kirk and Kemp to be associated with erosive activity. The backwash scour zone is wide and seaward circulation of sediments through the breakers occurs continuously resulting in extensive foreshore erosion.

As previously mentioned, tidal influences are transmitted to a narrow width of the beach due to the steepness of the foreshore. However Kirk measured rhythmic variations in flow energy at given points across the shore over the tidal cycle. These were attributed to varying flow depths and structures and to effects induced by the changing beach water table. The strong retarding effect of groundwater storage by the sand and gravel mixture causes maximum energy levels to occur just after high water, when the water table is high and infiltration losses from the swash zone into the beach are relatively small. High rates of groundwater return to the swash zone may also cause fluidisation of the bed sediments resulting in the formation of rills and rhomboidal scour marks on the foreshore visible after individual backwashes and during the ebbing tide.

Neale (1987) used two methods to determine the depth of disturbance in the swash zone under 0.8 metre waves. The first method involved using plugs of traceable material inserted into the foreshore face and measuring the depth of disturbance of the plug. This method proved to be difficult to carry out in the field without causing undue disturbance to the natural surface and so a ruler was inserted into the surface during the passage of swash. Downward force was exerted on the ruler that was less than that required to push it into the undisturbed surface while not subjected to swash passage. Movement of the ruler into the beach was assumed to be due to a reduction in the resistance of the beach as individual sediment particles were moved by wave energy. Results of each method were comparable and gave depths of disturbance caused by a single swash cycle of 30 mm ± 5 mm.

Most pertinent to the present study, Kirk (1970) found that the fundamental measures of swash characteristics and foreshore beach changes were linked to dynamic flow properties such as turbulence, incidence of bed scour, amount of suspension of sediments in the water column and asymmetry of pressure application to the bed surface. These measures are all phase dependent and provide a realistic model of swash zone processes over a wide range of energy regimes. The most significant changes to the beach occur during periods of high phase differences.

2.5 River Mouth Dynamics

Hewson (1977) examined changes to the river mouth behaviour of the Waitaki River as part of the larger South Canterbury Coastal system. Kelk (1974) and Todd (1983) examined the Ashburton and Opihi river mouth dynamics respectively and in more detail. Kirk (1991) advanced many of the ideas developed on river-beach interaction on mixed sand and gravel coasts, with specific emphasis on the Rakaia River. These rivers as with the Rangitata River in Mid-Canterbury are important parts of the mixed sand and gravel beach systems of the South Island east coast. Most of the rivers in the area have a 'lagoon' type system at the outlet, being impeded by spit forms and barriers of mixed sand and gravel, and dominated by river or sea processes or by a combination of both, giving rise to distinct hydrodynamic patterns.

Kirk (1991) stated that these river mouths are non-tidal and non-estuarine in character. The systems are mainly dominated by marine processes except for short periods of time during river flooding. Kirk (1991) developed Zenkovich's (1967) concept of 'small' and 'large' rivers. Small rivers were considered to be those that do not provide enough sediment to protect the coast from erosion by waves or storm encroachment. Rivers were considered large by Zenkovich if the sediment load contribution to the coast

was such that the position of the coast was maintained or prograded despite losses from longshore transport or abrasion of the beach material. The total sediment load is not as important as the "proportion of (bed) load coarse enough to nourish the coast" (Kirk 1991, p 269). Most of the rivers of South Canterbury can be considered as 'small' rivers. The morphology of the mouth systems reflect the dominating longshore drift of the coastal system that is interrupted by high river flow states. Kirk stated that the sediment supply from the river is insufficient to stabilize or overcome coastal erosion.

There is a strong interaction between the pattern of sediment input to the coastal system from rivers and longshore sediment drift. The river mouth lagoon system can act as a source of sediment to the coast during or as a result of high river flows but because the system is dominated by coastal processes, the lagoon is more often a sink or trap for river sediments. High flows or floods causing breaching of the lagoon barrier or spit, inject 'pulses' of coarse sediments into the coastal system. These pulses vary in size depending on the intensity of the breach and the amount of sediment removed from the barrier. They also occur at varying time intervals as they are event dependent. Neale (1987) identified and examined the movement of the sediment pulses originating from the Waitaki River. His work is discussed further in Section 2.6. It is not only the nature of the high flow and breaching event that is important to the injection of river transported coarse sediment into the coastal system. At times of low flow the spit develops and denies sediment to beaches downdrift. This can temporarily accelerate erosion in these areas (Kirk 1991).

Kirk (1991) also discussed spit beach throughflow and permeability of mixed sand and gravel beaches. He noted the significant differences in the structure of the landward and seaward slopes of the spit. Kirk found that the landward slope of the spit was surfaced with a cap of well-sorted gravels and sand. Beneath this cap is an interbedded mixture of well-sorted washover materials and poorly sorted river deposits. Within the interbedding are layers of low permeable river silts that have filtered in from suspended load. This causes measured throughflows of the spit to be much lower than theoretically possible to surface deposits of mixed sand and gravel. Kirk noted that the average throughflows on the Rakaia spit were 102.3 $m^3.s^{-1}$, while theoretical values were 393 $m^3.s^{-1}$ (Kirk 1991, p282). Therefore water flow through the beach is impeded by the impermeable deposits causing ponding within the lagoon during high flow events, developing a strong pressure head between the river and the sea. Kirk stated that as the lagoon level rises it reaches surface layers of well sorted and therefore more permeable gravels, more rapid throughflow is established and this ultimately results in breaching.

Some of the river mouth processes on the east coast, South Island mixed sand and gravel beaches discussed by Kirk are important to the development of an understanding of morphological changes to the beaches downdrift. Notably these are the spit bypassing mechanisms for littoral drift and injected coarse material, pulsing of the littoral drift, and the role of permeability of the spit (barrier) in river mouth breaching and spit elongation.

2.6 Longshore Sediment Transport on a Mixed Sand and Gravel Foreshore

The mixed beach profile is dominated by the processes of swash and backwash. These processes are driven at most times by a single breaker line. This and the steep foreshore result in a narrow surf zone. Because the swash zone is the 'engine room' of this beach type, any lateral direction of energy transfer to the beach due to the line of breakers approaching the shore at an angle is an important factor in causing longshore transport of sediment. This process is clearly visible at the coast. A wave approaching the beach at an angle forms into a plunging breaker as the most landward end crosses the nearshore step. Observing from the beach, this appears as a peeling break running alongshore in the direction of longshore transport.

Neale (1987) examined the processes, patterns and rates of longshore sediment transport of the mixed sand and gravel beaches south of Timaru. He emphasised that although sand beaches and mixed beaches are governed by distinctly different process environments, approaches in the scientific literature concerning the mechanics of longshore transport for the different sediment types are essentially similar.

Net northward longshore drift along the coast south of the Port of Timaru results in an accumulation of coarse material against the harbour breakwater. Neale estimated transport rates for south of Timaru by calculating the net accumulation to be 51,288 $m^3.yr^{-1}$. This value was used to calibrate a linear relationship between the transport rate and the longshore component of wave power. Neale used a simplified version of an equation representing the relationship between the longshore transport rate (Q in $m^3.yr^{-1}$) and the longshore energy flux factor (P_{ls} in $J.s^{-1}$ per linear metre of beach) from C.E.R.C. (equation 4-50a, C.E.R.C. 1984, p 4-96) to calculate a 'k' factor. 'k' is a dimensional constant used to relate field data for longshore transport rates to longshore energy flux. For sand beaches, k is estimated as 1290 (C.E.R.C. 1984, p4-96). Neale presented estimates of 'k' for mixed sand and gravel beaches under different wave conditions and for different time scales (Neale 1987, p191). He found that 'k' should be in the range of 13.8 to 92.7. Kirk (1990; in press(b)) revised the k factor to 87.2 using updated estimates of annual net transport. This 'k' factor although not theoretically

'pure', is a practical value for estimating littoral transport rates on mixed sand and gravel beaches. Notably, it is vastly different from the value derived for sand beaches. This emphasises the difficulties encountered in applying coastal theory developed for sand beach systems to mixed sand and gravel systems, and the need to consider the specific environment under investigation as a distinct type.

The notion of 'slugs' of sediment movement as developed by Neale was referred to in Section 1.4. The slugs reflect episodic supply of sediment from large rivers during floods, and from cliff erosion. Neale considered it to be an important step to examine longshore transport as possessing varying spatial and temporal relationships. He attempted to integrate the two 'dimensional' aspects of sediment motion within a single framework to inspire an overall or holistic perspective of sediment transport along the South Canterbury foreshore. 'Shore morphology' was described by Neale as the pattern of distribution of the sediment volume. Changes in shore morphology over time were considered to represent movement of sediment volume through space. Neale considered that the slugs migrated alongshore as a consistent protrusion to the beach morphology and at a constant rate as represented in Figure 2.12. Figure 2.12 also shows the wavelike nature of the slugs.

Neale used profile surveys from a number of locations along the South Canterbury coast held by the South Canterbury Catchment Board. These surveys had been repeated at varying intervals since 1977. In all, coverage of nineteen beach profiles were used (including three used in this study), surveyed at approximately yearly intervals for ten years. Beach volumes of each profile at each survey time were used in his analysis. For comparison, the data was standardised using the formula;

$$B_z = (B_t - B_x) / B_x \qquad\qquad eq. 2.1$$

where B_z is the standardised profile volume, B_x is the mean of the measured volumes at a given profile ($m^3.100\ m^{-1}$ above 1m AMSL), B_t is the volume at time t ($m^3.100\ m^{-1}$ above 1m AMSL).

Therefore, above and below average volumes at a profile are assigned positive or negative standardised values respectively and the average volume has a value of $B_z = 0$. His graphed results are shown in Figure 2.13a. Rising and falling curves about the horizontal average represent periods of change from accretionary to erosional respectively. Neale then compared positions of the crests and troughs of each profile curve. He hypothesised that the patterns shown in Figure 2.13 could be explained as 'localised movements of fluctuating volumes of material drifting past each profile line' (Neale 1987, p203).
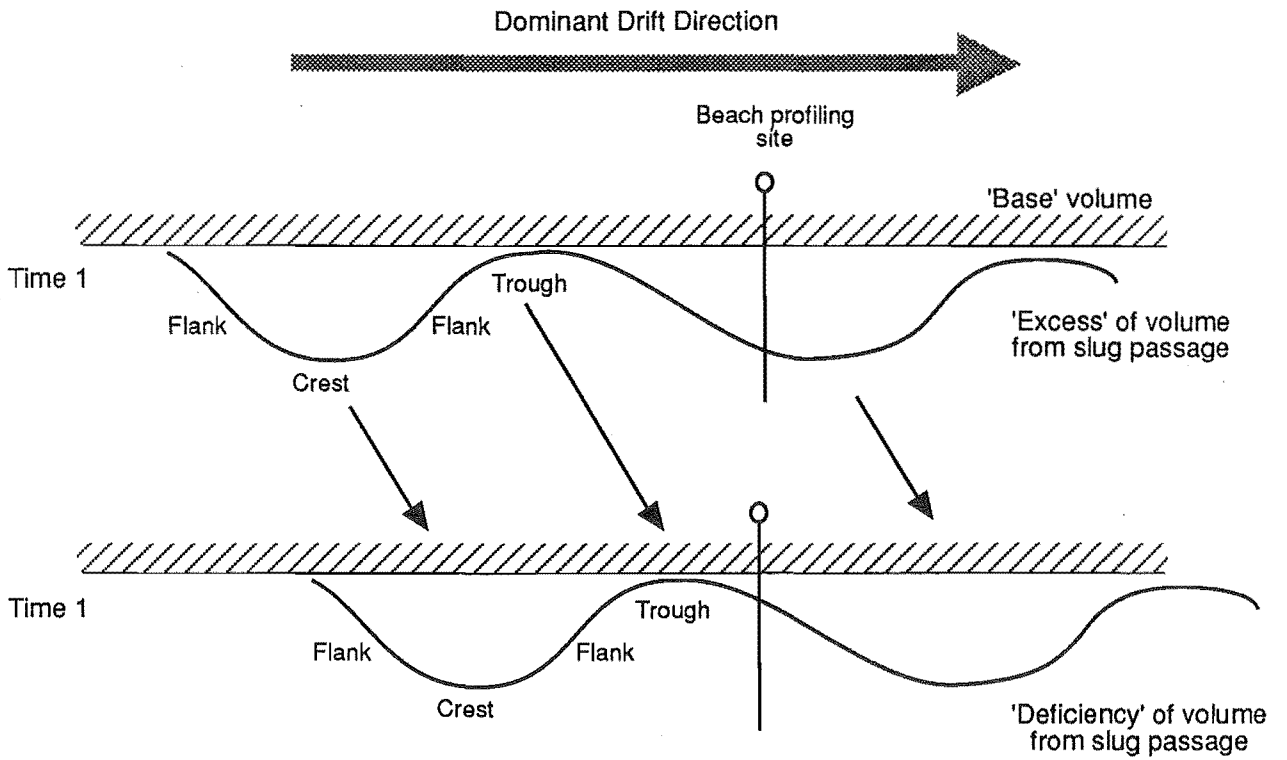
Figure 2.12 The translation of a 'slug' of sediment alongshore (after Neale 1987, Figure 6.4).
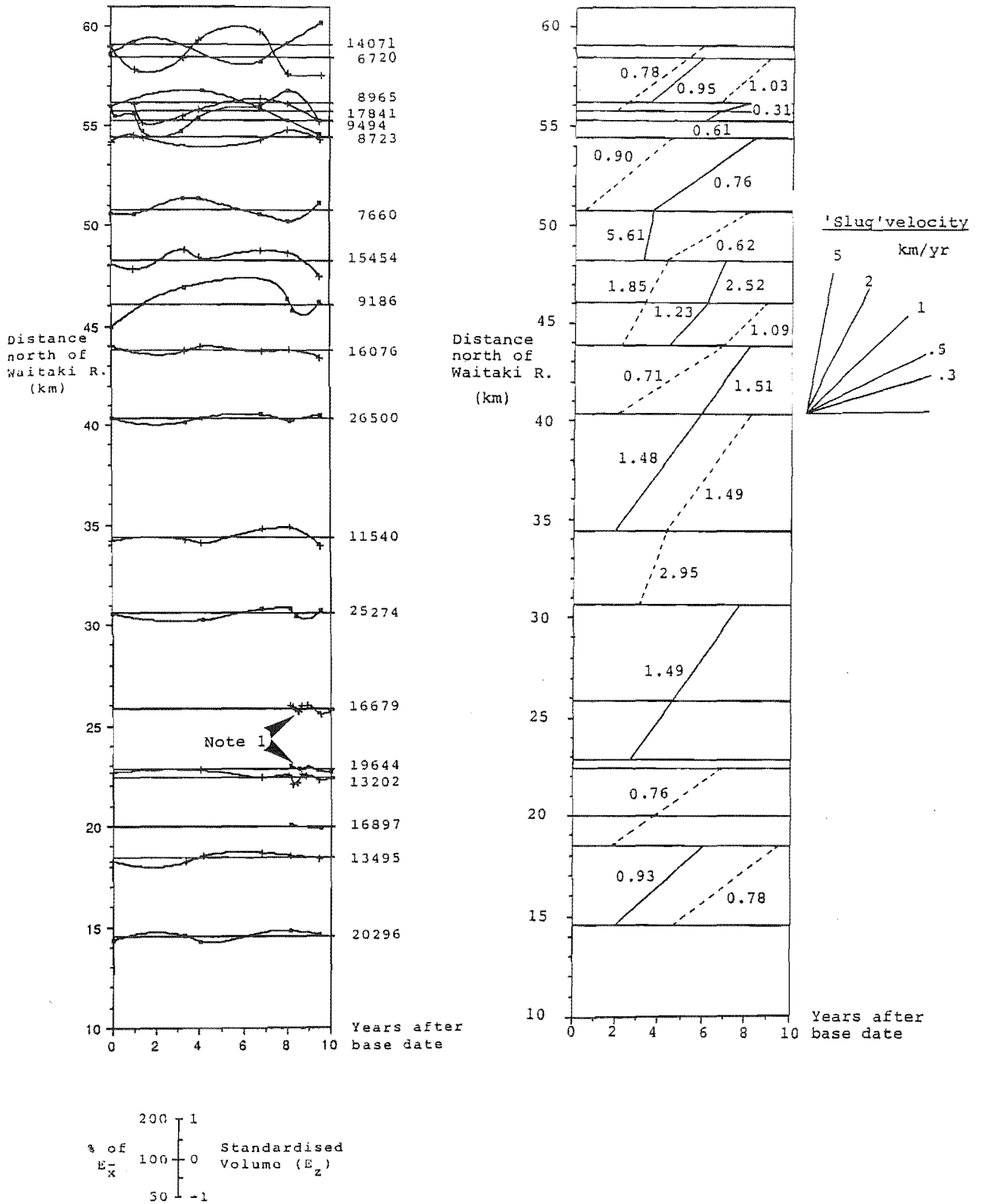
Figure 2.13 Foreshore profile volume variations between Waitaki River and Timaru, 1977-1987 (from Neale 1987, Figures 6.3 and 6.5).

a) Volume variation from selected profiles. Measured means (E_x) are shown on right, in units of $m^3.100m^{-1}$.

b) Possible linkages of high (solid lines) and low (dashed lines) profile volumes, suggesting a movement of 'slugs' alongshore. Implied velocities are shown in $km.yr^{-1}$.

Using Figure 2.13b, Neale calculated mean velocities of travel of the slugs by linking the crests and troughs of the volume variation curves (Figure 2.13a). Mean velocities between profiles ranged from 0.3 to 5.61 km.yr^{-1}, averaging 1.4 km.yr^{-1}. Neale determined that the velocities are strongly influenced by the prevailing angle of wave incidence at the shore.

The incidence and passage of the slugs passing a given position on the coast affects the shore morphology and therefore the response to the wave environment. Neale calculated that the average maximum volume change caused by the passage of a slug of material was 45 m^3 per linear metre of beach, with a standard deviation of 27 m^3 .m^{-1}. The average lifetime of a slug at any location - the time taken for a trough-crest sequence to pass a position on the coast - was found to be 4.9 years, with a standard deviation of 2.7 years. The presence of a slug crest at a location may act as protection from breaching and overtopping due to storm wave attack as there is sufficient or an excess of sediment to dissipate wave energy. However conversely, an area may become more susceptible to storm damage during the passage of a slug trough through the area due to the reduction of beach volume. The volume of the beach, beach width and crest height are important criteria in determining the likelihood of occurrence of beach breaching or overtopping. Any factor influencing sediment volume will also have an impact on the performance of the beach as a protective barrier. This is especially applicable along the Wainono Lowland Coast, therefore the notion of slugs is a significant determinant of changes to the beach morphology in the study area. Neale's concepts and their relevance to this study are discussed further in Chapters Four and Six.

2.7   Unpublished Technical Reports

The distribution of population in New Zealand along it's coastline has led to an interaction between the physical coastal environment and the human use systems. As a consequence hazardous situations have come about, mainly where property and economic livelihood have become subject to the impact of coastal erosion or flooding. In South Canterbury, coastal geomorphologists have been consulted in an attempt to find remedies for existing problems and to help prevent further damaging coastal hazards.

A number of major coastal projects were carried out by Kirk in association with the South Canterbury Catchment Board (now the Canterbury Regional Council), the Timaru City Council and the Timaru Harbour Board (now the Timaru Port Company) (for example Kirk 1984; in press (a); in press (b), Kirk and Weaver 1985). In carrying out

these projects many principles pertaining to the dynamics of the mixed sand and gravel beach systems had to be recognised as there were no existing guidelines for coastal works on this beach type. Kirk (in press(a); in press (b)) presents two of the major projects carried out in the Timaru area which contributed significantly to a better understanding of mixed sand and gravel beach morphology and processes. These projects concern an experimental beach reconstruction and renourishment scheme at Washdyke, and the growth of an artificial beach for protection of the Port of Timaru breakwater at Southbeach (in press (a) and in press (b) respectively).

The purpose of the Washdyke renourishment was twofold. It was designed principally to protect the Timaru City sewer outfall for a period of up to five years while a new 'hazard free' system was located further north. The design was also a field experiment of a potential 'soft engineering' solution or control to the severe erosion and inundation hazards of the Washdyke Lagoon coast (Kirk and Weaver 1985, Kirk in press (a)). The protection was designed to combine both beach reconstruction and renourishment. Reconstruction utilised beach material that had been 'rolled over' from the foreshore to the backshore by storm wave overwash. This sediment was used to raise the crest height by 2.0 to 2.5 metres, cutting down inundation and overwash frequency and hampering rollover of sediments from the beach face which consequently removes the sediment from active wave energy dissipation. The renourishment part of the project consisted of adding a cap of river gravels that were much coarser than the existing beach material to the reconstructed beach. This effectively coarsened and steepened the foreshore with material more resistant to erosion.

The reconstruction and renourishment was considered by Kirk to be highly successful in meeting the initial aims. The objective of protection for the Timaru City sewer outfall was met with the outfall maintained until the commissioning of the new structure. Kirk is also of the view that reconstruction and renourishment was shown to be a successful means of combating erosion along the Washdyke Lagoon barrier beach.

This project also contributed significantly to the pool of knowledge concerning mixed sand and gravel beaches. Kirk (1981) noted the significance of sediment 'rollover' to the beach process and morphology. He stated that rollover of sediments to the backshore contributed 25% to the total erosion loss of material from the foreshore. The rest of the losses are due to longshore drift and the abrasion of gravels. Important findings were also made concerning the internal structure of the beach. Kirk noted the depletion of available coarse sediments on the Washdyke - Seadown coast, and the

importance of the underlying base structure in defining the subsurface boundary of the beach. These points were also raised by Benn (1987) and are discussed earlier in this study in Section 2.3.4.

Assessment of the performance of the reconstruction and renourishment structure was carried out using repeated beach profile survey data. This data was analysed using normalised excursion distance plots fitted with regression lines to distinguish long term trends in performance from short term 'noise' related to short duration changes in the wave environment. This method is also used in this study as a tool for analysing changes in the beach morphology of the Wainono Lowland coast. The methodology and techniques of excursion distance analysis are explained fully in Chapter Four.

The methodology and parameters of reconstruction developed at Washdyke were applied on the Wainono Lowland Coast by C. Ruddenklau in 1985 after 1.2 km of beach was lowered by wave overtopping. Sediment deposited landward of the backshore was bulldozed back onto the beach and shaped to present a more classical mixed sand and gravel beach profile to the wave environment.

Kirk (in press(b)) is concerned in this case with a need to manipulate existing coastal theory to fit a specific environment. The project involved the creation of an artificial beach by utilizing the naturally abundant longshore drift of coarse material. The purpose of the beach was to protect the harbour breakwater from direct wave attack and required a 150 metre long spur groyne to be constructed near the harbour entrance. The beach was referred to by Kirk as a 'spending beach' whereby wave energy was expended in breaking and swash on the beach rather than as impact against the breakwater. Kirk details the site and situation, costs, benefits and methods of designing the project and presents the progress of the beach since the groyne construction started in May 1987. He also notes the value of cooperative research in this project, with facets of the investigation drawing on previous work carried out by himself, staff of Timaru Harbour Board and research students from the Geography Department at the University of Canterbury.

Longshore drift on the mixed sand and gravel beach is the driving process of the artificial beach construction Therefore the principles of the drift system were an important factor in the design of the project. These principles have been examined earlier in Section 2.6. To recap, longshore transport occurs by means of two distinct but closely related sediment systems. Offshore of the single line of breakers runs a longshore system comprised of northward moving, mainly fine, sands. The movement of coarse sands and gravel sized particles is important in beach construction landward

of the nearshore step. The offshore system transports approximately ten times more volume of sediment than the system operating landward of the breakers in the steep narrow swash/backwash zone. The strictly defined boundary between the two transport environments and the sharp steep boundary of the coarse grained beach were significant in enabling Kirk to apply mathematical models to represent the coastal system. The project is still in progress and has been successful in saving the Timaru Port Company many thousands of dollars in costs of maintenance of the breakwater.

2.8 Summary of the Nature of New Zealand Mixed Sand and Gravel Beaches

2.8.1 Base character, plan and profile shape

New Zealand mixed sand and gravel beaches are mainly situated on the East coast of the South and North Islands. They occur at the sea/land interface of Pleistocene and Holocene fluvial outwash fans and plains. The Canterbury fans and plains are a result of periods of glacial advances, the latest being the 'Otira Advance' between 75000 and 10000 years BP, and have been eroding in response to sea level rising from a low of 130 to 240 metres below present sea level 10,000 years ago, to above the present level and falling back to stabilise at about the present level in the last 4000 to 5000 years. Other areas, mainly around Kaikoura in the South Island and Hawkes Bay in the North Island are a result of fluvial outwash from rapidly eroding mountain ranges.

The hinterland ranges from high eroding unconsolidated cliffs to low-lying wetlands, although in some areas an underlying base of basalt, or consolidated tertiary or loess deposits is thinly mantled by beach sediments. The hinterland is dissected and crossed by many large braided rivers that are susceptible to flooding and have a large sediment yield. However much of the sediment is of an unsuitable size to be retained on the beach. The unconsolidated cliffs and much of the lowlying land is comprised of sediments of a comparable size range and composition to those found on the beaches and are a major source of beach material.

In plan shape, most of the mixed beach systems are concave seawards, with the convex seaward fans of the Clarence and Waitaki Rivers being notable exceptions. Most of the beaches are orientated towards the dominant swell direction and as such are aligned to face East-south-east to South-east. McLean (1967) showed that many of the South Island mixed beaches satisfy at least some of the criteria of equilibrium beaches.

2.8.2 Sediments

Mixed sand and gravel beaches contain a large range of sediment sizes, from sand to boulders. New Zealand mixed beach sediments are derived from greywackes, a bedded tertiary deposit, uplifted to form the basic rock character of New Zealand's central mountain range, eroded by glaciation and other weathering processes, and transported to the coast by the many rivers East of the mountains. Greywacke is easily abraded to silt and mud sizes. Therefore it is a transitory resident of the beach, with fine sand being eliminated by abrasion, impact and grinding. The bedding nature of greywacke helps to determine the dominant shapes of individual particles on the beach. Discs are the most common granule and pebble shape, followed by blades and elongated blade shapes. There are few large spheroid particles.

The range of particle sizes are not distributed equally across the profile. The nearshore face is made up of predominantly coarse gravels that are either spheres or discs. The lower foreshore has a combination of gravels and coarse sand, with the larger particles mainly disc shaped or bladed. Sediments in this zone are well sorted. The upper foreshore contains coarse gravels that are moderately sorted, but lenses of sand can also be found on the seaward faces and between elevated storm berms. The top of the storm berms contain poorly sorted coarse gravels with sand particles in the interstices of the gravel. The backshore is dominated by large discoid pebbles.

2.8.3 Process-response system

The mixed sand and gravel beach is driven by swash zone processes. A single line of breakers is usually present above the nearshore step, and due to the steep foreshore there is little horizontal translation of this break point through the tidal cycle. Waves are of a plunging type although during storms, large waves will spill and reform offshore to break again in the lower foreshore. There is a high degree of turbulence in the surfzone. Wave height determines the amount of run-up and therefore the elevation to which the beach profile is affected by the swash processes. Wave steepness is not as important as the wave and swash period ratio in determining whether erosion or accretion will occur. Low phase differences occur when the swash flow has vacated the swash zone before the next wave, high phase differences occur when there is continual interference between the incoming wave and the outgoing swash flow. Low phase is conducive to accretion and high phase is associated with enhanced erosion. Medium phase differences provide a transitional action where scour developed by interferences in the backwash offsets swash deposition.

Longshore transport is an important feature of the mixed sand and gravel beaches. There are two separate transport processes at work. One operates seaward of the nearshore step, and causes the transport of fine and medium sands in the nearshore zone. The other process occurs in the swash zone of the beach. The single breaker approaching the shore at an angle is not refracted by a continuous sloping nearshore seabed but reaches the breakpoint at a sharp transition in water depth. All of the residual lateral energy is available for transport of beach sediments along the shore.

2.9 Concluding Remarks

The aim of this chapter was to present a review of studies carried out in New Zealand on the mixed sand and gravel beach type. The purpose of the review was to present the developments in understanding of the processes and morphologies of the mixed sediment beach in order to provide a scientific context for this study. It has been shown that mixed sand and gravel beaches exist separately from either pure sand beaches of the classic type, or pure gravel or shingle beaches such as described for situations in England and Wales . The morphological form is distinct and the beach process/response system is implicit to a mixed sediment system rather than being a mixture of sand or gravel beach process features. The University of Canterbury, Geography Department, Coastal Studies Group has studied mixed beaches intensively for fifteen years. However, many of the discoveries and conclusions as to the way that mixed sediment beaches operate are not available to the international scientific community. The reviewed work is concerned mainly with overall patterns and processes. Many phenomena have been discussed but there has been no establishment of event specific process - morphology relationships. By examining high energy or storm events as a type of process environment and how they affect and impact upon the beach, short term response to processes, and medium to long term beach adjustments can be attributed to specific types of wave episodes.

McLean (1970) and Marshall (1929) have listed common and important features of the workings of mixed sand and gravel beaches. Marshall also discussed the effect of sediment size on the beach morphology. However his work was surpassed by that carried out by McLean and Kirk (1969). From the work reviewed in this chapter, McLean's common features can be expanded, while the considerations presented by Marshall can be more clearly defined. To recap, McLean's four common features of New Zealand mixed sand and gravel beaches are listed below.

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.

4. They are exposed to the high energy waves of an East Coast Swell Environment (Davies 1964). (McLean 1970, p142)

To this list can be added:

5. The dominant shape of particles falls into the discoid class (from Folk 1965) with bladed shapes being the next most common.

McLean and Kirk (1969) found that both source area effect and hydraulic selection of sediments must occur on the mixed sand and gavel beach. Source area exerts the primary control on the gross patterns of sediment distribution, while variations in the hydraulic factors (or process environment) have a secondary effect on the spatial and temporal variability of the sediment characteristics. Apart from the size of the sediments, the shape of the larger particles was also noted as being an important control on the type of deposition that occurs. Disc shaped pebbles that are difficult to entrain but transport easily once in motion, are carried up on the swash and stranded as the swash percolates into the beach. Rounded or blade shaped particles roll more easily and are more susceptible to erosion as movement will be instigated by lower velocities of water movement such as those found in the backwash. These factors are significant to determining how the beach responds to high energy waves.

Developments in the understanding of mixed sand and gravel beach morphology and processes lead to further expansion of the list of common features for this beach type. Following from the list above, these are:

6. The lower foreshore is moderately steep (5 - 12°) and wave breaking occurs in this zone. At most times there is a step between the mixed sediments of the foreshore and the fine sand low gradient nearshore seabed.

7. The surfzone is narrow, most often consisting of one line of breakers, usually of the plunging type, and there is little horizontal translation of the position of the breakers during the tidal cycle.

8. The profile is dominated by swash and backwash processes.

9. There are often tiers of berms related to deposition and erosion episodes of differing magnitudes. Constant adjustments to the foreshore in the short term are masked by storm induced changes.

The list of considerations of the effect of 'rough seas' on the beach put forward by Marshall (1929) and discussed in Section 2.3.1 is concerned with swash zone

processes during storm conditions, and as such could be an extension from point 8 above. Marshall's basic premise was thought to be that the volume of water arriving on the beach with each wave during storms exceeds the capacity for percolation into the beach. This is also addressed by Kirk (1970) in advancing the importance of the phase ratio between wave period and swash period. Kirk offered this concept as a much more applicable predictive parameter of beach erosion than the wave steepness, which is used to determine whether waves are potentially erosive or accretionary for sand beach situations. The importance of the swash zone as the 'engine room' of the mixed sediment beach comes directly from points 6 and 7. The single line of breaking waves are confined to a narrow section of the beach profile therefore the dissipation or absorption of the energy in the wave must occur with breaking or in the swash processes. The swash is therefore very turbulent and will cause entrainment and landward transport of sediment particles.

CHAPTER THREE

WAINONO LOWLAND COAST

The South Canterbury coast has been extensively studied by coastal geomorphologists since the mid 1960's. As discussed in Chapter Two, many of these studies have produced ideas and conclusions of significance in augmenting the understanding of the working of mixed sand and gravel beaches in general, and of this coastline in particular. This chapter describes the morphological character of the Wainono Lowland coast with the purpose of developing an understanding of the study area as a physical sub-unit of a larger interacting coastal system. A basic description of the area and the beach type was given in Chapter One (see Section 1.2). Figure 3.1 shows aspects of the study area illustrating the type of environment under investigation. At the first approach the barrier appears imposing and barren. The dynamic nature of the beach can be seen from Figures 3.1a and 3.1b which show the change to the barrier beach at Profile 1 between February 1990 and July 1991.

3.1 Early Descriptions of the South Canterbury Coastal Environment

Written descriptions of the South Canterbury coast were first made in the 1840's by travellers using the beach as a walking track between Christchurch and Dunedin. In January 1844, Dr Edward Shortland an interpreter to the Lands Claim Commissioners and a 'Protector of Aborigines', walked from Moeraki to Akoroa. He noted a 3 mile pebble beach ridge separated the Waihao lagoon from the sea, and that the pebbles and shingle were soft underfoot causing slower travel (Gillespie 1971). He also noted the presence of several smaller lagoons to the north of this large one. In May 1852, W.H. Valpy, an early settler, became the first man to travel by horseback from Christchurch to Dunedin. In a letter to John Godley, he described the "extraordinary beach", "20 miles long". He went on to state that "The wall of shingle is in parts 25 feet high and not more than 50 yards broad, forming at one end of the sea side three terraces" (Gillespie 1971, p64). It is supposed here, that the terraces referred to were intermediate storm berms and beach ridges similar to those present today.

Articles from the Timaru Herald gave descriptions and theories of development of the coast and beach structure around Timaru. An 1891 piece "The 140 mile Beach. Our Great Shingle River.", described in general terms the nature of the shingle beaches between Banks Peninsula and Oamaru. It was suggested that the Canterbury rivers, especially the Waitaki River, were the major contributors of sediment to the coast. Because of the 'bold' seaward curvature of the coast around the mouth of the Waitaki, it

Figure 3.1 Wainono Lowland Coast.

a) Looking north from Profile 1 adjacent to Waihao Dead Arm, February 1990.

b) Same site as a), July 1991.

Figure 3.1 Wainono Lowland Coast.

c) Surveying Profile 4, June 1990.

d) Looking south from Profile 7 adjacent to Wainono Lagoon, February 1990.

was also suggested that in geological history it had been a major source of sediments. The differing characteristics of sediments from different river sources were noted, including the distribution of sediments of different sizes and compositions. It was suggested that the abrasion resistant Waitaki greywackes and quartzes were dominant as far north as the Rangitata River. It was also noted that the beach sediment moved both northwards and southwards, and that this movement was dependent on the direction of wave approach, i.e.: that waves approaching from the north move beach sediment to the south and waves from the south would induce a northward movement. The more dominant southerly storms had caused a noticeable net northward displacement of beach material.

"A Nature Study: The Beach Shingle" (Hardcastle 1905), discusses the geology and mineralogy of the beach shingles found on the South Canterbury coast. An alongshore drift of beach material was noted, as was the presence of a build up of material against the southern side of the Timaru Harbour breakwater. Hardcastle noted that the dominant shape of the shingle was disc like. At the time this was commonly believed to be due to movement by wave action. However he suggested that this could also be due to the slate structure of the greywacke stones. A relationship between the size of shingle and the distance from its source was noted, with larger material being dominant near the Waitaki River mouth, and finer material just south of the Rangitata River, where a new coarse sediment input occurs. He also noted that abrasion of the pebbles results in fine sand and mud which is spread over the sea bed. The role of the shingle beach ridge was given by Hardcastle to be that of protection to the land adjacent to the coast, and that the removal of material or the damming of a longshore sediment supply such as by the building of the Timaru Harbour breakwater would result in beach erosion.

Todd (1988) presents a brief summary of the development of Timaru Harbour, while Tierney (1977) gives a more detailed account of coastal change around the port of Timaru. The supposed impact of the harbour breakwater construction had been noted as early as 1871 in a report by J. Carruthers a colonial marine engineer on the likely impact of building a large breakwater after observing the results of experimental groynes. Carruthers suggested that the structure would soon become ineffective as rapid shingle accumulation occurred on its south side. It was also considered that this would cause erosion of the shingle beaches to the north of the harbour. In particular, the detached spit enclosing Washdyke Lagoon would be likely to disappear completely (in Todd 1988, p26).

In actuality, effects adjacent and updrift of the breakwater were of immediate importance. The first 100 metres of breakwater were completed in 1878. Figure 3.2 shows the early development of the harbour works and the resulting changes to the adjacent coastline. Notably, these changes include accretion south of the harbour (now known as South Beach) and in Caroline Bay, and erosion at Waimataitai and Washdyke. One of the first economic impacts to result after accretion at South Beach, was the movement seaward of the George Street Landing Service equipment. By 1881, the Landing Service operations had ceased. Shingle accumulation updrift of the breakwater remained a concern through the 1890's, with attempts made to dredge and remove material that had been washed over the breakwater and deposited within the harbour. By 1900 the Eastern extension to the existing breakwater was started. The wall construction comprised large quarry stones, and was completed by 1906. However, additions were made between 1911 and 1915, while maintenance has been carried out after heavy seas since its completion (Todd 1988).

Downdrift of the structure, erosion was noted at Waimataitai, at the northern end of Caroline Bay, causing problems to the railway viaduct. However shoaling of the harbour and accumulation of sand in Caroline Bay was also noted in 1891 by C. O'Connor, a consulting engineer to the Harbour Board (in Todd 1988, p28). Fahy (1986) gives a detailed history of sand accretion in Caroline Bay from 1880 to 1986, and presents a computer model of future accretion and shoreline change. Fahy calculated that by 1920, the rate of accumulation in Caroline Bay since 1880 was 57,000 $m^3.yr^1$, while the rate of seaward movement of the low water contour was 2.4 $m.yr^1$. Accumulation by 1986 as measured by Fahy was of the order of 33,700 $m^3.yr^1$, suggesting that accretion is continuing but at a slower rate.

3.2 Geomorphological Background

The geomorphological development of the study area has occurred during the Quaternary period and is attributable to deposition of gravels - from the Waitaki River draining the alpine regions of the McKenzie Country and some smaller coastal streams draining the Hunters Hills - and to changes in base level either due to uplift of the land or to sea level fluctuations.

Figure 3.3 shows a simplified geological description of the study area. The major features that are shown are the large area covered by alluvial gravels, the seaward convexity of the coastline around the Waitaki River mouth, and the major influence of the Waitaki River on the topography. The Waitaki River has been established since the early Pleistocene (Gage 1957), and has alternately deepened and widened its valley
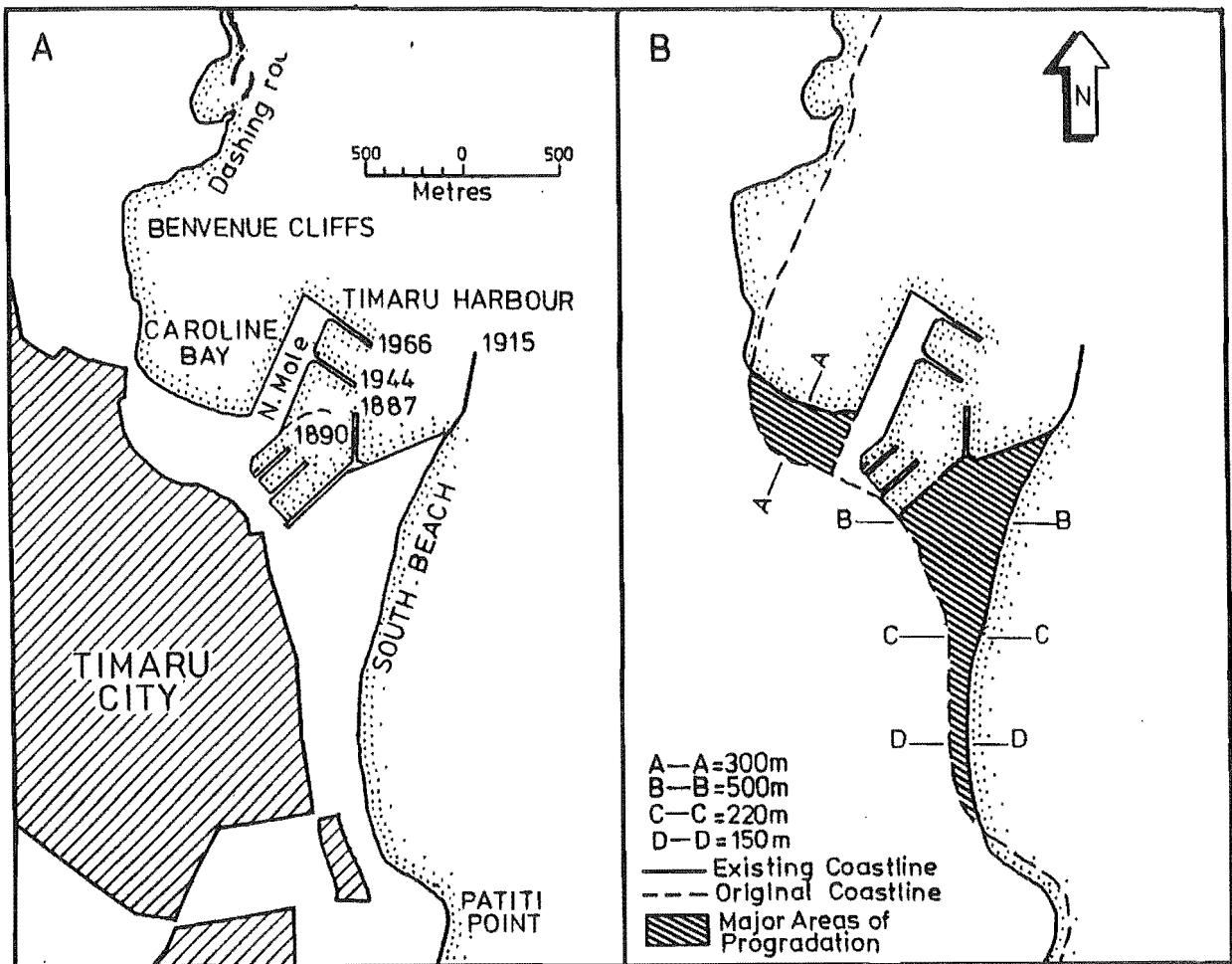
Figure 3.2 Harbour developments and coastline change in the vicinity of Timaru Harbour 1879 - 1967 (from Tierney 1977, Figure 4).
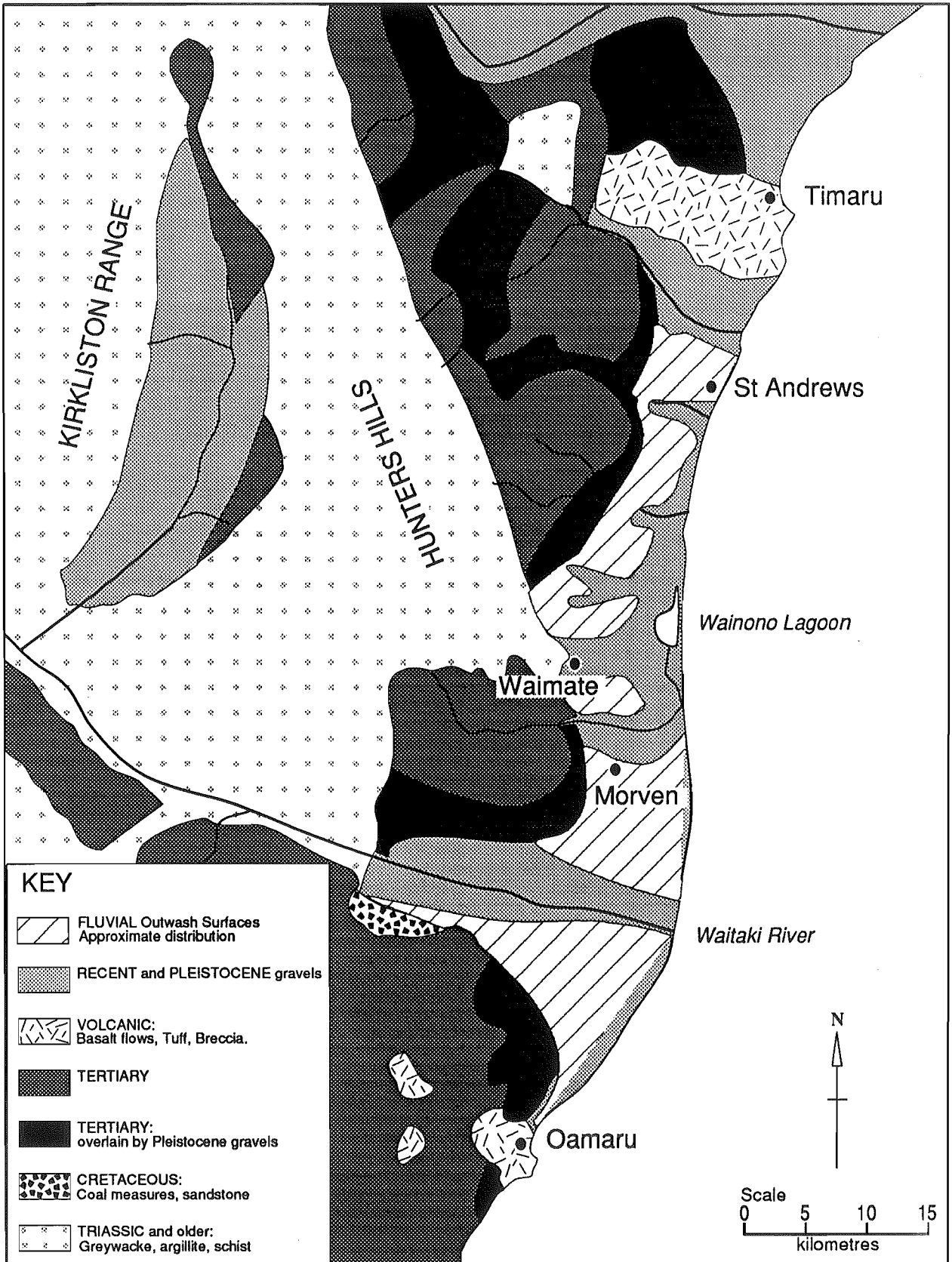
Figure 3.3 Geology of the Waimate area, South Canterbury (after Hewson 1977, Figure 4).

within a great tectonic depression in response to base level changes that have been complicated by climatic fluctuations. The river drains 2400 square kilometres of the central alpine region of the South Island including present day glaciers and late Quaternary moraines and outwash gravel surfaces. The sediment available for transportation by the river is predominantly greywacke with minor low-rank schist and argillite and their fine grained derivatives (Oborn 1978).

Holland (1962) wrote a geomorphological reconnaissance of the area as a Masters Thesis, discussing the formation of the major fluvial outwash surfaces between the Hunters Hills and the coastline. The Waituna Surface is sited on the low hills seaward of the Hunters, at heights ranging from 190 m to 210 m, and is comprised of coalescing fans of gravels ranging in age from the lower Pleistocene to 10 000 years B.P. (Wilson 1953, in Holland 1962). The gravels are similar in character to contemporary fan gravels. Collins (1953, in Holland 1962) found marine fossils of Pleistocene age in the banks of the Makikihi River, eight kilometres from the present coastline which indicated that the gravels were deposited in a coastal environment as sea level was lowering (Holland 1962, p48).

A steep escarpment running from just south of the Pareora River to The Waitaki Plain separates the highest unit of the coastal plain sequence, the Willowbridge Surface, from the lowest and youngest unit, the Morven Surface. The Willowbridge Surface slopes at approximately 0.6° (1 in 100), while the Morven has a surface slope of about 0.23° (1 in 250). The Morven Surface is backed by the steep escarpment to the Willowbridge Surface and slopes from about 15 m above sea level to approximately 3 m above sea level adjacent to the seaward boundary of greywacke and sandstone mixed sand and gravel barrier beach. Holland (1962) suggested that all of the surfaces were formed over the top of gravels and non-truncated marine deposits of lower Tertiary age. He found that his evidence suggested that the gravels were deposited in both marine and terrestrial environments associated with a falling sea level or a slowly rising land mass. This is also backed up by Marwick (1946, in Holland 1962) who explained the presence of the gravel cliffs between the Waituna and the Willowbridge surfaces as resulting from a change in base level. Holland (1962) stated that the cliffs were evidence of uplift in recent times, or post-glacial unloading and subsequent rising of the South Island.

3.3 Plan Shape

From Figure 3.3 it can be seen that Wainono Lagoon lies at the northern end of a convexity in the coast, adjacent to a change of orientation from facing North-Northeast

to facing just South of East. The hinterland surrounding Wainono is lower in elevation (in general less than 10 metres) than that south of the Waihao River and Morven where the beach is backed by coastal cliffs up to 20 metres high.

A study by McLean (1967) on the plan shape of beaches along the study coast was discussed in Chapter Two. It was noted that the convex seaward curved shoreline about the Waitaki River mouth was an exception to the general plan shape of the South Island mixed sand and gravel beach systems. McLean made no conclusion as to whether this coastline was representative of an equilibrium or subequilibrium state. It is assumed here that the convexity is due to a rising sea level encroaching upon the fan of the Waitaki River. This explanation is consistent with the presence of high gravel cliffs backing the beach between the Waihao River and the Waitaki River.

Hewson (1977) noted that the dynamic state of the beaches was 'attuned' to the prevalent southerly storm waves arriving at the coast, and that there is little seasonal variation in beach erosion rates and volume change. He ascribed the long term erosional trend of the South Canterbury Coast to adjustments in response to the post-glacial rise in sea level. As sea level has risen since the last glaciation the coastline has retreated, truncating the fan and perhaps rolling the barrier beach landward over the top of the low sloping hinterland surface, as the coast realigns to face the dominant wave approach - in this case from the South-east. This realignment has not been completed as the coast still lies at an angle to the south-east waves, causing a marked angle of incidence between the breaking wave and the beach resulting in strong northwards longshore transport of beach sediments. Hewson also stated that the long term retreat of the coastline reflected a deficit in sediment supply, and a prevalence of high energy waves.

3.4 Hinterland and Drainage

The dominant feature of the Wainono Lowland Coast hinterland is the 325 ha Wainono Lagoon (see Figure 3.4) surrounded by 140 ha of wetlands (Pemberton 1980). The lagoon is part of a large drainage system to prevent flooding of low lying farmland. The water level in the lagoon is generally 1.0 to 1.2 m above mean sea level. The lagoon is also an important wetland environment. The Department of Conservation (1990) and Davies (1986) have noted the significant natural and cultural values of Wainono Lagoon, citing reasons such as a high degree of 'naturalness', the presence of rare and unique species, communities and habitats, the important breeding, nesting and feeding environment, and a long association with Maori people of the area, especially as a source of food. The lagoon is also a vital link in a chain of South Canterbury

wetlands. It is the most substantial wetland area between Lake Ellesmere in Canterbury, and Karitane Estuary in Otago, and has a seasonal wildlife population varying from 4000 to 9000 birds. The bulk of the wildlife are waterfowl, including New Zealand and overseas waders which are considered 'Nationally' important (Department of Conservation 1990). The New Zealand Wildlife Service rates the area highly and has proposed it becomes a government purpose reserve (Davies 1986).

The vegetation of the coastal hinterland has changed considerably since Human occupation and the instigation of pastoral farming. The vegetation of the 1860's consisted of flax (*Phormium tenax*) and raupo (*Typha muelleri*) swamp grass (probably *Cortaderia sp.*) with isolated islands of cabbage trees (*Cordyline australis*), tall tussock (*Festuca novae-zelandie* or probably *Poa caespitosa*) and manuka (*Leptospernum scoparium* or *L. ericoides*) with forest around what is now Waimate and the base of the Hunters Hills (Holland 1988). By 1880 much of the swamp had been drained and the tussock ploughed. Introduced pasture grasses are now dominant.

After the initial drainage of the hinterland in the 1870's, records of stopbanking and drainage control show that work has been carried out in direct response to flooding problems as they have occurred (Todd 1988, p179). The locations and dates of construction of stopbanks are shown in Figure 3.4. The two banks running perpendicular to the coast south of Wainono Lagoon were constructed in the 1940's and 50's to prevent the lagoon encroaching upon farmland. A 3.6 km long bank was constructed along the Waihao Dead Arm in response to sea flooding caused by two storms in 1977. Water is contained within the stopbanks and directed along the Dead Arm to the Waihao River outlet. The outlet from the Waihao River to the sea consists of a 60 m long wooden box structure 4.6 m wide by 1.2 m high that penetrates the barrier beach. It is designed for 'normal' flows rather than flood flows and is closed for 75% of the time. Opening the flow entails the use of a bulldozer to clear beach sediments from the seaward outlet (Todd 1988, p125).

3.5 The Beach in Profile

The morphology of mixed sand and gravel beaches has been discussed in Chapters One and Two. The general description given there can now be used as a basis for discussing the beach profiles in the study area. The discussion in this section is mainly a descriptive account of the beach and is an introduction to a fuller investigation in Chapter Five of the beach morphology and how it changes over time.
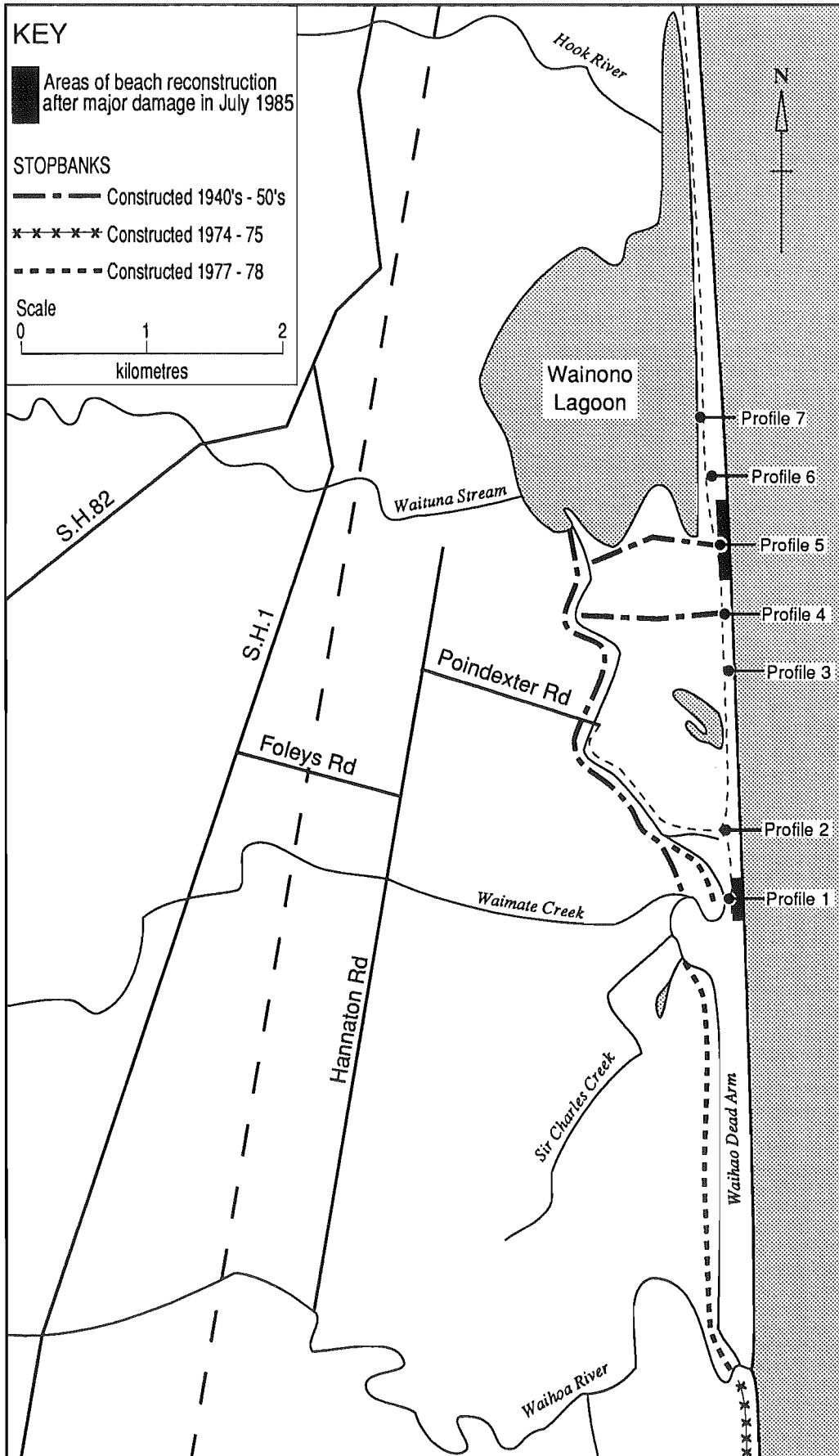
Figure 3.4 Map of named locations in the field area.

3.5.1 Profile shape

Figure 3.5 shows examples of beach profiles surveyed in the study area. Notable differences are exhibited between these profiles, although there are also some similarities. The profiles shown are representative mainly of the different backshore conditions found within the study area. The profiles were surveyed at varying time intervals between February 1988 to June 1990. A more detailed description of the survey method is given in Chapter Four. They are located along the coast as shown in Figure 3.4 and are labelled in accordance to their position from south to north, following the direction of dominant longshore drift. Locations and labelling structure for the profiles are shown in Figure 4.1.

Profile 1 (Figure 3.5a and Figure 3.1) is a steep narrow beach with a horizontal distance of 35 m from the crest to mean sea level and an average slope of 11°. The beach crest has been as high as 7.0 m above mean sea level (AMSL) during the study period. The beach volume above the 0 m contour and seaward of the crest during the study period averaged approximately 106 $m^3.m^{-1}$ of beach. The backshore of Profile 1 is restricted in natural development by the presence of a farm track immediately adjacent to the beach, and by a 25 m wide drainage channel (the Waihao Dead Arm). Vegetation on the backshore is sparse. The backshore and beach crest have been artificially shaped by the South Canterbury Catchment Board in an effort to reconstruct the beach after breaching during a storm in July 1985, and to maintain the Dead Arm flow characteristics. A discussion of the characteristics of this storm and the impact to the study area is presented in Chapter Five, Section 5.2.1. During the study period this section of the coast has suffered some minor overtopping and backshore slumpage/ subsidence. There have also been major changes to the foreshore in response to erosional and accretional episodes. Beach width at the 4.0 m contour varied by nearly 20 m from 1988 to mid 1990, while beach volume varied by 40 $m^3.m^{-1}$ of beach, representing 38% of the average beach volume seaward of the crest.

Profile 3 (Figure 3.5b) is a broader, flatter beach than Profile 1, being 60 m from crest to MSL with a slope of 6°. The backshore slopes at 5.7° (1 in 10) to grass covered farmland and is vegetated by grasses, native sedge (*Carex pumila*) and shore convolvulous (*Calystegia soldanella*) which indicate some stability of the landform. Changes in the foreshore have occurred predominantly below the 5.0 m contour. The volume of the beach has varied by about 30 $m^3.m^{-1}$ of beach over the study period, representing only 16% of the average beach volume seaward of the crest. The beach crest has been stable at 6.5 m AMSL and there has been no overtopping at this site during the study period.
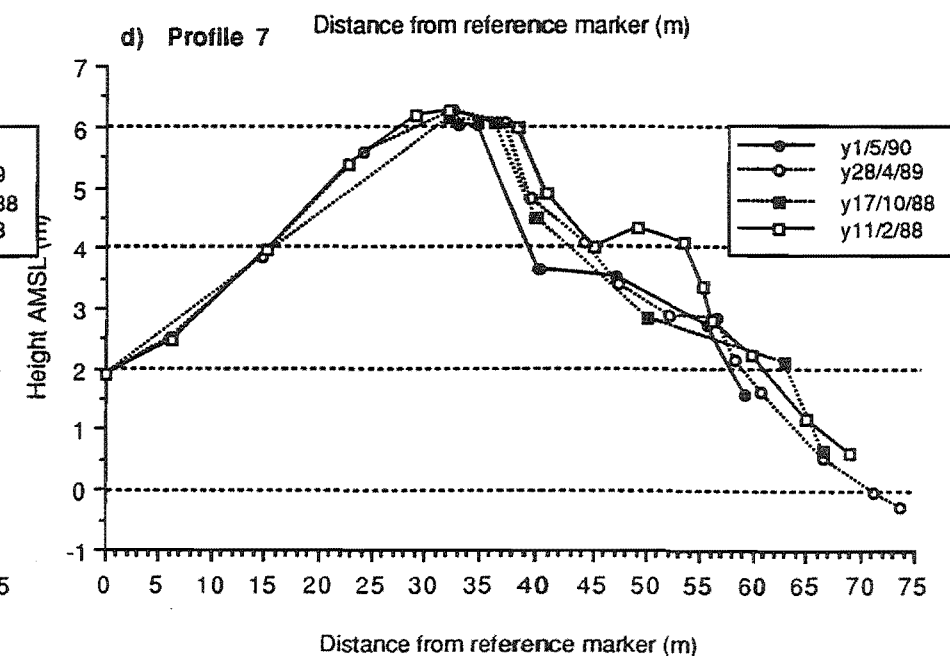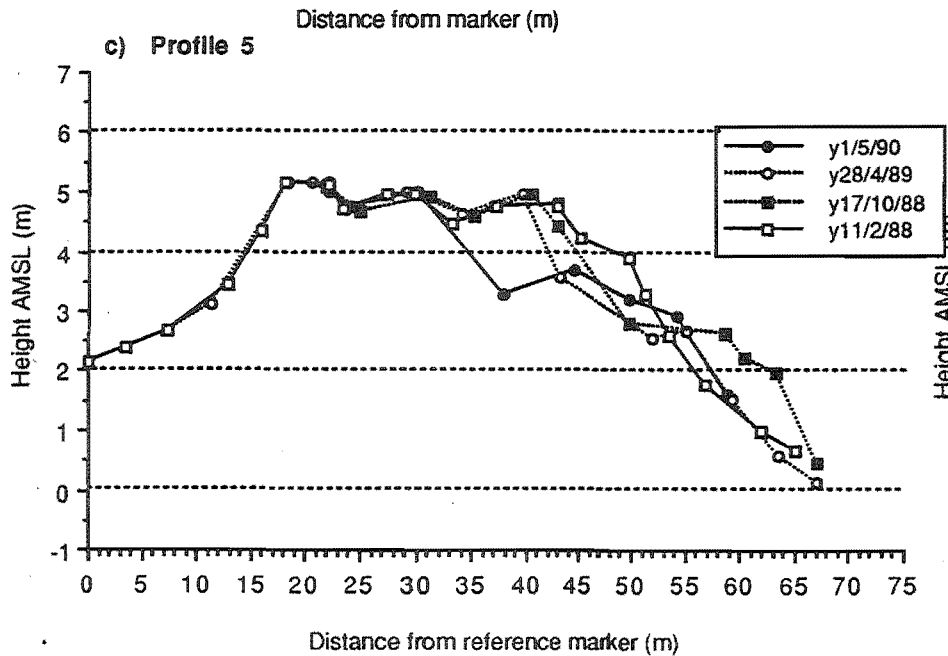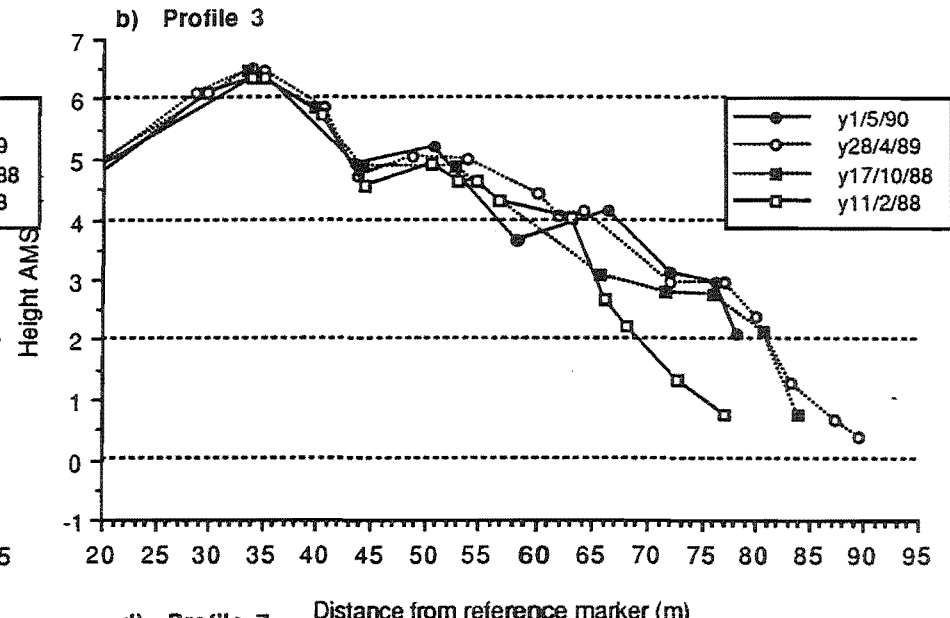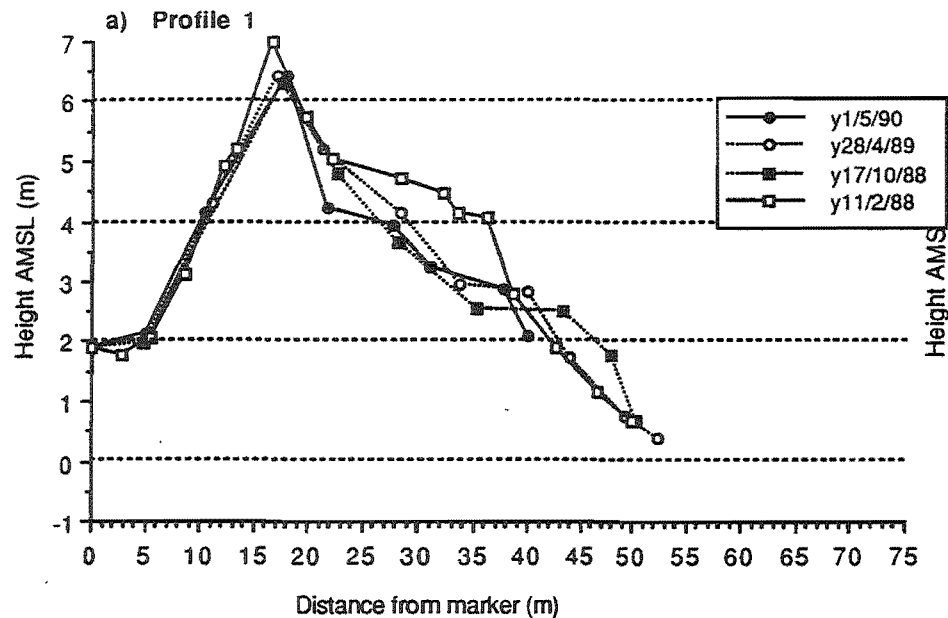
Figure 3.5 Examples of beach profiles from the Wainono Lowland Coast.

Profile 5 (Figure 3.5c) is adjacent to a flood protection stop-bank running perpendicular to the beach at the southern end of Wainono Lagoon. This site was subjected to major overtopping and breaching during the same storm that caused breaching at Profile 1. In response to the storm damage the beach was reconstructed by Mr C. Ruddenklau, the owner of the farmland fronting the beach. Under advice from the South Canterbury Catchment Board and Dr R.M. Kirk, Ruddenklau used a bulldozer to push the overwashed material back onto the beach in an attempt to reconstruct a new beach profile similar to that prior to the breaching. This site also has an access track on the base of the backshore slope, and has an unnaturally steepened concave shaped backslope of 9°. The slope is slightly revegetated by sedges and shore convolvulous. The South Canterbury Acclimatisation Society has also started planting some flaxes and tussocks. There is no single crest to the profile at this site. Instead there is an undulating plateau approximately 15 m wide, sloping seaward from a crest elevation of 5.2 m AMSL to 4.8 m AMSL. Seaward of this plateau, the beach has undergone many changes during the study period. Horizontally the beach has varied by 13 m at the 4.0 m contour. The beach volume has varied by 42 $m^3.m^{-1}$ of beach, which is 28% of the average beach volume seaward of the crest.

The backshore at Profile 7 (Figure 3.5d and Figure 3.1) runs into the edge of Wainono Lagoon. It is heavily vegetated by lupins, broom, sedge and shore convolvulous to within 5 m ground distance of the beach crest. The backslope is 8° (1 in 7) and is steeper than that at Profile 3. An interesting aspect of the foreshore is the presence (and subsequent removal between March and June 1988) of a large intermediate storm berm, cresting at 4.5 m AMSL and with a very steep (22°, 2 in 5) seaward face. The average beach volume seaward of the beach crest over the study period was approximately 119 $m^3.m^{-1}$ of beach. However, this volume varied by 44 $m^3.m^{-1}$ of beach which amounts to 37% of the average volume. The shape of the foreshore slope also varied, from being slightly convex seaward to slightly concave.

Kirk (1967) discussed the concept of subequilibrium in relation to beach profile change. He stated that if a beach was in short term equilibrium - with a small envelope of change - but was retrograding in the long term, then it was in a state of subequilibrium. This seems to be the case for the Wainono Lowland Coast, whereby within a short term - of months or years - the beach in profile undergoes small changes in regard to wave attack but is seldom altered landward of the beach crest. The beach volume fluctuates but there is no large net reduction in volume of sediment. However over a long term - ten years and longer - the beach crest is moving landward at a rate of 0.38 $m.yr^{-1}$ (Kirk 1987a, Table 5, p71). This argument can also be expressed by

examining changes to the shape of the beach as separate from changes in position of the beach in relation to some stable datum (in both the vertical and horizontal planes of reference). Equilibrium of sediment volume and beach shape is maintained while the position of the beach as a total entity moves landward. This is an important concept in regard to the ongoing morphological changes of the beach in response to wave conditions and will be examined further in Chapters Four and Six.

3.5.2 Sediment Characteristics

Kirk and McLean (Kirk 1967; McLean 1970; Kirk and McLean 1969) have noted the complex nature of the sediment characteristics of mixed sand and gravel beaches. Kirk (1967) stated that at any specific site along the Canterbury Bight, the range of sizes found could be as large as the range of sizes for the whole beach. McLean (1970) in studying two Kaikoura beaches found that there was no significantly well-developed zonal arrangement of particle properties across his study beaches, and that examples of both small and large mean sizes, and poor and good sorting were found.

The above conclusions are also evident along and across the Wainono Lowland coast. Figure 3.6a shows the sampling locations and mean grain sizes of surface samples. The selection of sample sites was non-random, so as to obtain representations of different morphological features. Four of the study profiles and one other profile site off Hook Swamp Road (P 10) six kilometres north of the study area were sampled. Position 1 is sited on the backshore seaward of any established vegetation, but approximately 5 m ground distance from the crest. A sample from this position was not analysed from Profile 5 as the site had been extensively modified during beach reconstruction as discussed above, and the surface sediments did not represent deposition or transport by wave processes. Position 2 is situated on or just seaward of the crest. Samples from Position 3 represent the seaward facing slope landward of the most recent active storm berm. Position 4 is situated seaward of the most recent storm berm on the sloping face. Position 5 is representative of the nadir of the interberm depression between the most recent storm berm and the high tide berm. Position 6 is sited approximately 6 m seaward of the high tide berm.

Bagged samples weighing about 2 kg were removed from Position 6. The samples were washed and air dried. Approximately 600 grams of material was split from the sample and dry sieved. Sediment particles larger than 4 mm in diameter were sieved by hand through four screens with the largest mesh size being 9.5 mm. Samples contained a significant portion of sediments greater than 9.5 mm in only one case. 43% of the sample from Position 6, Profile 2 consisted of material larger than 9.5
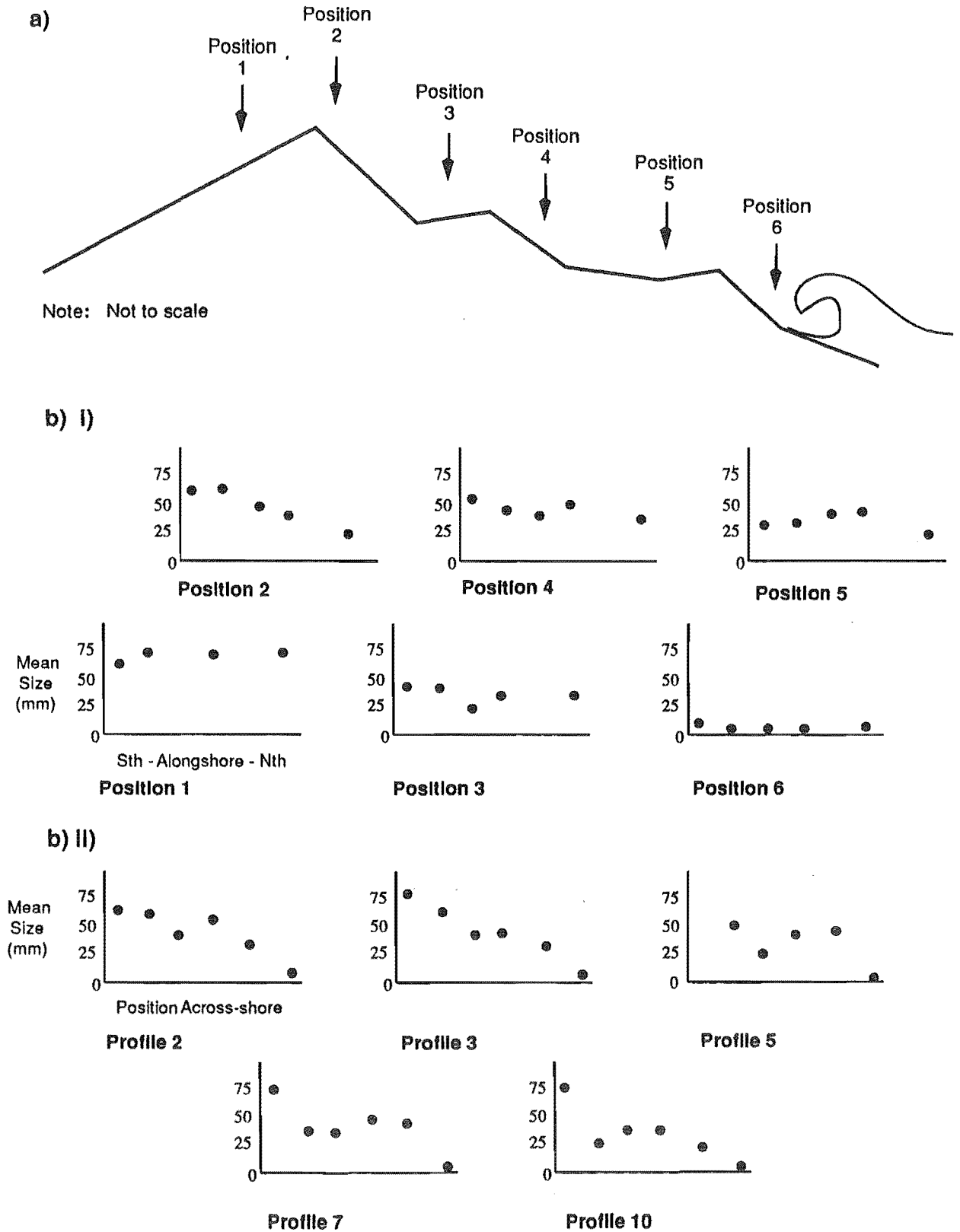
Figure 3.6 Sediment samples from the field area.

a) Sediment sampling positions across the profile.

b) Mean sediment size (b-axis) distributions; i) alongshore by across-shore position. ii) across-shore by profile.

mm, while in all other cases less than 8.5% was above this size. Material less than 4 mm was shaken for twenty minutes in an 'Endrock' shaker through 0.25ø sieve intervals. Apart from Position 6, Profile 7 all samples contained less than 1% of material less than 1mm in diameter. Profile 7 contained 6% less than 1mm in diameter.

Tri-axial measurements were made of surface particles sited at the intersection points of a 100 mm grid covering 1 m² for the samples from Positions 1 to 5. This sampling method tends to favour larger particles. It was used mainly in an attempt to obtain descriptive information of the shapes of sediment particles noting that it is only indicative of the larger material. Particles with a b-axis of less than 2 mm were classified as 'equant or spheroid' (see Figure 3.7a). It is also noted here that at this point in time there is no economically viable or statistically acceptable method of sampling for a descriptive analysis of the large range of sizes - for example b-axis measurements ranging from 0.5 mm (medium sand size) to over 100 mm (cobbles) in 1 m² of beach surface - present on mixed beaches.

From Figure 3.6b it can be seen that there are no obvious patterns of mean sediment size either across shore or alongshore. However, it can be stated that the material is much coarser on the backshore slope than any other position. Hewson (1977) made observations of grain size and sorting characteristics from analysis of samples taken from along the Waitaki coast. His examination of sediment samples from the backshore and wave swash zone of seventeen beach profiles between Oamaru and Timaru Harbour showed the sediments to be texturally submature, reflecting their alluvial origin and injection into the beach system from cliff erosion. He found similarities in sediment patterns to Kirk (1967), with little variation in sediments along the coast but larger flatter particles were deposited in the backshore in comparison to those found on the foreshore. Although the average composition of the samples was 70% gravel and 30% sand, Hewson found that there were a full range of sizes present along this section of coast with mean grain sizes ranging from coarse sand (0.9 mm) to pebbles and cobbles (32 mm). Some large particles were measured in the field as having 'a' axes in excess of 256 mm. He also found that there was a lack of material finer than 0.25 mm in diameter. These size ranges are similar to those found by Kirk (1967) along the beaches of the Canterbury Bight, and by McLean (1970) on Kaikoura beaches. Hewson identified across-shore trends in mean sediment sizes to be more significant than any trends along the coast. His pattern of mean sizes is similar to that shown in Figure 3.6b whereby there is a decrease in mean size from the backshore to the upper foreshore, then a slight increase in mean size seawards to the most recent storm berm, and then a sharp decrease in size towards the nearshore. As

with the samples analysed for this study, Hewson's samples were representative of only the surface layer of sediments and may mask variations in sediment characteristics within the active sediment layer under varying wave processes.

Figure 3.7 and Figure 3.8 present results from a shape analysis of the sample sediments from Positions 1 to 5 in accordance with the Zingg method of shape distinction as outlined in Blatt, Middleton and Murray (1980, p66). The shape categories are presented in Figure 3.7a. It can be seen from Figure 3.7 that the majority of the sediments are disc shaped with bladed, roller and spheroid shapes respectively present to lesser degrees. There is little longshore variation discernible. Separating the samples into across shore groupings as in Figure 3.8 shows more variance between groups and differences in clustering within groups. The samples taken from the backshore show the most similarity and tighter clustering of shape type, while the sediments from Positions 3, 4 and 5 exhibit much more variation in shape. The shape of individual sediment particles will influence the response of the particle to the wave and swash processes acting on it. Therefore any patterns found in shape distribution across or along the beach could represent different processes occurring at different positions on the beach.

With the known difficulties in using size and sorting as descriptive properties of the sediment characteristics of mixed sand and gravel beaches, shape studies may be a more viable method for sediment studies on these beaches. The difficulties of sediment analysis and description of mixed sand and gravel beaches are discussed further in Chapter Six. The ideas introduced here in relation to establishing shape categories as a descriptive tool for investigating mixed sediments are also expanded upon. Zingg shape categorisation of the samples is compared to the shape categories of Sneed and Folk (1958). Variations in the shape of sediments across and along the beach are also discussed in connection with changes in morphology (as represented by changes to the beach profile), in response to wave events of differing magnitudes and frequencies.

3.6   A Sediment Budget for the South Canterbury Coast

Hewson (1977) examined the South Canterbury Coast from Oamaru to Timaru. His thesis aim was to describe the present state of this section of coast in respect to the ongoing processes. Much of his thesis is devoted to a detailed description of the morphology and sediments of this coast, and as such has been included previously in this study. Hewson used Krumbein's 'Process-Response' model (Krumbein 1963) as a conceptual framework for his study, and estimated a coastal sediment budget for this coastal system based on the 'Sediment Budget' model of Bowen and Inman (1966).
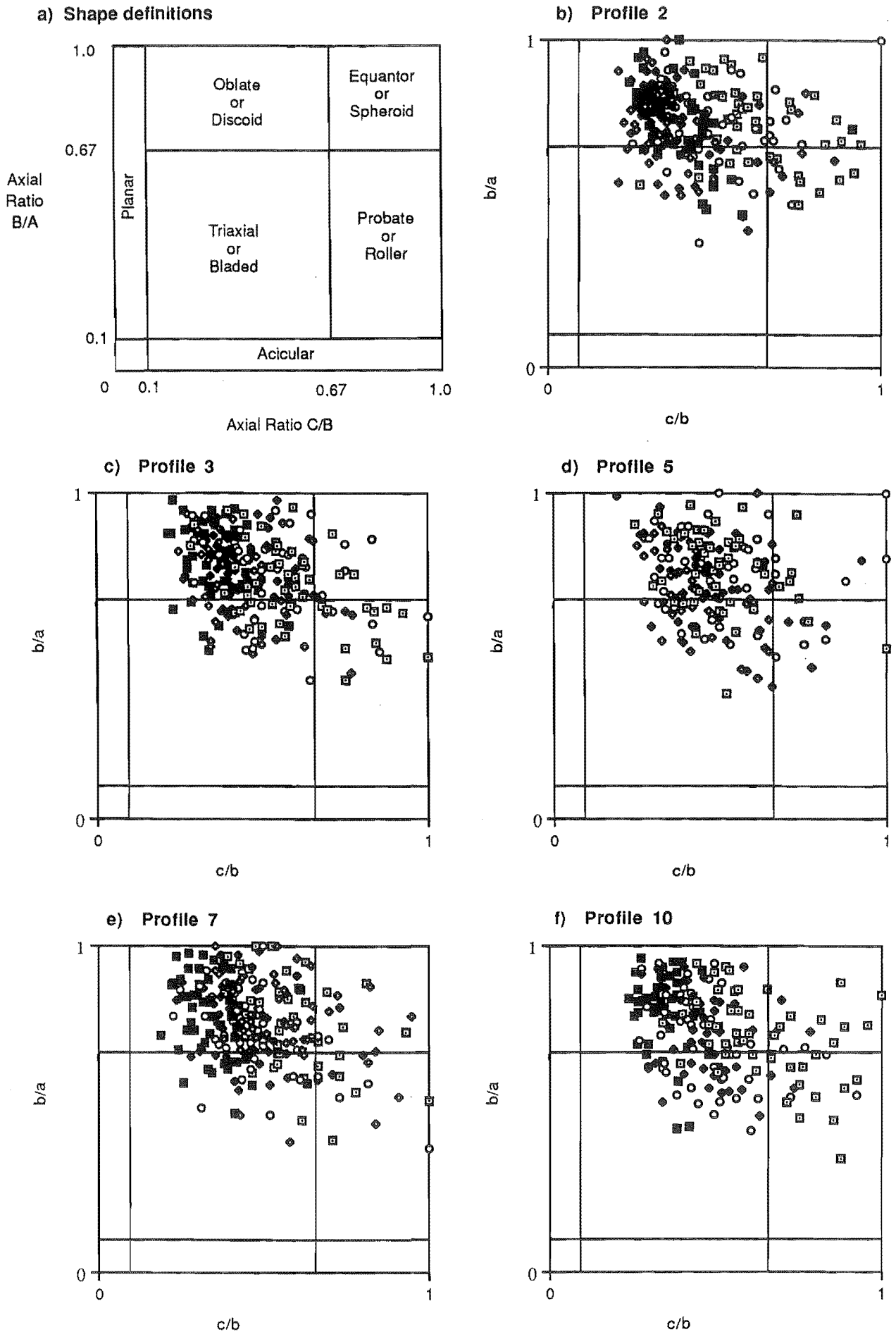
Figure 3.7 Shape analysis of sediment samples according to the Zingg method of classification. Shape analysis plotted by profile.
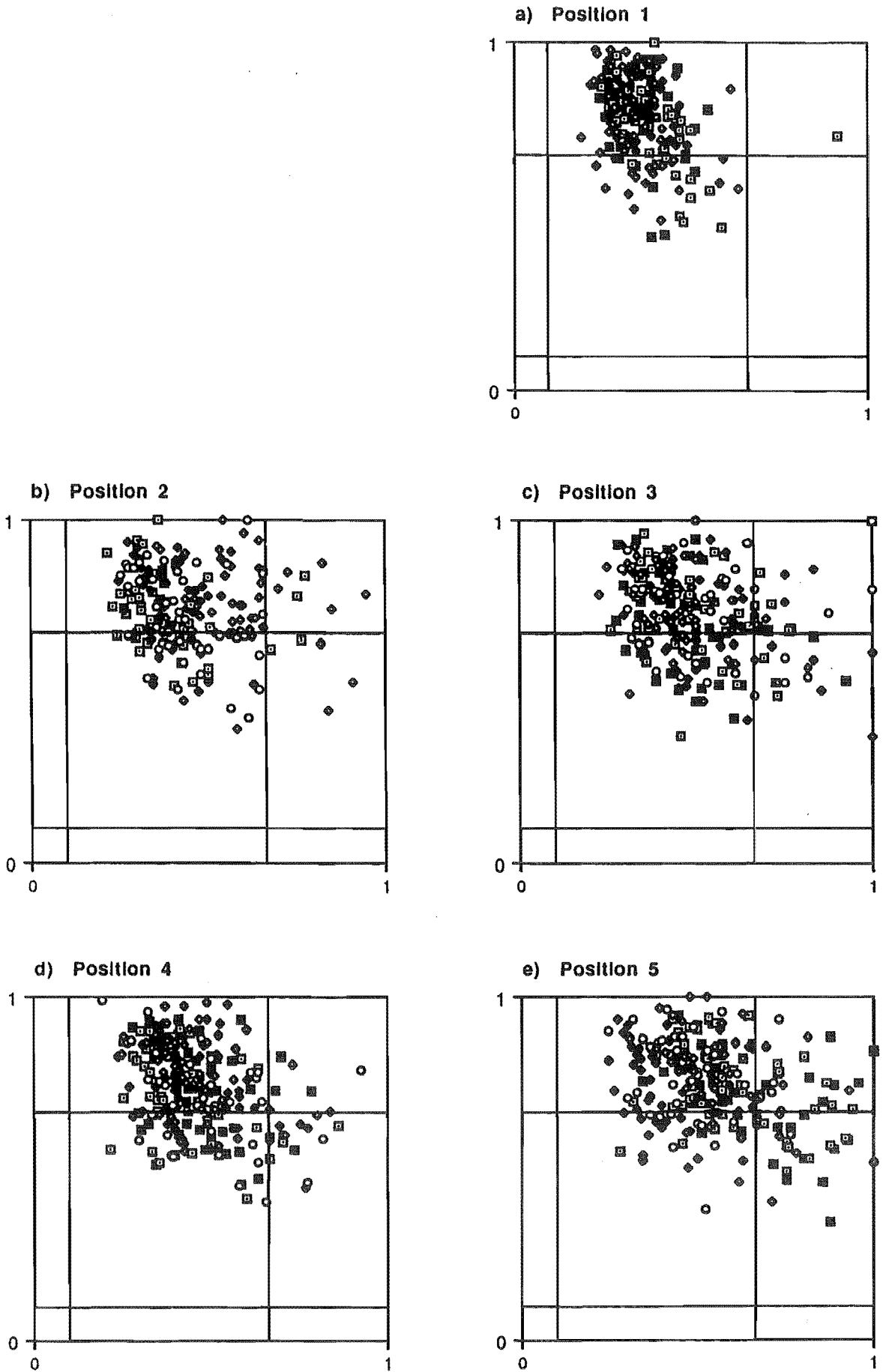
Figure 3.8 Zingg shape distinctions plotted by position of the sample on the profile.

Figure 3.9 is a diagram of a sediment budget for the South Canterbury Coast derived by Kirk and Hewson (1978) expanding from work done by Hewson for his Masterate. Kirk and Hewson gave four purposes for the calculation of this sediment budget. These were to:

   a) Estimate total transfers within the 85 km of shoreline.

   b) Estimate the annual contribution of coarse sediment to the coast
      from the lower river channel below the Waitaki Dam.

   c) Define the annual contribution to the beach sediment budget from
      the eroding cliffs.

   d) Estimate the average annual losses from the system by transport
      offshore, alongshore past Timaru Harbour, by coastal gravel
      extraction and by storage in the Waitaki Dam. (Kirk and Hewson
      1978, p95)

In fulfilling these purposes, the information provided by the sediment budget is useful for this study in that it gives an idea of the state of balance of sediment transfers for the study area. This is important background knowledge as to the sources and destinations of the beach sediments, and adds to the overall picture of the morphological processes.

The calculated budget considers river flow patterns and sediment yields, and contributions to the coastal throughflow of sediments from cliff erosion, shore-normal and alongshore transport. It also includes consideration of human influences to the system in the form of coastal gravel extraction and storage of river sediments upstream of the hydro-electric power schemes commissioned on the Waitaki River since 1935. Longshore transport was estimated by computing the longshore flux of wave power for five refracted wave input conditions and five segments of shoreline chosen from wave refraction analysis as representing different longshore transport regimes. The lateral system boundaries are the headland of Cape Wanbrow around which negligible northward transport of gravel occurs, and the eastern breakwater of Timaru Harbour, where gravel has accumulated and been extracted since the harbour construction in 1878. The landward boundary was taken as the top of the eroding gravel cliffs. The seaward boundary was defined as the surf zone. This reflects a consideration of the sharp discontinuity between the gradually sloping fine sand nearshore bed and the gravel nearshore face, and the two distinct sediment transport systems of these zones.

Hewson (1977) calculated the total beach volume to be 20,977,000 m³, while the total amount of transfers in the system is 3,560,180 m³.yr⁻¹ . Therefore the gross·

Offshore and Northward

past Timaru 37,717

35,000   21,000   Gravel Extraction   6,000

| 5 | 4 | 3 | | 2 | 1 |

Qg = 1,175,566

Qn(5) = 175,720

Qnth = 675,612

Qsth = 499,954

Qg = 1,218,528

Qn(4,5) = 211,550

Qnth = 716,781

Qsth = 501,747

Qg = 234,738

Qn(3,4) = 217,350

Qnth = 225,709

Qsth = 9,029

Qg = 747,648

Qn(2,3) = 217,350

Qnth = 482,353

Qsth = 265,295

Qg = 183,700

Qn(2,1) = 100,383

Qnth = 41,561

Qsth = 142,139

79,296   15,104   137,967   26,279

TIMARU

Waitaki
River

OAMARU

4,750   26,550   Cliff Erosion   11,800

94,400   164,216

59,000

Figure 3.9 Full sediment budget for the South Canterbury Coast. All quantities are in $m^3.yr^{-1}$
(from Kirk and Hewson 1978, Figure 3).
Qg - gross volumetric change, Q(x,y) - net flow from cell x to cell y, Qnth - flow north,
Qsth - flow south.

budget affects 17% of the beach volume on average annually. The total net budget is 922,353 $m^3.yr^1$, 89% moving net northwards from the Waitaki River and 11% south. The contribution from the Waitaki River must be considered as a maximum as no attempt was made to estimate the gains from the other rivers in the area. There is considerable transport of material in both directions which is a result of the variability of wave approach directions. For Cell 3 which contains the main area of observation for this study, the northward drift volume is 25 times greater than movement to the south. Cliff erosion is lowest in this cell as the beaches are mainly backed by low lying land. Estimates of contributions from the Waihao and Makikihi Rivers were not made as they were considered to be negligible in relation to the Waitaki River and to cliff erosion.

Contributions to the sediment budget from the Waitaki River and from cliff erosion are variable from year to year. The input of coarse sediment from the Waitaki River is variable because of natural variations in flood periodicity and magnitude and because of human modifications to the flow regime of the river in the form of storage dams for hydro electric power generation. Construction of the Waitaki Dam (see Figure 1.1) in 1935 effectively stopped any transportation of coarse sediments from the upper Waitaki catchment. Consequently, all the present gravel output must come from erosion of the river bed and river banks in the 60 km of the Lower Waitaki River (Kirk and Hewson 1978). It was estimated that the Waitaki Dam trapped an average of 382,277 $m^3.yr^1$ of sediment between 1935 and 1960, of which 20% - 76,455 $m^3.yr^1$ - was considered to be coarse enough to remain on the beach (Kirk and Hewson 1978, p106). On the assumption that the present contribution of coarse sediment to the beach from the lower Waitaki River was no less than that prior to 1935, Kirk and Hewson calculated that the dam had reduced the amount of sediment available for beach construction by 32%. They concluded that this material might have offset the contribution to the sediment budget of erosion of the coastal cliffs.

Kirk and Hewson also noted that there was evidence that a decline in the mean grain-size and available range within the beach was being reflected in changes to the beach morphology, mainly with the beach becoming wider and lower. They state that this effect is separate from but additional to human induced changes to the sediment budget. They concluded that the rapid erosion of the coast was primarily due to natural causes related to late Quaternary changes in sea level, and the high energy wave environment acting on poorly consolidated fluvial sands and gravels. However, damming of the Waitaki River and gravel extraction have had a marked negative effect on coastal stability which is not yet completely realised.

3.7 Concluding Remarks

This chapter has brought together descriptive information about the South Canterbury coast, particularly the area between Oamaru and Washdyke. The information has ranged from written descriptions from early settlers, to scientific analysis by Canterbury coastal geomorphologists. The purpose of the chapter was twofold, in that the section of coast focussed on in this thesis was located and topographically described, and the contextual setting of the greater South Canterbury coastal process system of which the study area is a part was developed.

To summarize, the study area is a section of the coast south of Timaru, that extends for approximately 4 kilometres from Wainono Lagoon south to a site adjacent to the confluence of Waimate Creek and the Waihao Dead Arm drainage channel. This section is part of the area also known as the Wainono Lowland Coast, and the Southern Lowland Beaches (Kirk 1987a). The beach is a continuous stretch of mixed sediment sizes, ranging from sands (less than 2 mm in diameter) to cobbles (up to 100 mm across the 'b' axis), formed into a narrow barrier with a crest 4 metres above the hinterland, and has been a consistent feature of the landscape for the short human history of the area. The barrier varies in width from 45 metres at the narrowest site, at the southern end of the area, to 100 metres at the widest site, this being in the centre the study area. The barrier crest ranges from 6.5 metres above mean sea level to 5 metres above mean sea level. Foreshore widths vary from 30 metres to 60 metres. Much of the backshore is vegetated but there is evidence of overtopping of the crest by wave run-up and deposition of beach material on the backshore. Two sites were severely damaged during recent storms. These sites have subsequently been reconstructed by the South Canterbury Catchment Board in one case and by the landowner, Mr C Ruddenklau in the other. In the process the sites were modified structurally and reshaped to approximate the natural barrier form.

The foreshore slopes steeply down from the crest to a more level section which makes up the crest or 'backslope' of an intermediate berm. The seaward face of this berm is also steep and can be broken by the presence of smaller low elevation accretionary berms at the limit of low energy swash. Seaward of the swash zone, the nearshore step or wave breakpoint separates the mixed sand and gravel barrier beach from the fine sand, low gradient nearshore seabed. Waves break in a single line and are of a plunging or collapsing type.

The sedimentary characteristics of the study area follow the complex patterns found for other mixed sand and gravel beaches. The range of sizes found at any one

site was as large as the range of sizes found for the whole area. There were no obvious patterns of mean sediment size either across the profile or alongshore. However there is a decrease in mean size from the backshore to the upper foreshore (70 mm to 55 mm), then a slight increase in mean size for the samples near the intermediate berm (up to 45 mm) and a sharp decrease in mean size as the sampling area gets closer to the nearshore zone (approximately 5 mm and less). Surface sediments were found to mask the variations in sediment characteristics of the layers beneath the surface. Discoid and blade shapes dominated the samples and the largest scatter of shape types were found in the swash zone. It was suggested in this chapter that studies of sediment shapes may prove to be a more viable analysis tool than using size and sorting as descriptive properties of the sediment characteristics of a sample site. This concept will be developed further in Chapter Six.

The hinterland is an area of local and national importance (Department of Conservation 1990). Especially significant are the wetlands of Wainono Lagoon as a habitat for many species of flora and fauna. The economic viability of the adjoining farmland is dependent on the maintenance of the barrier beach as protection against the sea. The barrier also protects an intricate drainage network and flood protection works.

Work by Hastie (1983), Kirk (1984; 1987a, with Owens and Kelk 1977, with Hewson 1978) and Neale (1987) has shown that the South Canterbury Coast is dominated by a northerly longshore sediment transport system. There are two parts to the system, the fine offshore sediments and the coarse beach sediments. There is some interaction between the two systems in that material of all sizes is easily transported offshore, but the transport of coarse material from offshore onto the beach is a very slow process. The Wainono area as part of the larger system, reflects changes in the supply of sediments from the south. This includes variations in the output of coarse grained particles from the Waitaki River due to human modification of the flow regime or to flood episodes, and to the injection of material from the Glenavy - Morven cliffs. The passage of sediment slugs as discussed by Neale (1987) will also be reflected in changes to the sediment volume of the study sites as they move through the area. This concept in particular is examined further in Chapter Six, in relation to the position of the study area in the context of the larger coastal system. In Chapter Four, the contribution of the study area to the sediment budget for the South Canterbury coast, as developed by Kirk and Hewson (1978) will be addressed.

The following chapters examine the role of high energy events in determining long and short term morphological adjustments to the beach. The discussion of the study

area in a broad context in this chapter is augmented by a more detailed examination of changes to the form and shape of specific beach profile sites . This incorporates an analysis of short term and medium term changes to the beach and an examination of the impacts of recorded storm events.

CHAPTER FOUR

BEACH RESPONSE TO THE PREVALENT WAVE ENVIRONMENT FROM AN EXAMINATION OF PROFILE CHANGE

4.1 Introduction

Zenkovich (1967) described a beach as a "natural extinguisher of wave energy", and stated that if the beach was sufficiently developed, the land behind the beach would not be destroyed by the sea. Komar (1976) also discussed the protective nature of beaches, and stated that "The beach profile is important in that it can be viewed as an effective natural mechanism which causes waves to break and dissipate their energy. The beach serves as a buffer, protecting sea cliffs and coastal property from the intense wave action." (Komar 1976, p288). Komar also noted that the 'problem' of the beach profile is three-dimensional rather than two-dimensional, in that it not only considers length (or width) and height, but includes some factor that reflects the passage of beach material through a given profile due to alongshore sediment transport.

Kirk defines the beach as a "... three-dimensional body of unconsolidated sediment, resting on some basement, and through which a constant stream of materials is passing." (Kirk and Hewson 1978, p95). This definition assumes that the beach is a dynamic entity which is affected by some as yet unstated processes. In examining the beach purely by changes in shape and position - i.e.: surveyed beach profiles, the oceanographic processes are divorced from the beach response. However, measured changes can be separated to distinguish types of beach response, such as erosion or accretion, and these can then be related back to the processes at work over the time of change. Therefore wave and oceanographic processes are reflected in the changes to the beach morphology. The type and magnitude of change can be characteristic of the magnitude of the processes.

In this chapter the beach profile is used as a descriptive tool to give a rigorous and objective description of a specific site on the beach at a specific time. In essence the plotted, surveyed profile is used to represent the shape and location in space of features of the beach and to display changes over time. A number of surveyed beach profiles in the study area were repeatedly measured during the period from February 1988 to July 1991. These are examined to describe changes to the beach over time. Changes at different elevations are examined with reference to horizontal changes in position of individual contours on the profile using the method of excursion distance

analysis put forward by Winton, Chou, Powell and Crane (1981). Changes in beach volume are also examined in this chapter.

4.2 Methodology

The profile sites used for this study were initially established and surveyed by the (then) South Canterbury Catchment Board (SCCB, now the Canterbury Regional Council) as part of a beach profile monitoring network on the South Canterbury Coast. Bench Marks or datum points and heights for the landward starting point of the beach profiles were surveyed into position by the Coastal Investigations Officer and a survey team from the SCCB. The Bench Marks are identified by either a small stainless steel rod embedded in the centre of a 20 cm by 20 cm concrete pad, or a 2 metre long steel waratah standard hammered approximately 1 metre into the surface of the backshore or farmland landward of the barrier beach. Diagrams used to locate the Bench Marks with the bearings of the profiles (or beach cross sections) are held in the Timaru offices of the Canterbury Regional Council. The profiles used for this study are located on Figure 4.1.

Surveying was carried out using a Sokkisha DT 20E Digital Theodolite and a survey staff graduated to 5 mm intervals. Reduced height data were available for all of the surveyed profiles from the SCCB Bench Marks. The surveyed data were reduced to heights above mean sea level (AMSL) as calculated for the Port of Timaru, and to horizontal distances from the fixed datum points, using an Apple Macintosh computer system. A spreadsheet was created on 'Microsoft Excel' (a data manipulation package) to reduce field data to 'x' (horizontal) and 'y' (vertical) coordinates. In carrying out the profiling, the survey staff was placed at breaks in slope to distinguish morphological features such as berms and interberm backslopes. All profiles run perpendicular to the local shoreline. Due to the dangers involved in surveying seaward of the breaking wave swash, the seaward limit of the profile was determined by the sea conditions, the steepness of the foreshore and the timidity of the staff holder. In most cases this point occurred within the swash zone.

As stated in Chapter Three, the sites chosen for this study are representative of the differing backshore characteristics in the study area. Profile 1 is backed by the Waihao Dead Arm, a drainage channel that runs from the Wainono Lagoon south to the Waihao River mouth. The beach slopes steeply landward of the crest and the landward extent is confined by a farm access track and the drainage channel. The backshore of Profile 2 slopes more gradually back to low lying farmland (approximately 3 metres AMSL) as does that of Profile 3 which is situated 1470 metres to the north of Profile 2.
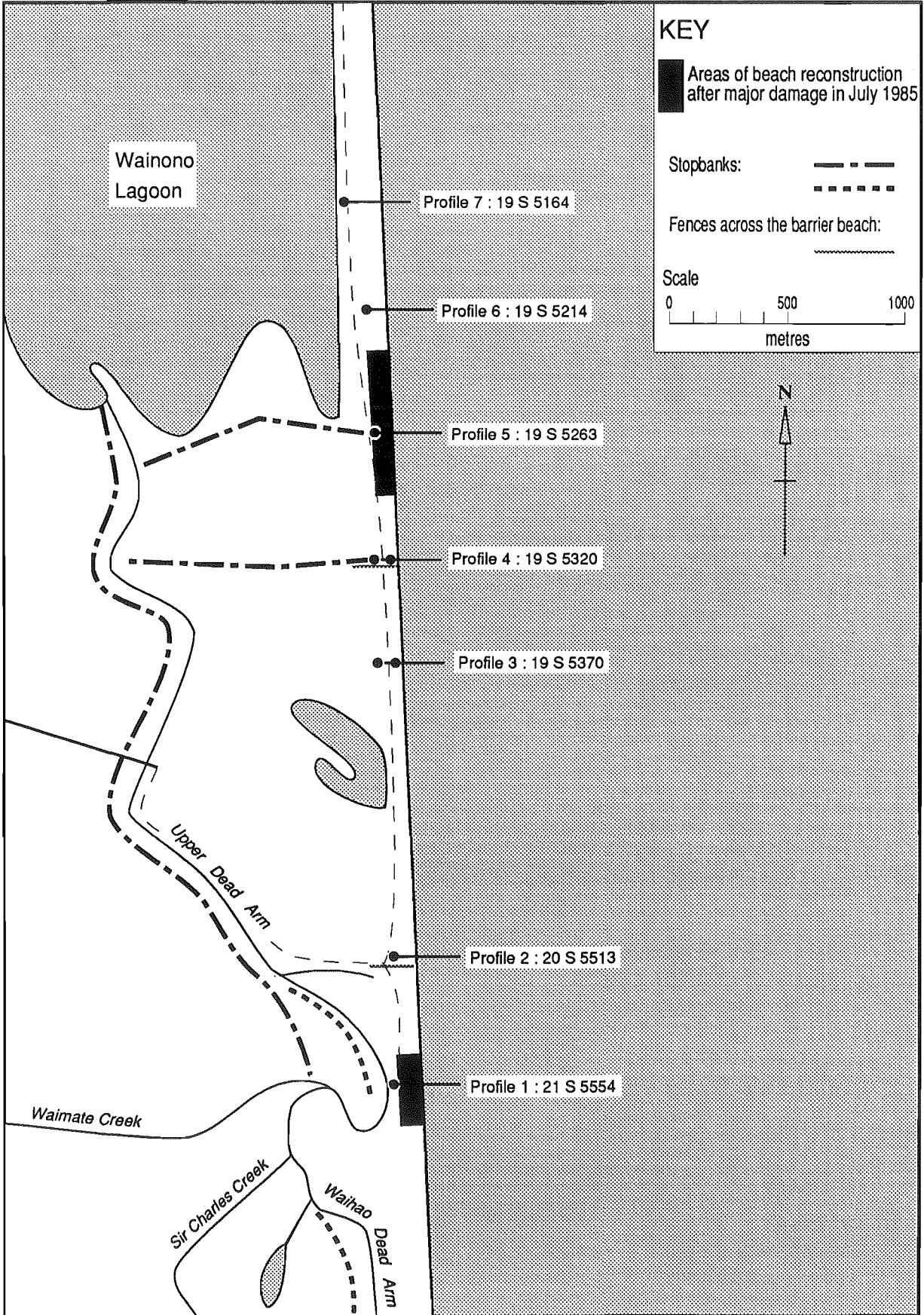
Figure 4.1 Location and labelling of study profile sites.

Both Profile 4 and Profile 5 back onto shore normal stop banks which cause some disruption to the backshore slope. However Profile 5 is at a site of beach reconstruction. This is described further in Chapter Five, Section 5.2.1 in relation to the storm event that caused the damage to this section of beach. Profiles 6 and 7 are both sited between Wainono Lagoon and the sea. The water level in the lagoon is approximately 1 metre AMSL and washover lobes from the beach encroach into the lagoon. All sites except Profile 5 were set up by the SCCB in or about March 1985 as part of its beach monitoring network. Profile 5 was set up after the July 1985 storm as a special investigation site in order to monitor the response of the Ruddenklau beach reconstruction. Profile 1 is also a site of special interest due to the close proximity of the Waihao Dead Arm and the narrowness of the barrier beach.

The labelling of the sites follows two systems. For the purposes of this study the sites have been numbered Profile 1 to Profile 7 following the direction of net longshore sediment transport such that Profile 1 is the most southerly site. This system reflects the interaction between the sites and the importance of the longshore component of wave energy to this section of coast. The SCCB method of labelling is in two parts. The prefix denotes the profile number from the initial monitoring network such that 20S is the twentieth survey site south of Timaru. The second part of the label is the distance along the coast from Timaru in tens of metres, such that 20S 5513 is 55.13 kilometres along the coast from the Timaru Harbour breakwater.

Table 4.1 shows the dates at which the profiles were surveyed. Initially the profiles were to be surveyed at regular intervals of about three months, and also immediately after storm events. The aim of this was that a comparative analysis could be made of changes to the beach morphology due to different storms of known magnitudes. Long term changes would also be examined from the collective data. However the dearth of storm events over the study period made the achievement of this aim infeasible. Wave conditions for the study period were not as predicted at the outset, in that there were fewer storm events than would be expected after an analysis of Table 1.3 (showing the incidence of recorded storms from 1962 to 1986). However the data do record medium term changes to the beach morphology - i.e.: changes that occur over three to six months. The hypothesis here is that these changes reflect the wave conditions between survey dates and that they also reflect the passage of longer term morphological adjustments in response to irregularities in longshore sediment transport.

The reduced survey data were plotted using 'Cricket Graph 1.3' (a graphing package), also using an Apple Macintosh computer system. Due to the complexity of

Surveyor	Date	1	2	3	Profile 4	5	6	7	Days since 1/1/87	
SCCB	17/2/87	-	-	-	-	-	√	√	48	
SCCB	12/8/87	-	-	-	-	-	√	√	224	
MS	2/9/87	√	√	√	√	√	√	-	245	
SCCB	11/2/88	√	√	√	√	√	√	√	407	
MS	7/3/88	√	√	√	√	√	-	√	432	
MS	30/6/88	√	√	√	√	√	√	√	547	
MS	28/7/88	√	√	√	√	√	√	√	575	
SCCB	5/9/88	√	√	√	√	√	√	√	615	
MS	17/10/88	√	√	√	√	√	√	√	656	
MS	24/4/89	√	√	√	√	√	√	√	845	
SCCB	28/4/89	√	√	√	√	√	√	√	849	
SCCB	19/9/89	√	√	√	√	√	√	√	993	
MS	22/2/90	√	√	√	√	√	√	√	1150	
SCCB	1/3/90	√	√	√	√	√	√	√	1157	
MS	16/3/90	√	√	-	-	-	-	-	1172	
MS	1/5/90	√	√	√	√	√	√	√	1217	
MS/SCCB	1/6/90	√	√	√	-	√	-	-	1248	
MS	30/7/91	√	√	√	√	√	√	√	1641	
SCCB	6/3/92	√	√	√	-	-	√	√	1859	*
SCCB	25/5/92	√	√	-	-	-	-	-	1939	*

Note: - Not surveyed, or data not available
       * Surveyed after the field period for this study
   SCCB Surveyed by the South Canterbury Catchment Board (or Canterbury
         Regional Council)
     MS Surveyed by the author

Table 4.1   Profile survey dates.

many of the graphs as the data set increased, interpretation of the information was made from the colour screen image rather than the printed output. The methods used for data reduction and display have proved to be fast and reliable.

4.3 Surveyed Beach Profiles

4.3.1 Description of profile change

The surveying of a number of different beach profiles over a long period of time has resulted in the acquisition of a large amount of data. The usefulness of this data and the ease of analysis is dependant on how the data are displayed. A repeated plot of distance and height data for a profile at different times over the study period as shown in Figures 4.2a to 4.2g results in a complex diagram made confusing by the amount of information present. Figures 4.2a to 4.2g show the collective survey data for each of the study beach profiles.

Although the Wainono Lowland Coast barrier beach is a continuous mixed sand and gravel beach system, the profiles vary markedly. For example, the steep narrow cross-section of Profile 1 is very different from the broad low cross-section of Profile 5.
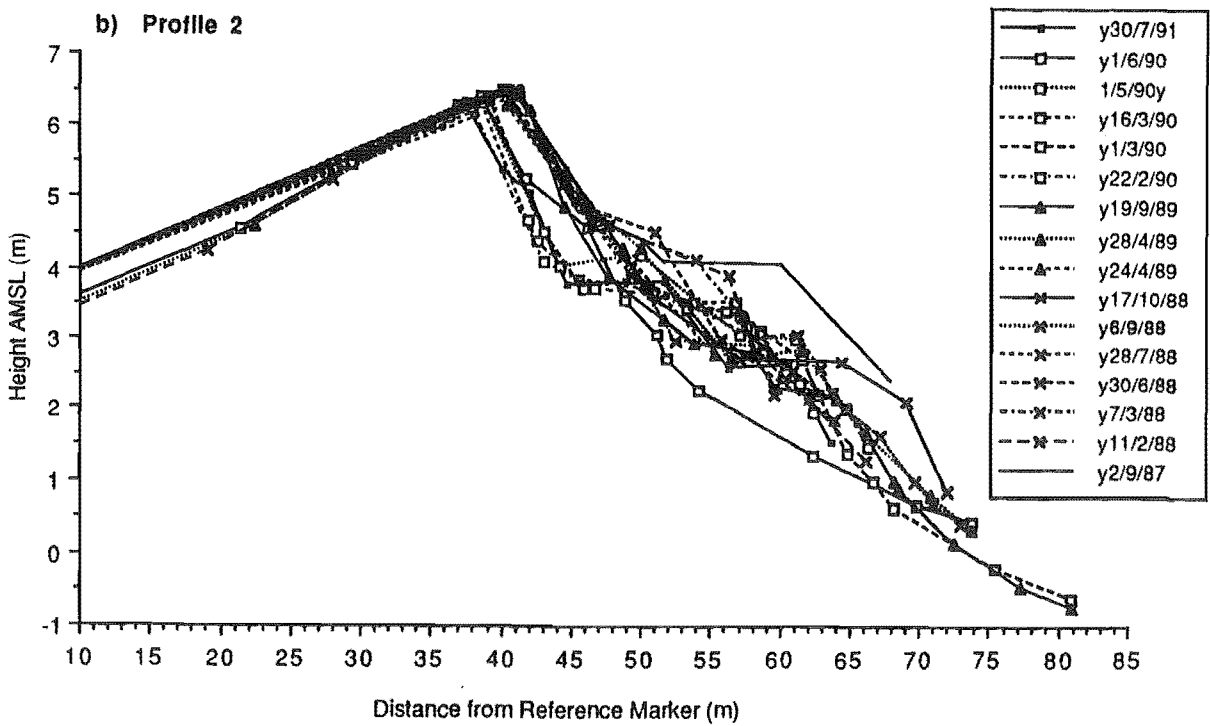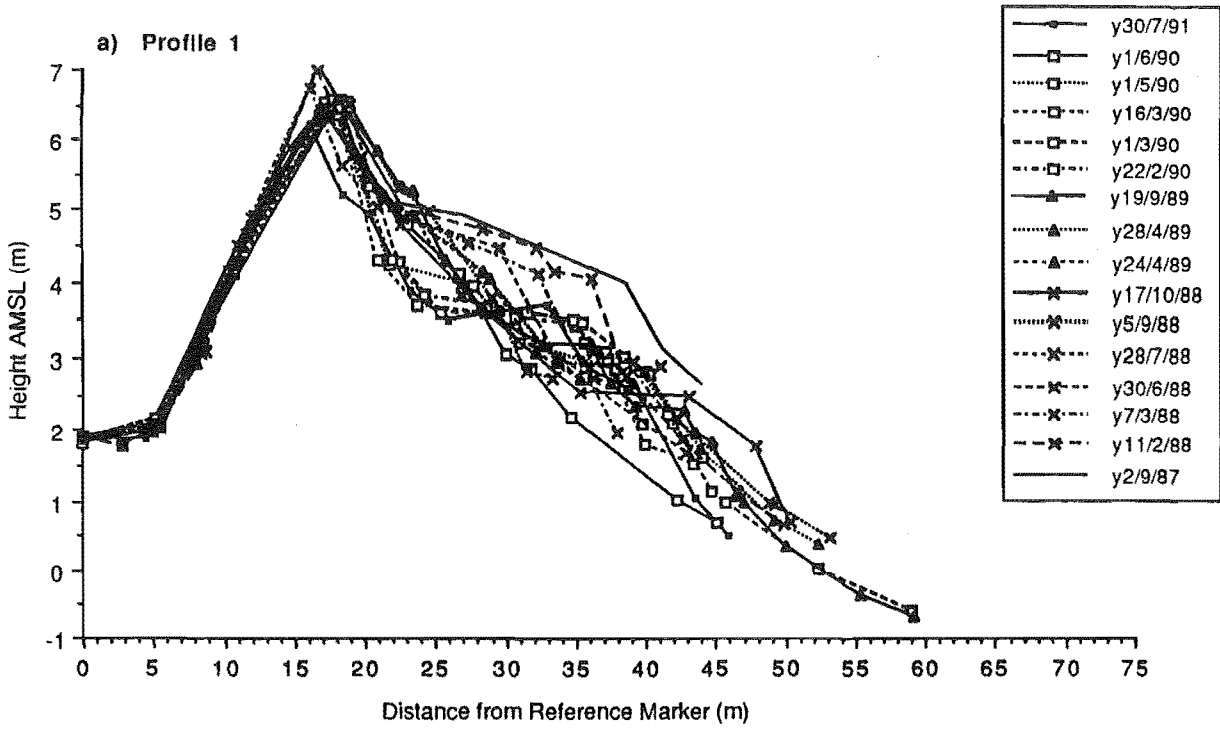
Figure 4.2 Plotted survey data of study profiles.
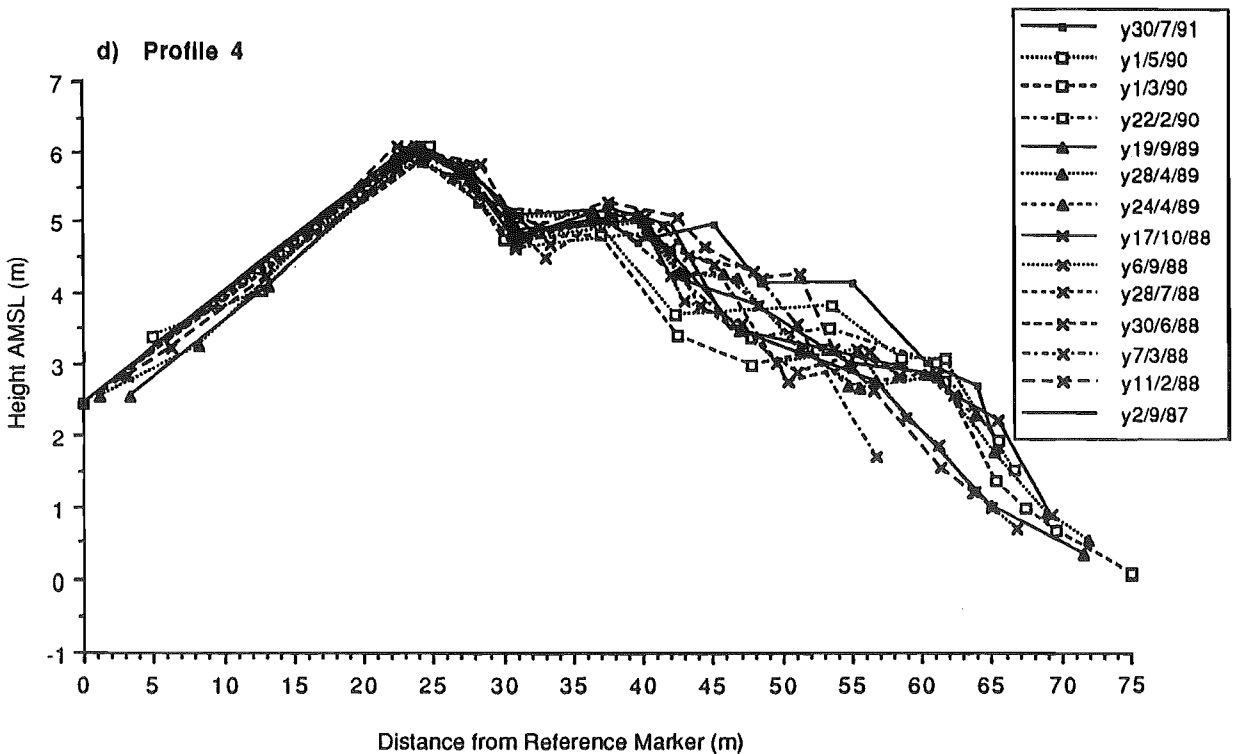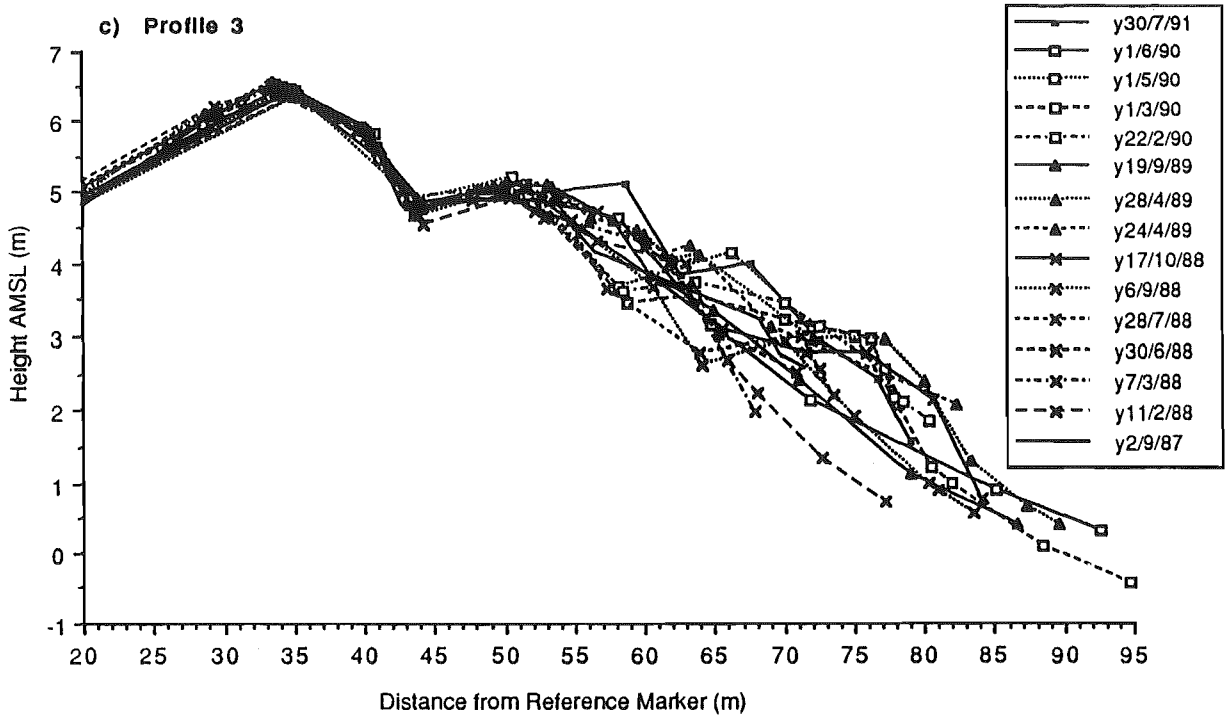
Figure 4.2 Plotted survey data of study profiles.
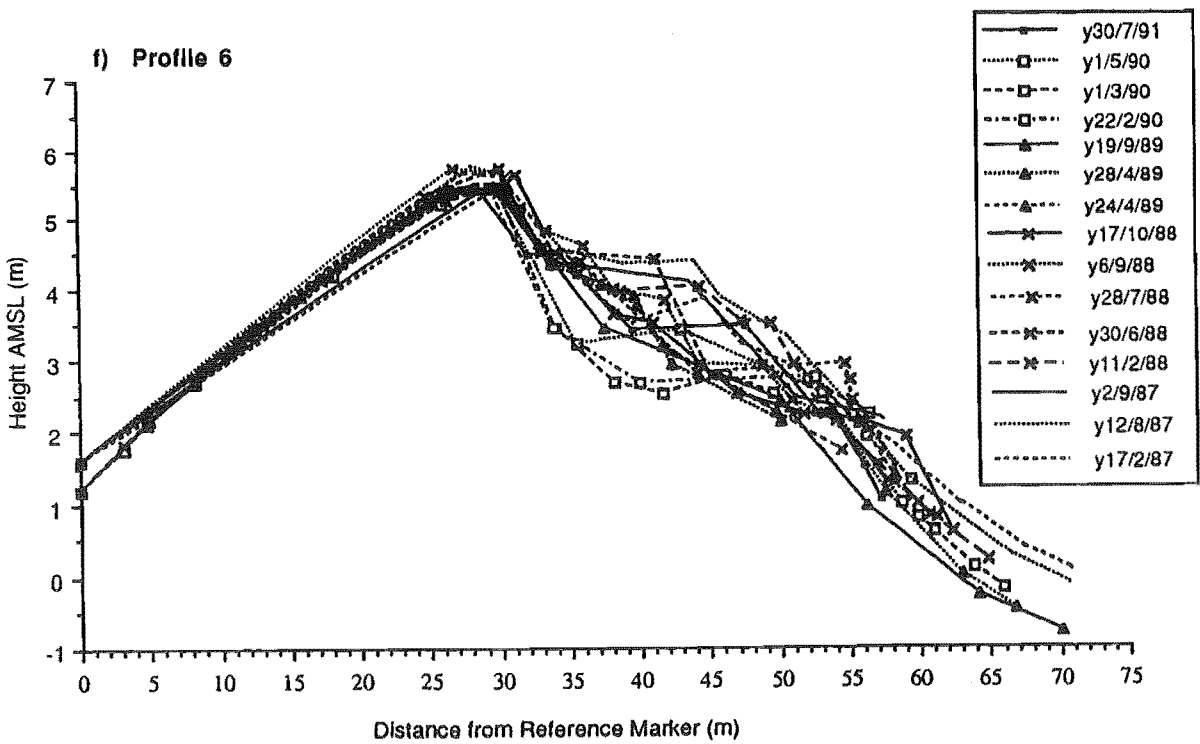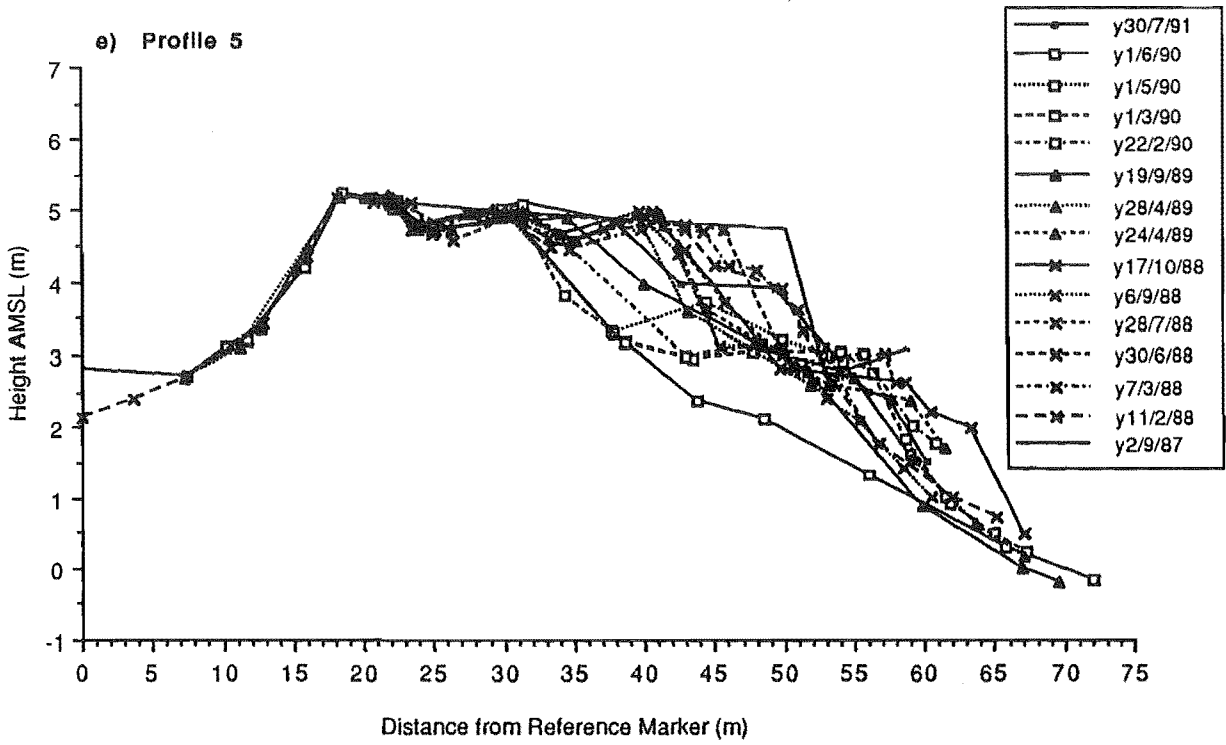
Figure 4.2 Plotted survey data of study profiles.
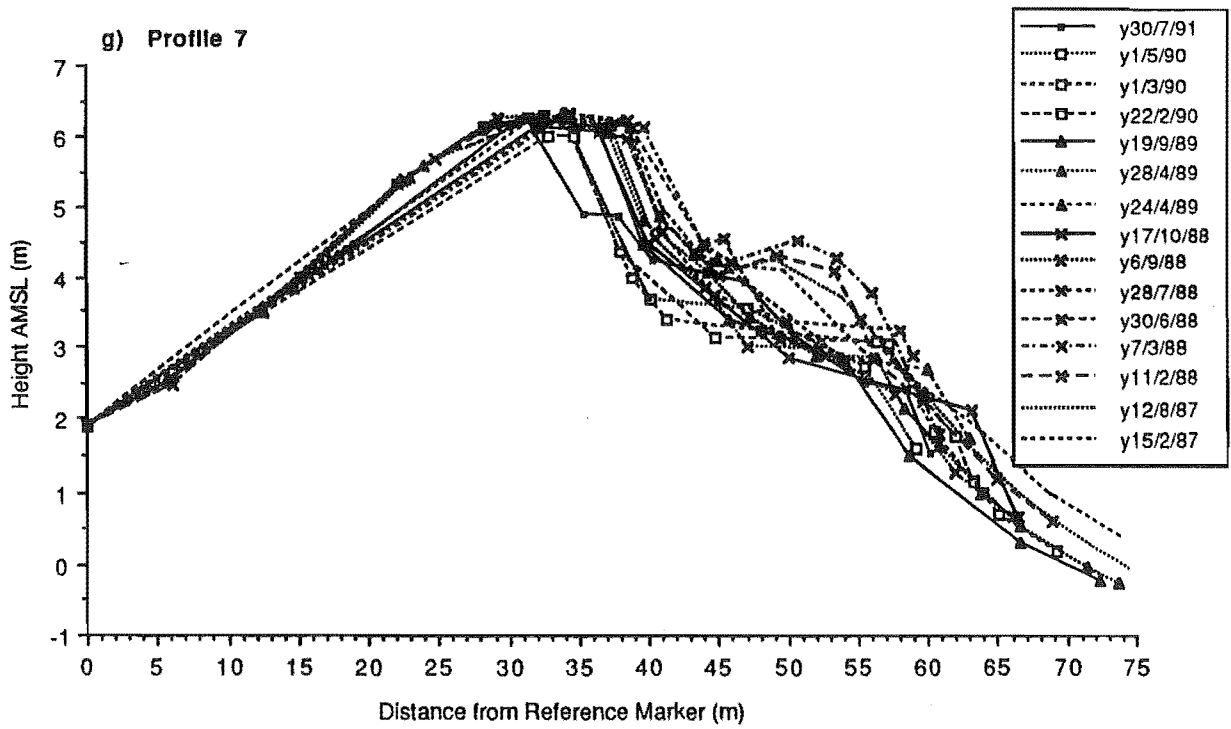
Figure 4.2 Plotted survey data of study profiles.

However both of these profiles exhibit similarities. They were both damaged by storms in 1985, by breaching and overtopping respectively, and were reconstructed as a means of beach restoration. Over the study period both sites have undergone episodes of erosion and accretion across the beach although these episodes did not necessarily occur at the same time for each profile.

The differences in profile change for the different sites can be seen from the plots of the surveyed profiles. Although the method of presentation of the data is complex, basic descriptive statements can be made from these plots. Due to the complexity of the data, two blocks of the profile survey data have been extracted and plotted for four of the study profiles and are shown in Figure 4.3. The upper graphs of each pair of adjustments for a particular profile show the changes through the period from March 1988 to April 1989. The lower graphs show the changes between April 1989 and May 1990.

Intermediate storm berms were present on all of the profiles at most times. These berms are seaward of the barrier crest but above the observed limit of swash for low energy conditions. They indicate the limit of affect to the beach of the last highest active waves, which would obliterate most prior evidence of wave action seaward of this limit. As such they are a relic feature. They are also a depositional feature with a steep seaward face and in some cases a landward sloping 'backshore' with an interberm nadir between the storm berm and the 'unaffected' beach.

Descriptions of the beach adjustments for each of the profiles during the study period follow.

Profile 1 (Figure 4.2a, Figure 4.3a and b)

Profile 1 has been noted as having a very steep backshore and a narrow overall profile from the low lying hinterland (in this case the Waihao Dead Arm drainage channel) to the lower foreshore. The foreshore from the barrier crest to Mean Sea Level is approximately 40 metres wide. There is a wide envelope of changes for the study period. The widest part of the envelope is situated between 0.5 m and 5 m elevation. The greatest horizontal change is 14.5 metres. During the period of observations there was 0.75 m vertical and 2.5 m horizontal erosion of the barrier crest.

At the first survey the barrier crest was 7 m AMSL, and the middle foreshore was convex in shape. This convexity was removed by 30/6/88 and there was erosion of the barrier crest during this period with 0.4 m lowering occurring. There was further erosion of the mid-foreshore by 17/10/88 and accretion to the lower foreshore. A low berm
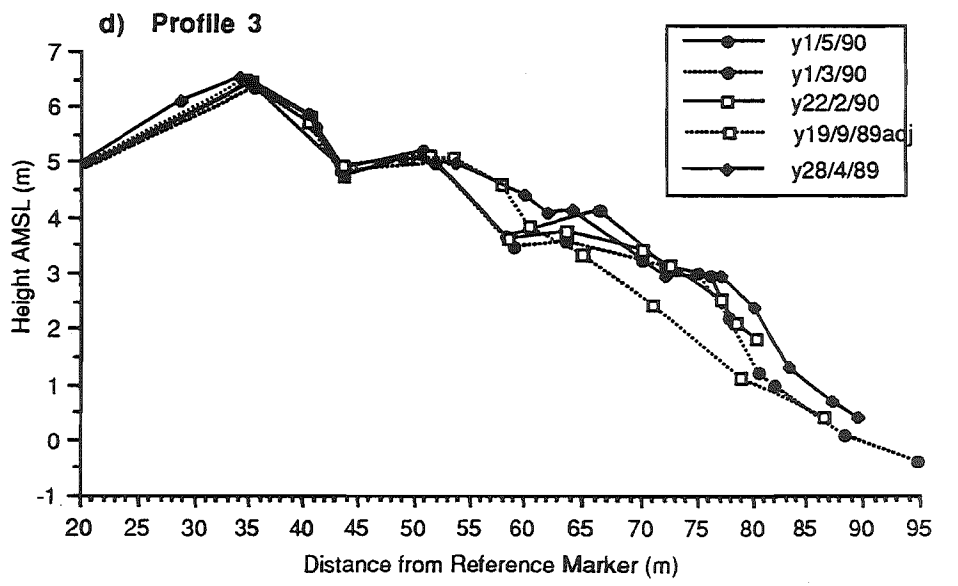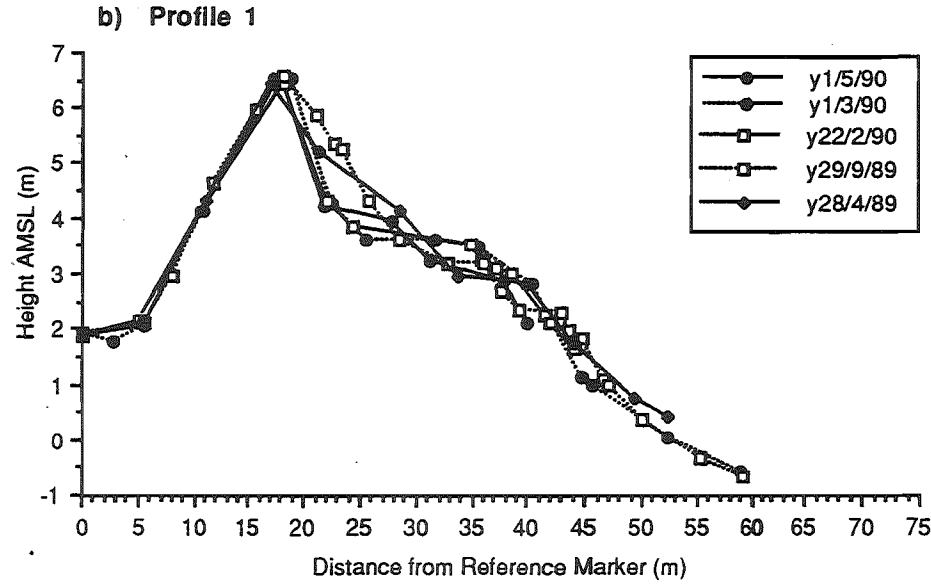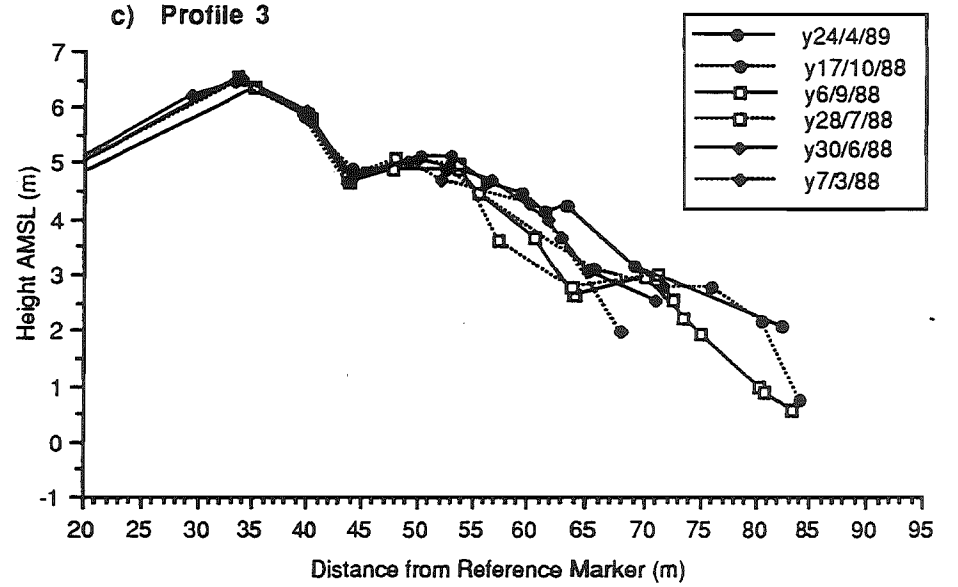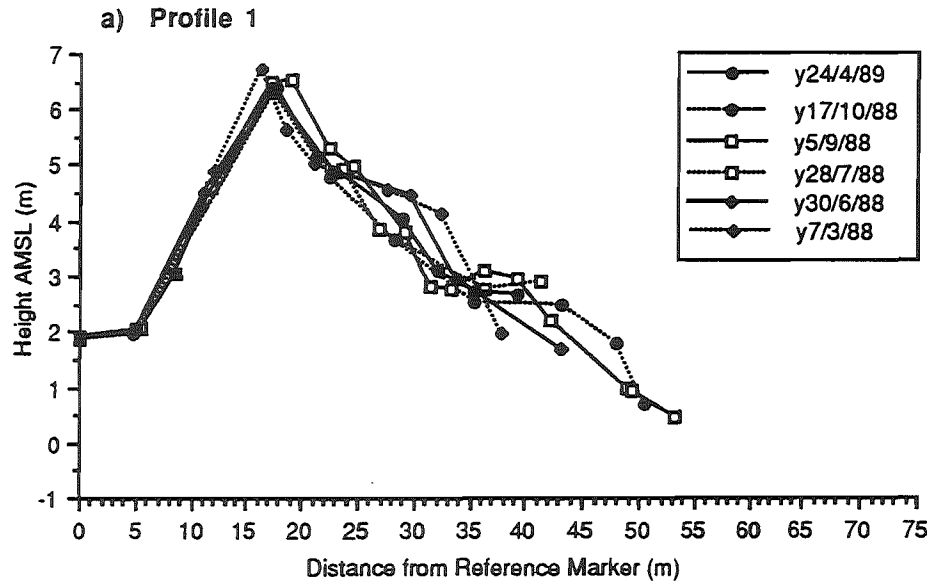
Figure 4.3 Sample of beach profile plots.
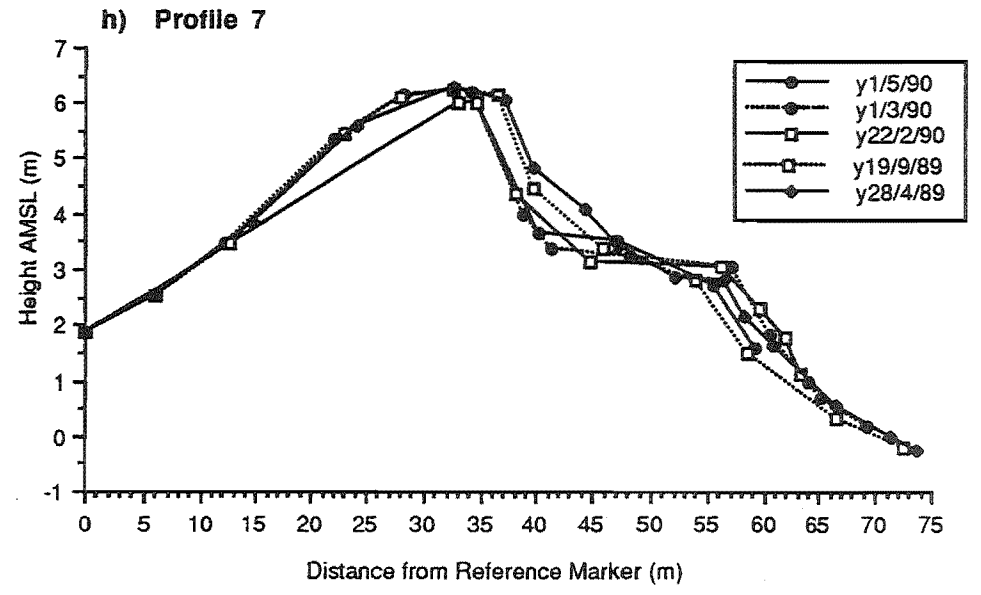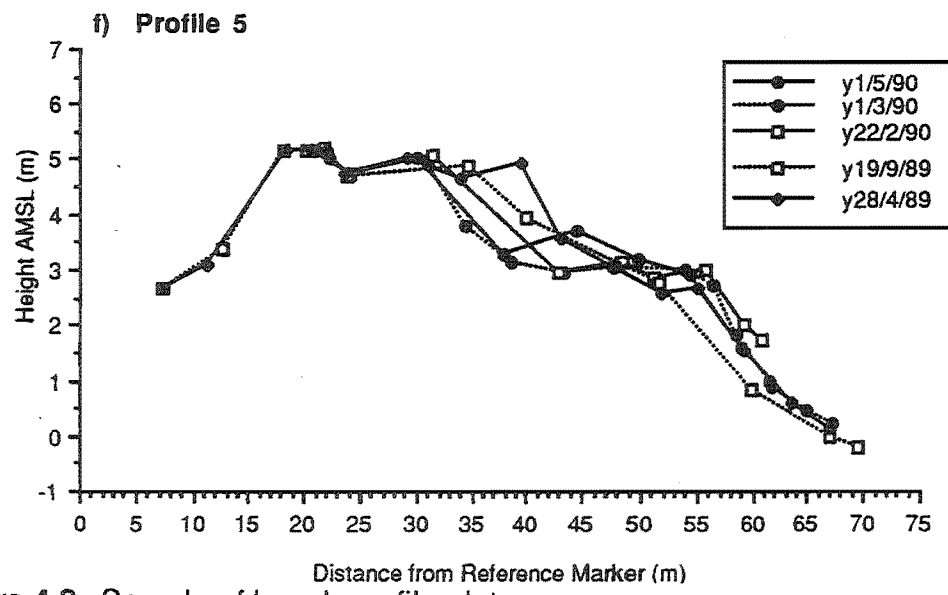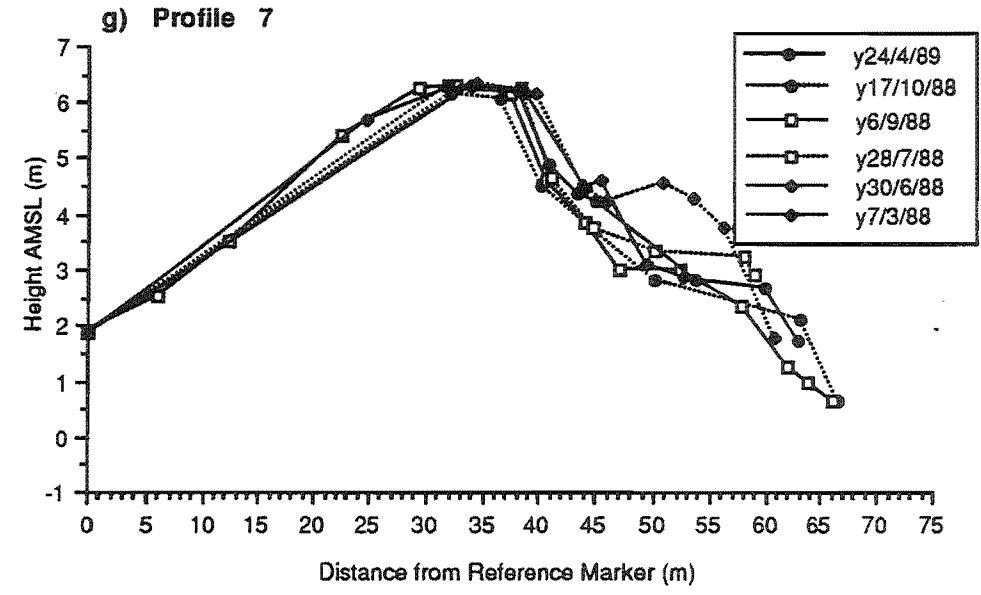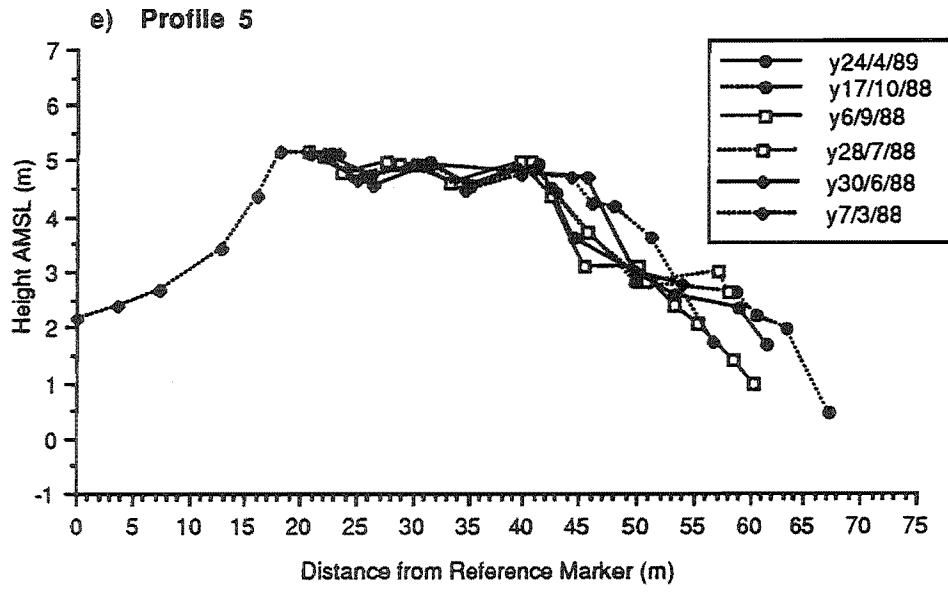
Figure 4.3 Sample of beach profile plots.

formed with a crest at 2.4 m elevation. During 1989 there was accretion of the upper foreshore including accretion on the mid-foreshore increasing the intermediate berm crest to 3.2 m. However there was erosion of the lower foreshore by 19/9/89. Between 19/9/89 and 22/2/90 there was erosion of the upper and mid-foreshore including accretion to the intermediate berm, increasing the crest elevation to 3.6 m. By 1/5/90 accretion to the upper foreshore above 4.2 m AMSL continued, but there was erosion of the intermediate berm and mid-foreshore. Between the 1/5/90 and 1/6/90 a storm event was recorded. This event resulted in accretion to the upper and mid-foreshore but removal of the intermediate berm and lower foreshore. The overall profile shape became more linear, with an unbroken slope from below the barrier crest to the lower foreshore. By the 30/7/91 there was 0.3 m lowering and 2 m retreat of the barrier crest. Erosion of the upper and mid-foreshore was accompanied by accretion to the middle foreshore and rebuilding of an intermediate berm with a crest at 3.7 m elevation. There was a small berm development on the lower foreshore at about 2.5 m elevation.

Profile 2 (Figure 4.2b)

The foreshore of Profile 2 seaward of the crest was slightly narrower than at Profile 1 for most of the study period, being approximately 35 metres in width. During this time there were 5 metres of retreat of the barrier crest and 0.5 m lowering in height from 6.5 m to 6 m AMSL. There was a wide envelope of changes between 1 m and 4 m elevation.

The intermediate berm was removed between 2/9/87 and 11/2/88. During 1988 the erosion of the mid-foreshore continued. By 17/10/88 there was no evidence of an intermediate berm in the middle foreshore but there was accretion in the lower foreshore in the form of development of a berm with a crest at 2.5 m elevation. Further erosion of the upper mid-foreshore and lower foreshore occurred during 1989. Although there was some increase in height of the small intermediate berm at 2.8 m elevation, there was 5 m retreat of the 17/10/88 crest position. Erosion of the barrier crest occurred by 22/2/90 with 3 m retreat and 0.3 m lowering occurring. During this period there was accretion to the mid-foreshore. By 1/5/90 there had been some building of an intermediate berm with a crest at 4 m elevation. However by 1/6/90 there had been erosion of the mid-foreshore but accretion on both the lower and upper foreshores. The period between 1/6/90 and 30/7/91 resulted in 0.3 m lowering and 2.5 m retreat of the barrier crest and erosion of the upper foreshore. However there was accretion in the middle and lower foreshore with the development of an intermediate berm cresting at 3.7 m elevation. Similar to Profile 1, there was some development of a small berm on the lower foreshore with a crest at 2.5 m AMSL.

Profile 3 (Figure 4.2c, Figure 4.3c and d)

Profile 3 has the widest foreshore of the study sites being 55 m in width seaward of the crest, the backshore also slopes gradually for 35 m to the adjacent farmland. The envelope of changes is contained below 5 m in elevation. A major feature of the beach adjustments during the study period was the lack of change to the barrier crest (at 6.5 m AMSL). A large intermediate berm cresting at 5 m AMSL with a well formed interberm nadir acted as a buffer to wave attack on the barrier crest. At times there were also two other intermediate berms seaward of this position.

Between 2/9/87 and 11/2/88 there was erosion of the lower foreshore. By 30/6/88 erosion of the mid-foreshore and accretion on the lower foreshore had resulted in an intermediate berm with a crest at 3.3 m elevation. There was progradation of the lower foreshore and erosion of the mid-foreshore by 17/10/88. Between 17/10/88 and 28/4/89, there was accretion on the middle and lower foreshore with two berms with crests at 3.4 m and 4.3 m developing. By 19/9/89 there was erosion right across the foreshore with removal of the intermediate berms up to 4.7 m elevation. Erosion of the upper and mid-foreshore continued between 19/9/89 and 22/2/90 but there was accretion on the lower foreshore which resulted in the building of an intermediate berm, cresting at 3.2 m, by 1/3/90. By 1/5/90 the crest of the intermediate berm had risen to 4.3 m, but with the storm between 1/5/90 and 1/6/90, the intermediate berms had been removed. However during this period there was accretion to the lower foreshore and accretion to the upper foreshore to 5 m elevation. By 30/7/91 there was further accretion to the upper foreshore, with 5 m progradation of the secondary berm crest at 5.2 m elevation and building of an intermediate berm to 4 m elevation and steepening of the lower foreshore.

Profile 4 (Figure 4.2d)

Profile 4 also has a wide foreshore (45 m width seaward of the crest) and showed very little change to the barrier crest. As with Profile 3, there was an intermediate berm with a crest height of 5 m AMSL acting as a buffer against erosion of the barrier crest. The horizontal width of the envelope of beach adjustments during the study period is widest (approximately 17 m) at about 4 m in elevation.

Between 2/9/87 and 7/3/88, there was accretion to the mid-foreshore and erosion of the lower foreshore. By 30/6/88, erosion of middle and lower foreshore had continued and there was erosion of the secondary berm crest seaward of the barrier berm. There was a small amount of accretion to the middle foreshore and a large

amount of accretion to the lower foreshore by 17/10/88. By 19/9/89, the material in the lower foreshore had been removed. Retreat and lowering of the secondary berm occurred between 22/2/90 and 1/3/90. There was also erosion of the mid-foreshore and intermediate berm about 3.2 m AMSL. By the 1/5/90 there had been accretion to the mid-foreshore and the intermediate berm had been rebuilt to 3.8 m. There was also a small amount of accretion to the lower foreshore. A survey was not carried out on 1/6/90, so the storm induced changes were not recorded. By 30/7/91, the upper and mid-foreshore had prograded to 5 m. The intermediate berm had increased in elevation to 4.2 m, and the lower foreshore had steepened. As with Profiles 1 and 2, there was some development of a berm on the lower foreshore at about 2.7 m AMSL.

Profile 5 (Figure 4.2e, Figure 4.3e and f)

Profile 5 is different to the other profiles in that it was reconstructed after major lowering of the barrier during a storm in July 1985. Overwashed material deposited in the backshore was bulldozed seaward of the reconstructed crest, and the foreshore was shaped to a more typical mixed sand and gravel barrier beach form. The result of this reconstruction was a 20 m wide plateau containing three shore parallel berms with crests about 5 m AMSL. The foreshore seaward of the most landward crest was approximately 50 m in width. Changes to the profile occurred seaward of the secondary crest. This reduces the width of the active foreshore to about 40 m. At the beginning of the study period (2/9/87) there was a tertiary berm with a crest about 4.5 m AMSL, 25 m seaward of the backshore. The seaward face of the upper foreshore was extremely steep (about 45°) with a lower berm seaward of this face. The gradient of the beach had lowered and the form of the foreshore had become more like the other profiles by 11/2/88. The eventual removal of the tertiary berm resulted in a very wide envelope of beach adjustment, especially in the upper foreshore where the horizontal change at 4 m elevation was 20 metres.

By 11/2/88 there had been 5 m retreat of the tertiary berm crest. A further 3 m retreat occurred between 11/2/88 and 24/4/89. The removal of material from the upper foreshore was matched by accretion in the lower foreshore. By 19/9/89, there was a further 7 m of retreat of the upper foreshore, with erosion right across the foreshore, including removal of the lower berm at about 2.5 m elevation. Between 19/9/89 and 22/2/90 there was 3 m retreat of the upper foreshore but there was rebuilding of the lower intermediate berm and accretion on the lower foreshore. Erosion and steepening of the upper foreshore occurred by 1/3/90. Between 1/3/90 and 1/5/90 an intermediate berm was formed, cresting at 3.5 m. The storm between 1/5/90 and 1/6/90 resulted in

removal of material from the middle and lower foreshore. However by 30/7/91 there had been 14 metres of progradation at 4 m elevation and steepening of the lower foreshore. A small berm had also developed at 2.5 m AMSL.

Profile 6 (Figure 4.2f)

The barrier crest of Profile 6 experienced some erosion during the study period. The height of the crest lowered from 5.8 to 5.3 metres, and there was approximately 4 metres of retreat. The foreshore extended 35 m seaward of the crest. There was also a large envelope of change, especially in the upper foreshore. Unlike the previous profiles discussed, survey data for this profile and Profile 7 was available for February and September of 1987. The lower foreshore at these times extended well seaward of the other survey dates, and resulted in a wide envelope of beach adjustment for this region of the beach.

By 30/6/88, the intermediate berm at 4.5 m elevation had been removed. Between 6/9/88 and 17/10/88 there was lowering of the barrier crest and progradation of the lower foreshore berm. During 1989 there was accretion in the upper foreshore and erosion of the lower foreshore. In 1990 there was erosion of the upper foreshore and accretion on the middle and lower foreshore. By 1/5/90 there had been rebuilding of an intermediate berm at about 3.5 m elevation. The net change by 30/7/91 included 2 m retreat of the barrier crest and accretion in the upper foreshore. There was a slight increase in the height of the intermediate berm, and this was accompanied by 5 metres progradation of the berm. The lower foreshore steepened and there was development of a small berm at 2.5 m elevation.

Profile 7 (Figure 4.2g, Figure 4.3g and h)

The height of the barrier crest remained constant during the study period at just over 6 m AMSL. However there was 8 metres of horizontal retreat of the seaward face of the crest. There was a large intermediate berm in early surveys with a crest at 4.5 m AMSL and a well defined interberm nadir. The removal of this berm during the study contributed to the wide envelope of beach adjustment. Retreat of the lower foreshore was similar to that on Profile 6 between 15/2/87 and 2/9/87.

By 30/6/88 the intermediate berm had been removed and there had been erosion of the barrier crest. Between 30/6/88 and 17/10/88 there was erosion of the mid-foreshore. However there was progradation of the lower foreshore at about 2 m AMSL. During 1989 there was deposition of material in the upper and mid-foreshore, and

erosion of the lower foreshore. The overall gradient of the foreshore steepened with the removal of the low gradient section of foreshore between 2.5 m and 2 m AMSL. Between 19/9/89 and 22/2/90 there was a build up of a lower foreshore berm. By 1/5/90 there was erosion of the middle and lower foreshore and deposition on the upper and mid-foreshore. The net change to the foreshore by 30/7/91 included 3.5 metres retreat of the barrier crest and deposition across the rest of the foreshore.

Variation in profile adjustment (Figure 4.4)

Figure 4.4 shows the detail of variations in the magnitude and form of beach adjustment for the different profiles over one time interval between surveys. On Profile 1 there was lowering of the barrier crest and deposition just seaward of this point. There was erosion below the intermediate berm or convexity in the profile and deposition in the lower foreshore. There was less change to the shape of the profile on Profile 2. However there was erosion of the middle foreshore, and accretion of the upper mid-foreshore with steepening of the lower mid-foreshore. There was also accretion in the lower foreshore. There was a small amount of accretion to the upper foreshore of Profile 3, with accretion on the intermediate berm and on the lower foreshore. The was a large amount of erosion of the middle foreshores of Profiles 6 and 7. On Profile 6 there was also a small amount of erosion of the upper foreshore. Conversely, there was accretion to the upper foreshore on Profile 7. There is also a possibility that there was accretion on the lower foreshore, seaward of the limit of the profile survey.

4.3.2 Discussion

The broad patterns of profile change during the study period and a more detailed examination of changes at each site have been presented above. It has been noted that this method of display becomes increasingly complex as more survey data is added. A more detailed discussion of the beach adjustments in the field area during the study follows with a description of changes at different elevations on the beach, and to the volume of sediment on the beach foreshore.

The changes to the beach profile reflect some information about the oceanographic characteristics of the events which caused them. With reference to Figure 4.4, it appears that for the majority of the profiles the limit of wave run-up was approximately 5 metres AMSL. During the interval between 1/6/90 and 30/7/91 there was an almost uniform development of a small accretionary berm at approximately 2.5 m elevation, indicating a period of low energy waves just before the survey date.
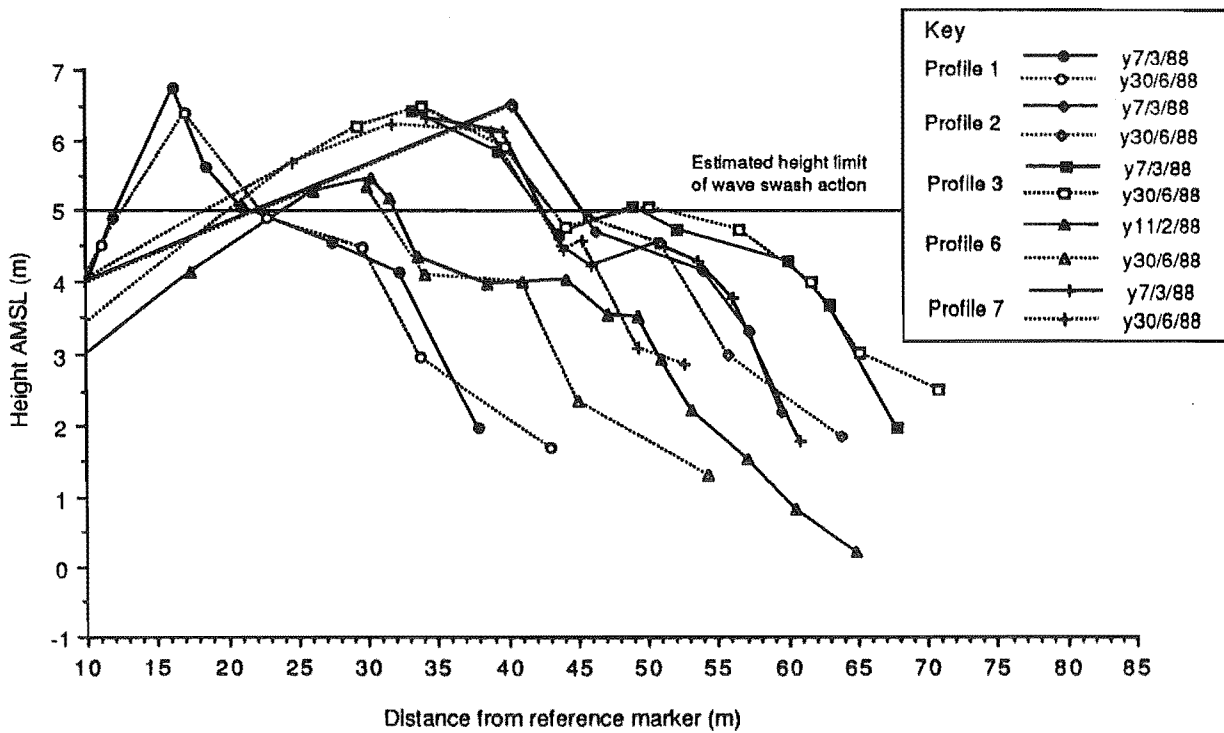
Figure 4.4 Variations in beach profile adjustment between 7/3/88 and 30/6/88.

The interpretation of the changes to the beach profiles has so far been descriptive in character. Surveyed and plotted profiles can also be used to obtain quantitative information such as the distance in metres of retreat or progradation, or the volumes of beach sediment change due to changes in the shape of the adjusting profile. The following sections extend the analysis of the profile adjustments by manipulation of the survey data.

4.4 Excursion Distance Analysis

4.4.1 Methodology

The survey plots of Figure 4.2 are a complex means of displaying a large amount of information. Winton, Chou, Powell and Crane (1981) described an analysis technique for examining the changes on a profile over time. The basis of the analysis is the excursion distance of a point on the beach, whereby the "...horizontal displacement of the planform position of any one point on the beach from one survey to another, is the excursion distance for that point for the survey period." (Winton et.al. 1981, p25). Kirk (1984, 1987a) explained the application and merits of this technique for describing and analysing profile data from the Washdyke beach renourishment experiment. The technique is referred to as "Excursion Distance Analysis" or EDA. Basically it is a diagrammatic technique where the horizontal distances from an arbitrary baseline landward of the beach to individual beach contours are measured for each survey and plotted as functions of time.

Comparing the excursion distance analysis between different profiles can give misleading information about similarities or disparities in the behaviour of the profiles over time. For this reason the EDA data can be manipulated to give more meaningful comparisons. The first manipulation carried out on the Wainono profiles was to standardise the basic excursion measurements of each profile to some common reference point. In this case the barrier crest as of 24/4/89 was used as a common landward limit of beach adjustment. The resulting Standardised Excursion Distance plots (SEDA) for each profile are different to the EDA plots in that distances on the 'y-axis' can be directly compared between profiles to give the width of the beach seaward from the crest for any contour height. This information can also be used to calculate the volume of the beach AMSL and seaward of the crest for any survey time.

The examples of SEDA plots for the study profiles are given in Figure 4.5. The profiles were compared for changes or patterns of changes over the study period. The contours displayed in Figure 4.5 are at 0.5 metre intervals above the survey datum of
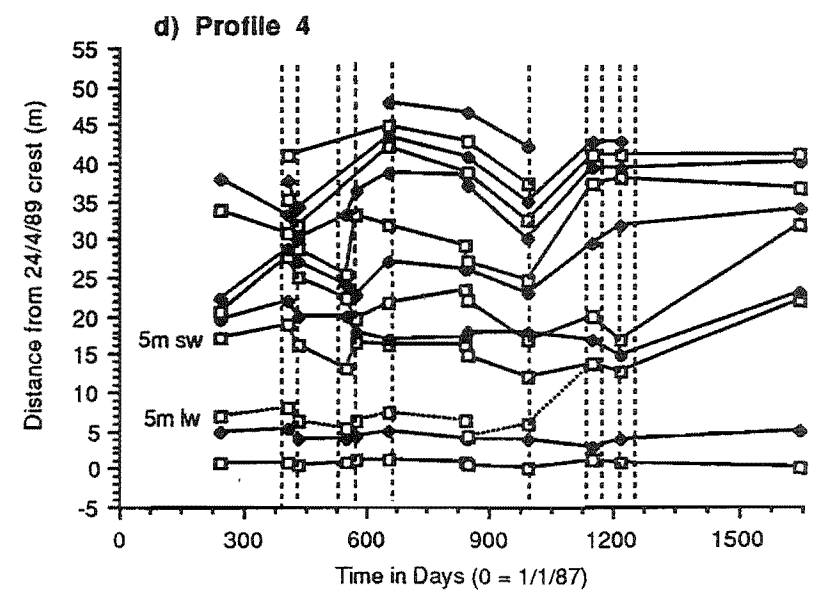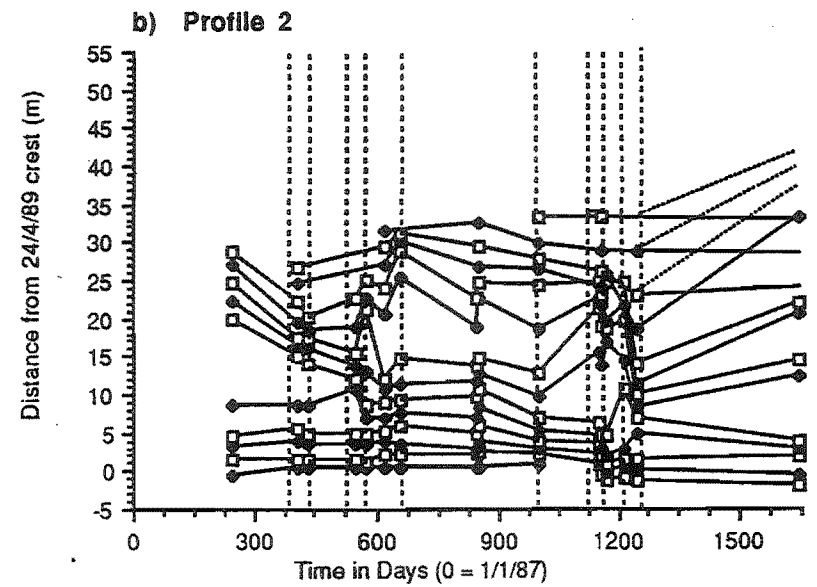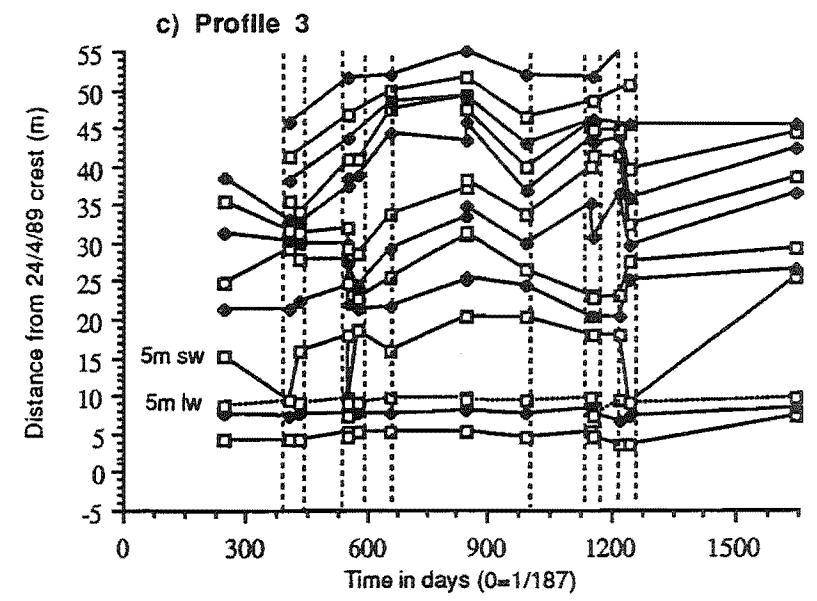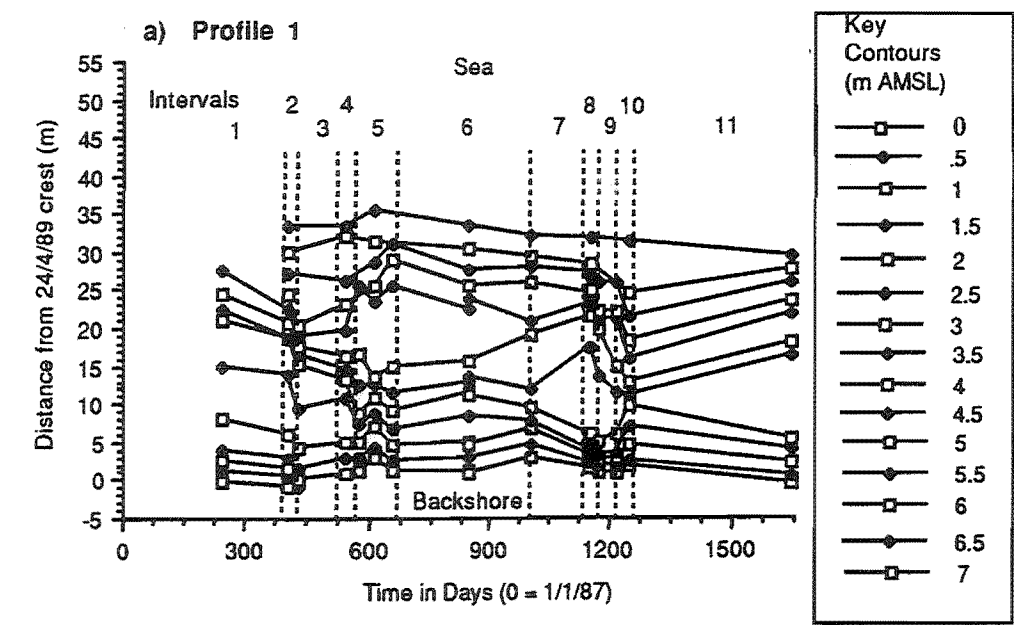
Figure 4.5 Standardised excursion distance plots of the study profiles.
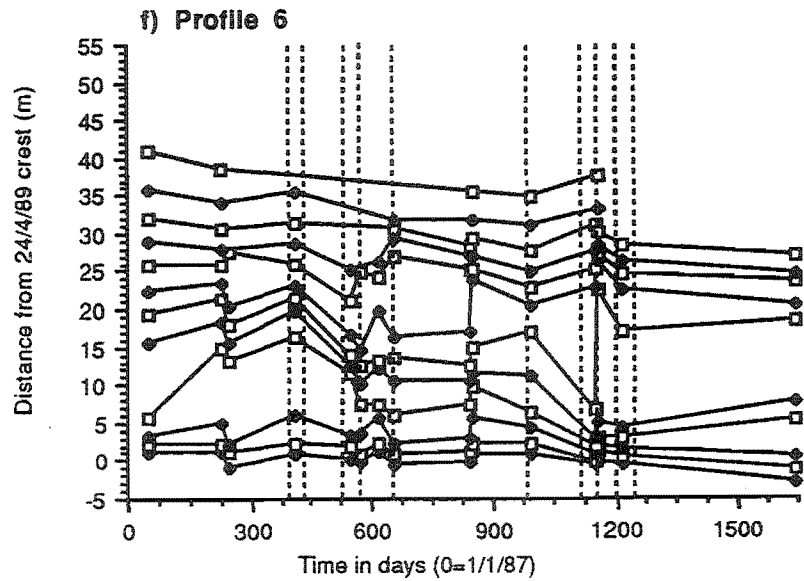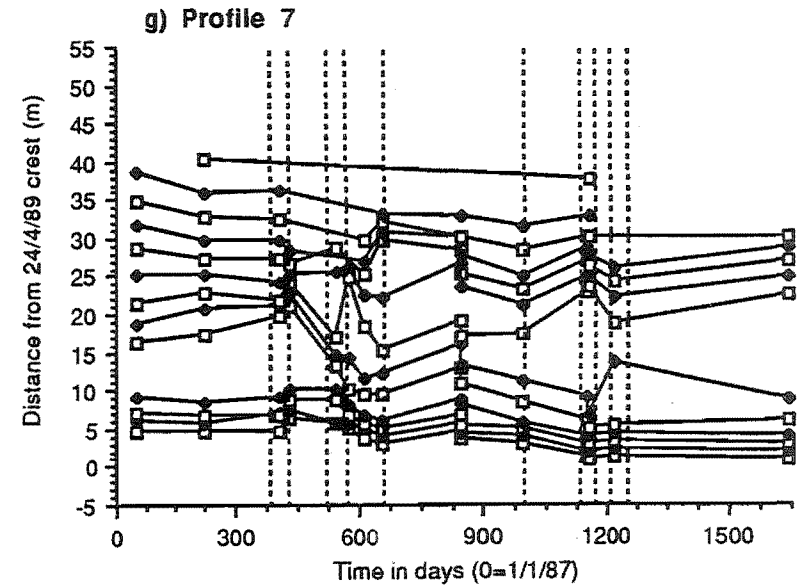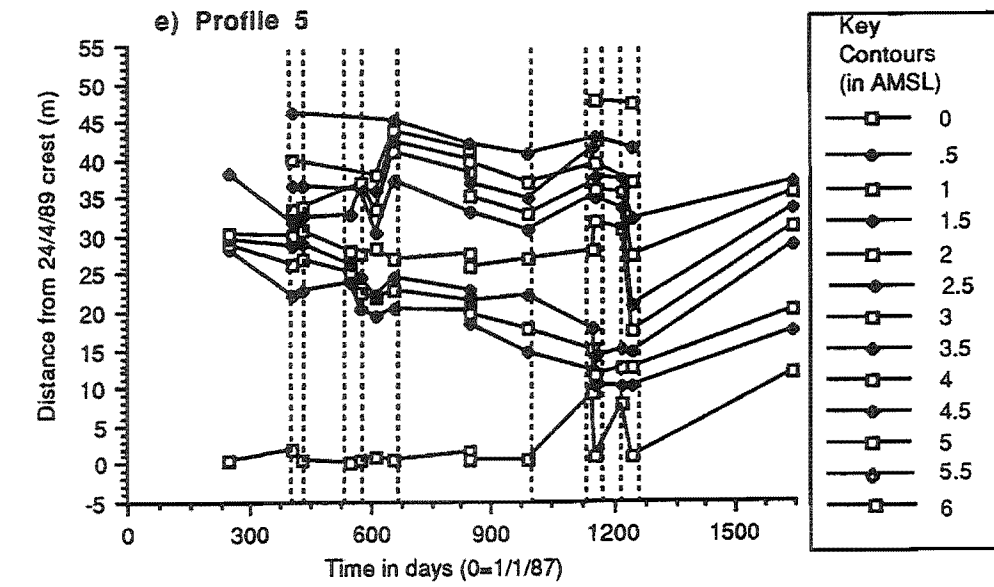
Figure 4.5 Standardised excursion distance plots of the study profiles.

mean sea level. The slope of the line indicates whether there has been erosion or accretion at a particular contour level on the beach. Negative sloping lines indicate erosion as the distance to the contour is shortened over time, while positive sloping lines indicate accretion. The gradient of the line is a measure of the rate of change and greater angles are associated with more rapid change (Kirk 1987a). If the line is horizontal then there has been no change. Similar to topographic contours, lines that are close together indicate a steeper slope than lines that are further apart. Therefore if the lines of consecutive contours are converging then that section of the beach is getting steeper. Conversely, if lines are diverging the beach is flattening. Kirk stated that excursion distance graphs contain useful information about the history of a profile site and about the short and long term response to wave conditions (Kirk 1987a, p68).

4.4.2 Results of excursion distance plots

From a broad overview of the data, the study period was divided into smaller time intervals. These intervals separate the total graph into periods with distinctive beach adjustments. An initial breakdown gave five periods of change. Three periods of relatively little change are separated by two periods of larger magnitude and more rapid change. Because of the variance in adjustment between the different profiles for the same survey intervals, the period was further segmented into eleven intervals. These intervals are shown by vertical dotted lines on Figure 4.5. These intervals vary in length from 22 days to 395 days and reflect the rate of excursion of the plotted contours rather than the magnitude of adjustment. Sharp changes occur for the five shorter intervals (Intervals 2, 4, 8, 9 and 10). The longer intervals contain more gradual changes. Most of the intervals contain both progradation and retreat of the contours. A description of the excursions of 0.5 m contours of each of the study profiles follows.

Profile 1 (Figure 4.5a)

The long term changes shown by Figure 4.5a include retreat of the lower foreshore (below the 1.5 m contour), divergence of the upper and lower foreshores and a change in the gradient of different parts of the foreshore. The upper foreshore became less steep, while the mid-foreshore was widened and became less steep. The lower foreshore was steeper at the end of the study period than at the beginning. Most of the variation in adjustment occurred between the 2.5 m and 4.5 m contours.

Short term changes are discussed with reference to the smaller intervals of change identified above. There was little change in the first interval in the upper foreshore while there was retreat and steepening of the lower foreshore. In the second

interval there was rapid erosion of the foreshore below the 6 m contour. The most pronounced change occurred at 4.5 m elevation. During the third period there was erosion of the 3 m and 4 m contours but accretion on other parts of the beach. The next period resulted in a divergent response to the wave conditions about the 3 m contour which shows no change. Below this level there was accretion and above the 3 m contour there was erosion. This pattern was reversed during the fifth period. Interval 6 was a period of little change for most of the profiles. On Profile 1 there was a short period of erosion across the whole profile during the eighth interval, while there was erosion of the lower foreshore and accretion to the upper foreshore during Interval 9. The last interval again shows a divergence in response with retreat above the 3.5 m contour and below the 1 m contour, and progradation between the 1 m and 3.5 m contours.

Profile 2 (Figure 4.5b)

The changes to Profile 2 show a similar pattern to those of Profile 1 until Interval 9. For this period there was accretion at the 2.5 m and 3 m contours, whereas there was erosion at these elevations on Profile 1. Interval 10 resulted in erosion to the 4 m contour. There was a lack of data for the lower foreshore for the last survey date but the beach adjustment was similar to Profile 1 although there was a greater amount of accretion for the 1.5 m contour.

Profile 3 (Figure 4.5c)

The long term pattern for this profile showed stability of the upper foreshore, with all variation of the profile occurring below and seaward of the 5 m contour. This change included erosion during the first period while at the same time there was accretion of the 4 m contour. The general pattern is different to that shown for Profiles 1 and 2, in that there was a large amount of accretion and broadening of the foreshore (up to 11 metres for individual contours) until the middle of the sixth interval. However the lower foreshore at this time became steeper. In the latter half of the sixth interval there was erosion of the profile below the 5 m contour while there was divergence in the beach adjustment about the 3.5 m contour for Interval 7. There was little change to the profile above the 3.5 m contour for Intervals 8 and 9. During the tenth interval there was a variation in response across the beach. There was erosion of the 5 m contour and below the 3.5 m contour, and progradation of the 4 m and 4.5 m contours. There was no change at 1.5 m elevation. There was accretion for all of the profile below the 5 m contour for the last period, with the mid-foreshore becoming broader and the lower foreshore steeper.

Profile 4 (Figure 4.5d)

The broad upper foreshore contains the secondary berm described for Figure 4.2d. Convergence of the 3 m and 4 m contours during the first interval is similar but of a greater magnitude to the adjustment on Profile 3. During the second interval there was widespread erosion up to the 5.5 m contour. Intervals 3, 4 and 5 are similar to Profile 3, while Interval 6 resulted in removal of the secondary berm crest and erosion of the lower foreshore. This trend of erosion reversed to accretion for the profile for the seventh interval. There is less detail of the survey data for Intervals 8, 9 and 10, but there was divergence of the contours below and above the 4 m contour with broadening of the mid-foreshore and steepening of the lower foreshore. During the last interval there was little change below the 3 m contour but erosion between 3 m and 5 m in elevation.

Profile 5 (Figure 4.5e)

The major feature of the changes to the SEDA for this profile is the retreat of the contours seaward of 4.5 m in elevation. This is linked to the removal of the tertiary berm discussed above, and overshadows minor changes. Contrary to the other profiles, changes to the foreshore in Interval 2 resulted in progradation. In Interval 3 there was erosion of the contours landward of 2.5 m and accretion to seaward. Erosion increased in rate during the fourth interval and there was steepening of the foreshore during the fifth interval. There was also erosion at most elevations of the foreshore during the sixth interval. There was divergence of response about the 3 m contour in the seventh interval, with erosion below and accretion above this level. This divergence of response was more pronounced in the next interval. The next two intervals resulted in accretion to the foreshore below 3.5 m in elevation. There was erosion across the complete profile during the last interval although the upper and mid-foreshore broadened while there was steepening of the lower foreshore.

Profile 6 (Figure 4.5f)

There was a general trend of foreshore retreat and steepening of the lower and upper foreshore, with net accretion and broadening of the mid-foreshore. The extension of the data coverage to before 2/9/87 shows the erosion of the lower foreshore that was described with reference to the surveyed profile plots. There was accretion at all elevations during Interval 1. Intervals 2 and 3 resulted in erosion of all contours and steepening of the mid-foreshore between 2.5 m and 4 m in elevation. During the seventh interval there was divergence of the beach response about the 2.5 m contour,

with accretion below this level and erosion above. During the last period there was little change below 3.5 m in elevation. There was progradation of the 4.5 m and 4 m contours and erosion of the upper foreshore. This is also shown in the survey plots of Figure 4.2.

Profile 7 (Figure 4.5g)

The adjustments of Profile 7 are similar in pattern to those of Profile 6, except the upper foreshore is much steeper and there is a pronounced less steep section of the profile between 3 m and 4 m in elevation. Divergence of response occurs above the 3 m contour, and is most apparent for the last interval where there was erosion of the 3.5 m contour and progradation of the foreshore below this level.

4.4.3 Discussion

From Figure 4.5 it can be seen that the profiles are of different widths from the crest to the 0.5 metre contour, and exhibit varying across-shore topographies. Profiles 1 and 2 have the narrowest foreshores, with a minimum of 30 metres and 28 metres from the crest to the 0.5 metre contour respectively over the study period. Profile 3 has the widest foreshore at 55 metres. Profiles 1, 2, 6 and 7 exhibit steep upper foreshores while profiles 3, 4 and 5 are flatter and include a large intermediate berm at about the 5 metre contour. Most of the profiles have a broad comparatively less steep middle foreshore between the 4 metre and 2.5 metre contour and are much steeper seaward of the 2 metre contour. The adjustment of Profile 5 over the study period displays the response to the beach reconstruction of 1985. The retreat of all of the contours seaward of the 4.5 metre contour is not consistent with the other profiles which show a greater fluctuation of erosion and accretion. There are no obvious trends of erosion for the profiles, although Profile 7 shows the most tendency towards retreat and narrowing of the foreshore. Profiles 3 and 4 appear to be accreting over the study period.

Sharp negative slopes of the contours are indicative of high energy episodes. Figure 4.6 shows enlarged and updated standardised excursion distance plots for Profiles 1 and 2. A major event is evident between days 1217 and 1248 (March and June 1990). This event is analysed further in Chapter Five. Six smaller events are also evident. These occur between days 407 and 432 (February and March 1988), days 547 and 575 (July 1988), days 575 and 615 (July and September 1988), days 615 and 656 (September and October 1988), days 1150 and 1157, and days 1157 and 1173 (February, March 1990). Figure 4.6 has been updated from Figure 4.5 to include the latest survey data to hand. This covers the period between early March and late May
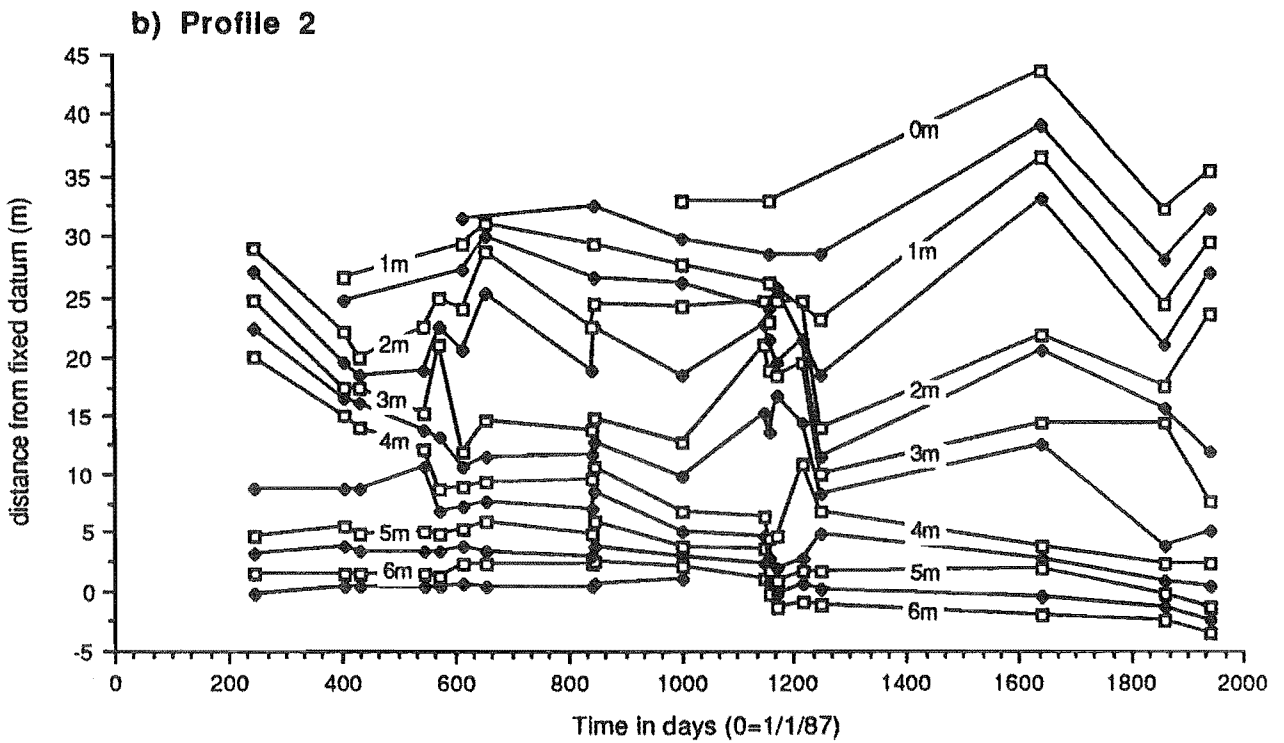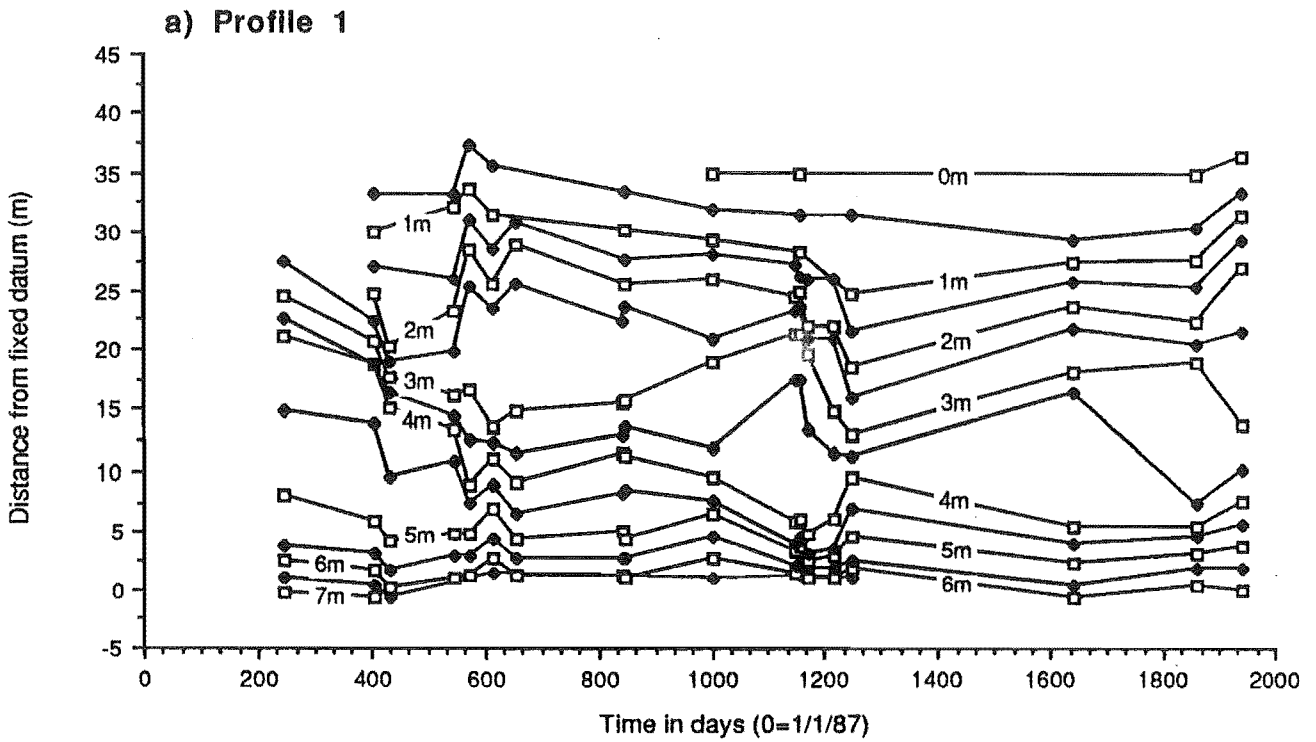
Figure 4.6 Detailed and updated standardised excursion distance plots for Profiles 1 and 2.

1992. During May 1992, two storm events resulted in large waves arriving along the South Canterbury Coast. In both events breaking waves were observed to be in excess of 3 metres in height, and caused overtopping at Washdyke Lagoon, north of Timaru. These events and the resulting adjustment to the beach profiles are discussed further in Chapter Five Section 5.3. The excursion distance plots do not show a rapid beach retreat as was the case for May 1990. There is however, a divergence of the contours, with accretion to the lower foreshore and erosion of the middle and upper foreshore.

It can be concluded from the beach response of May 1992 that a rapid retreat of the profile contours is not the only indication of the occurrence of high energy events. Accretion and erosion can occur to high levels on the beach indicating the occurrence of large waves associated with run-up to high elevations. The magnitude of the events that have occurred between survey periods can be gauged by the extent to which the contours on the excursion distance plot change and by the limit at which there is no contour response. Larger events cause a greater change and affect the beach profile to a higher elevation.

A spatial comparison of the survey data can be made by plotting the SEDA for each profile at a particular time against the relative longshore distances between the profiles. This analysis is included in Chapter Six.

4.4.4 Normalised excursion distances

Profiles of different shape can be made more comparable by a further manipulation of the excursion distance data, in which the raw excursion distance data is converted to normalised, dimensionless distances. The resulting Normalised Excursion Distances (NED's) can be used to display changes to a contour in relation to the position of the contour at the time of the initial survey. The normalised excursion distances are computed according to Equation 4.1, such that:

$$X_{norm} = 1 - \frac{(X_0 - X_t)}{X_0} \qquad \text{eq.4.1}$$

Where: X_{norm} is the normalised distance, X_0 is the initial excursion distance, and X_t is the excursion distance at any given time, t, after the initial survey (Kirk 1987).

The normalised excursion distance has been calculated for each 1 metre contour, for each survey time. The results for the study profiles are plotted in Figure 4.7. As with the EDA plots, negative sloping lines indicate erosion and positive sloping lines are indicative of accretion between the surveys. Horizontal lines are a result of no change. The interval between each NED line on the 'y' axis is 0.5. This is equivalent to a
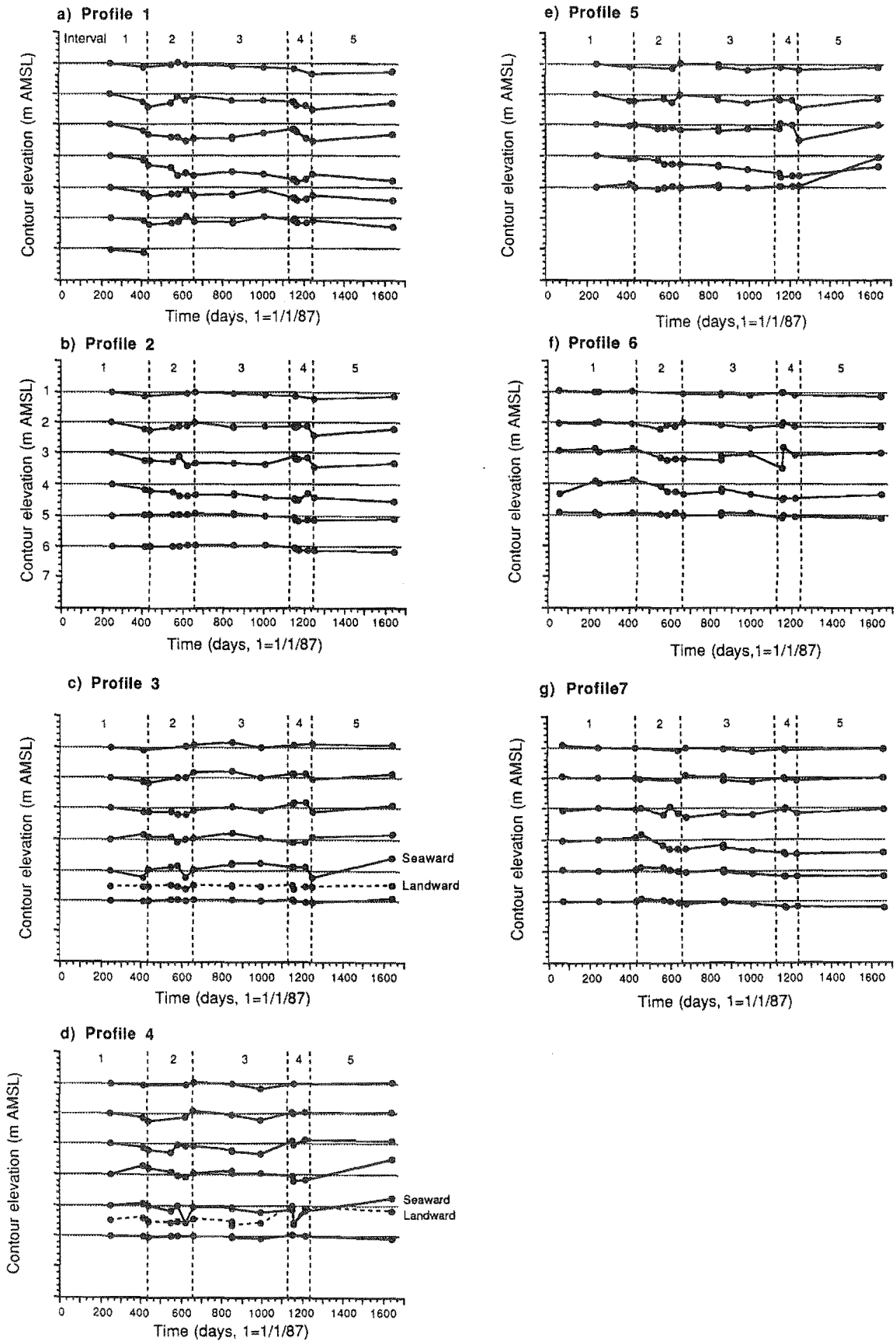
Figure 4.7 Normalised excursion distance plots.

change in position of the contour of 50% of the initial excursion distance, for example if X_0 equals 10 metres and X_t equals 5 metres, then X_{norm} would be equal to 0.5. The slope of the line is indicative of the rate of change, whereby a steep gradient represents a rapid change in contour position. High energy episodes can be identified by sharp negative sloping contours and by movement of the contours at higher elevations on the beach. Although each of the study profiles have different shapes, they are part of a continuous mixed sand and gravel barrier beach system. There are no offshore features of the seabed contours, for example submarine ridges or mounds, that would focus wave energy and raise run-up levels onto a particular site, therefore the response to wave and swash processes should be similar.

Figure 4.7 emphasises the variation in beach adjustment at different elevations across the profile. The normalised excursion distance plots also show distinct breaks between the type of response for different time intervals. Five intervals have been identified on Figure 4.7 by vertical dotted lines.

Profiles 1 and 2 (Figure 4.7a and b)

The first interval for Profile 1 shows erosion for all of the contours. The greatest change occurred on the 2 m contour. The second period contains at least two high energy episodes. The first resulted in retreat of all of the contours, while the second had accretion at all levels except the 3 m and 4 m contours. Erosion continued on the 4 m contour through the third interval as with most other elevations except for the 3 m contour which prograded during this interval. The fourth interval also contains high energy episodes and again the response varied for different elevations on the beach. There was net erosion for the 1 m, 2 m and 3 m contours and no net change or slight progradation to the other contours. The last period resulted in retreat of the 4 m, 5 m and 6 m contours and progradation of the lower contours. The net change for the study period shows erosion at all levels of the beach.

There was very little change to the upper contours of Profile 2 until the last two intervals, which showed net retreat. There was a general trend towards erosion for the 4 m contour except for a period of progradation in the fourth interval. The patterns of change for the lower three contours were similar for the study period with erosion followed by a period of accretion and then a stable period until the fourth interval which resulted in retreat of the contours. The fifth interval again showed a divergence in response between the lower and upper contours, with the lower contours prograding while the upper contours remained stable or slightly retreated. There was little net change for the period as a whole although there is a small amount of net retreat of all of the contours.

<u>Profiles 3, 4 and 5</u> (Figure 4.7c, d and e)

These profiles are complicated by the presence of the intermediate berms acting as buffers of protection to the barrier crest. Therefore there were minimal changes to the uppermost contours. Unlike Profiles 1 and 2, there was some disparity of response at different elevations on the profiles during the first interval, with erosion below 3 m and progradation above this level. During the second interval there was erosion followed by accretion at most elevations. Erosion of the 4 m contour on Profile 5 stands out as a difference in response to the other profiles during the third interval. In most cases there was progradation of the beach. During Interval 4 there was a period of erosion followed by accretion and then further erosion. The response of these profiles differs to that of Profiles 1 and 2 during the fifth interval in there being progradation at all elevations for all of the profiles. The NED plots for Profiles 3 and 4 are predominantly above or near the initial excursion distance for the period, and show a net tendency towards accretion or progradation.

<u>Profiles 6 and 7</u> (Figure 4.7f and g)

As with Profiles 1 and 2, the general trend is towards erosion for Profiles 6 and 7, although there is less departure from the initial excursion distance for each contour. The major variations occur for the 3 m and 4 m contours on both profiles. These contours show progradation for the first interval. The 4 m contours on both profiles then show net retreat for the remainder of the study period. Erosion of the 3 m contour during Interval 2 changes to accretion except for two episodes of retreat at the end of the third interval and for the latter half of the fourth interval. The net result for the 3 m contour is no change in the horizontal distance from the fixed datum.

There is a general pattern of retreat of the study profiles since the start of the study period. The exception to this pattern is Profile 3, which has adjusted about the initial position of each of the contours, but was predominantly accretionary. The variation in profile adjustment at different elevations has been noted. For most of the profiles the variation in response can be separated into changes to the lower, middle and upper foreshores. This spatial display in beach response to the wave environment is discussed further in Chapter Six.

4.5 Volume Change

If a beach profile is considered to be representative of the active beach sitting on some base structure, the area under the plotted profile can be used to calculate an estimate of the volume of beach material at that site. The area under the profile is given

volume by assuming the profile represents a 1 metre wide slice through the beach. The units used are therefore metres cubed per metre of beach ($m^3 . m^{-1}$ of beach). Some means of defining the limits of the profiles was needed to make the values of each profile comparable because the study profiles do not extend seaward to the limit of significant sediment transport (or in some cases to the limit of the foreshore adjustment), the calculated volume must be qualified. For this study, the area under the profile but above the 1 metre contour has been used as a basis for a comparative examination of the spatial and temporal changes in beach volume. The 1 metre contour was used because in most cases the surveyed profiles either extend to, or could be extrapolated to this level. However without knowledge of the internal structure of the beach the calculated volume is only an estimate of the amount of material within the profile that is suitable for addition to the beach morphology.

The envelope of changes to the profile (as shown in Figure 1.3) must be considered as an indication of the active beach. For this reason the total volume of a profile at a specific time is not as significant as the amount of change in volume of a profile between surveys. The information presented here involves net changes in volume or rates of change. It is not necessarily the result of a specific event at the coast as there is no survey information from immediately prior and immediately after an event. However, the information does show the magnitude of short and medium term changes to these mixed sand and gravel barrier beaches.

Figure 4.8 shows the mean volume of sediment for each of the study profiles for the study period. The volumes are divided into two sections. The lower half of the histogram indicates the proportion of the beach volume seaward of the barrier crest in respect of the total profile. This is a basic separation of the foreshore and the backshore. The backshore could not be determined accurately for Profile 5 because of the presence of a flood stopbank immediately behind the beach. This separation also highlights the possible availability or non-availability of material suitable for beach nourishment by material in the backshore, should erosion continue beyond the present barrier crest. During the study period there was minimal change to the profile landward of the crest. Most of the variations shown for the backslopes in Figures 4.2 and 4.3 are due to variations in the detail of the profile surveys. Note that the foreshore volumes for Profiles 1, 2, 6 and 7 are much smaller than for Profiles 3, 4 and 5. This facet of the profiles is in agreement with the SEDA plots of Figure 4.5 and the descriptions of the changes from the NED plots in Figure 4.7, and distinguishes the differences between the profiles in the centre of the study area from those at the ends.
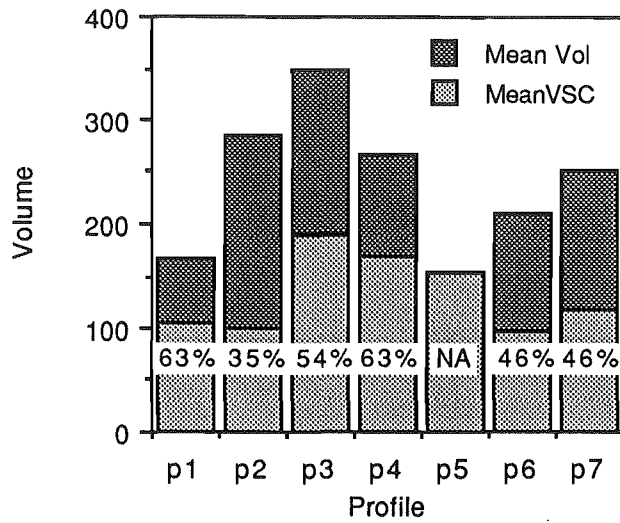
Figure 4.8 Mean volume of sediment for each profile.
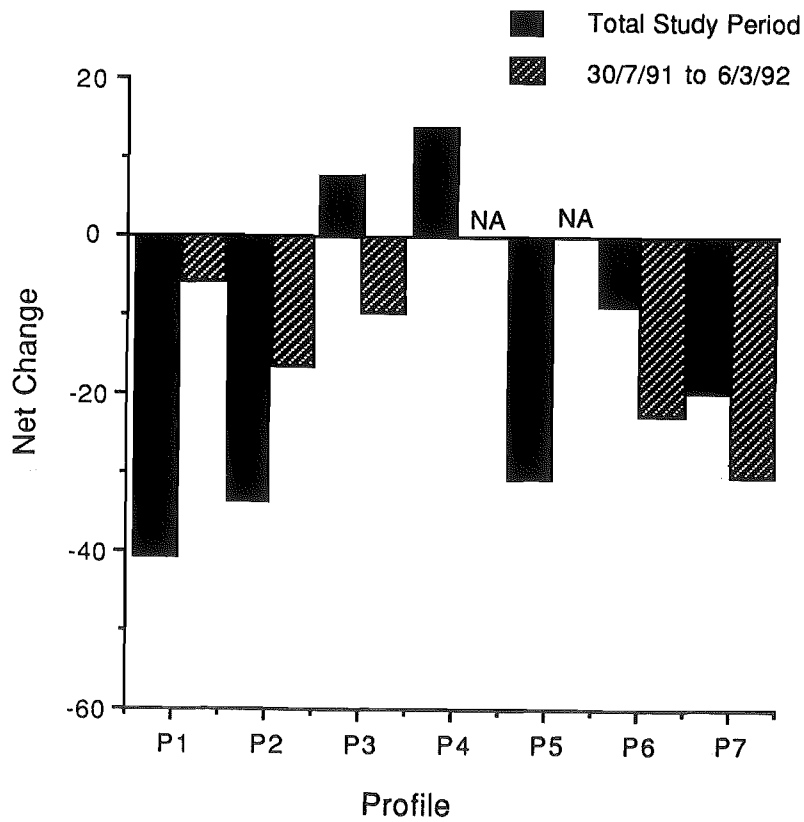
Figure 4.9 Net volume change seaward of the barrier crest for each profile.

Figure 4.9 shows the net volume change seaward of the barrier crest. Two time intervals are shown. The first time interval from 2/9/87 to 30/7/91 covers the main study period. The second time interval, from 30/7/91 to 6/3/92, covers recent changes to the area and uses updated survey information provided by the Canterbury Regional Council. There was net erosion of beach material during the study period for all of the profiles except Profiles 3 and 4. Again the difference between the end and central profiles is apparent. In general the narrow profiles with less foreshore sediment volume experienced a greater net change than the larger (by volume) profiles. The exceptions are Profile 5 and 6. The large amount of erosion from Profile 5 is likely to be due to readjustment of the profile after the beach reconstruction of 1985. This is shown in Figures 4.2e and 4.5e. The loss of material from Profile 5 may have resulted in addition of material to Profile 6, therefore decreasing the magnitude of the net change to this profile. Figure 4.9 also shows that the net change in the seven months between July 1991 and March 1992 was in three cases, greater in magnitude than the net change for the 47 months between September 1987 and July 1991. For Profile 3, in contrast to the net accretion for the earlier period, the net change for the latter period was erosion.

This medium to long term net change is indicative of the short term variations in volume change during the study period. Figure 4.10 emphasises the variability in magnitude of short term changes. The maximum change between surveys was a net erosion of 41 $m^3 .m^{-1}$ of beach from Profile 5, between 2/9/87 and 11/2/88. The largest net accretion was also on Profile 5, with a net increase of 30 $m^3 .m^{-1}$ of beach between 1/6/90 and 30/7/91. There was variation in the amount of change and the direction of change between profiles for individual survey intervals. Net erosion was recorded for all profiles on three occasions, 28/4/89 to 19/9/89, 1/5/90 to 1/6/90 and 30/7/91 to 6/3/92. Net accretion was recorded on all profiles for only one survey period, between 1/6/90 and 30/7/91.

The most significant rates of change between the survey dates can be seen from Figure 4.11 to be the shortest survey intervals. These are the four days between 24/4/89 and 28/4/89, and the seven days between 22/2/90 and 1/3/90. These two survey intervals bracketed 'minor' storm events. From the excursion distance analysis plots shown in Figure 4.5, these events, in the main, were not associated with large horizontal movements of the beach contours, nor (from Figure 4.10), with large absolute changes in volume. However the adjustments to the beach profiles occurred very rapidly. It is likely that these changes occurred over the space of the storm event, probably less than 48 hours, in which case the rates of change presented in Figure 4.11
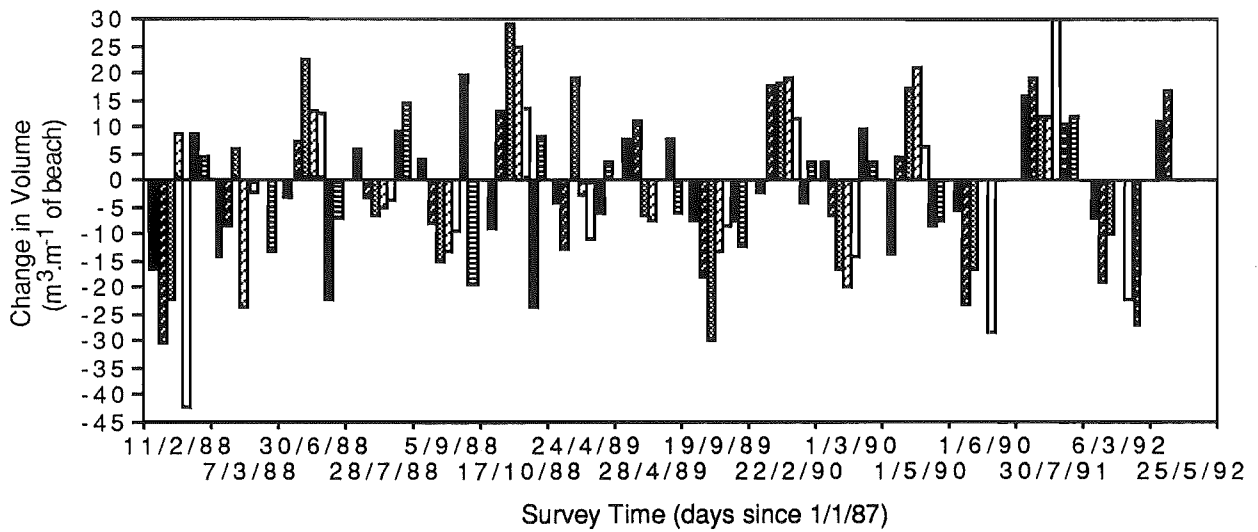
Figure 4.10 Net change in foreshore volume between beach profile surveys.
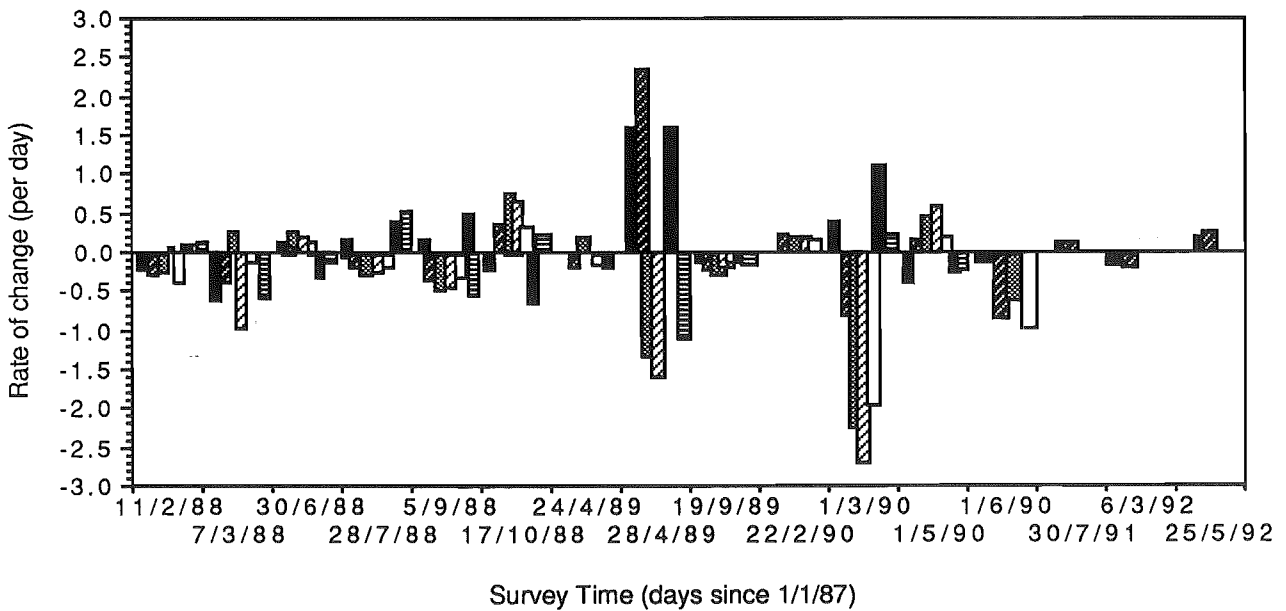
Figure 4.11 Rates of net foreshore volume change between beach profile surveys.

are a half and a third of the possible rates for each event respectively. The erosive and accretionary capacities for specific events and profiles are discussed further in Chapter Five.

If each study profile is considered to represent the section of beach on either side of the profile, extending to halfway between the adjacent profiles as in Figure 4.12, then an estimate for the total amount of sediment movement for the study area can be made. This has been calculated for the four study intervals discussed above and the resulting values are included in Figure 4.12. The long term net change in profile volume is -114,452 m^3 for the four and a half years from September 1987 to March 1992. This gives an average annual net change in volume of -25,434 m^3. This is less than the total removal of sediment between 22/2/90 and 1/3/90 which is estimated at 32,005 m^3 (of erosion) for the seven day period. This is in contrast to the net accretion to the study area between 24/4/89 and 28/4/89 of 8105 m^3, and again demonstrates the significance of variability of beach response over the study period. It is assumed that this variability reflects variations in the wave environment.

4.6 Discussion

Plotted surveyed beach profiles from the Wainono Lowland Coast have been used as a tool in describing the beach adjustments that have occurred between 2/9/87 and 6/3/92. Seven beach profiles representing the spatial variation in morphology of the Wainono Lowland Coast were surveyed by the author and by the South Canterbury Catchment Board coastal investigator, at near regular intervals over a four and a half year period. The aim was to obtain beach adjustment information for different time periods, including the beach response to high energy events.

It has been assumed that the 3.9 kilometres of coastline making up the study area, experienced uniform oceanographic conditions at all times. However, the oceanographic conditions experienced in the study area during the study period were different to those expected after an examination of the historical records of the incidence of storm events impacting on this coast. It was expected that two or three 'moderate' to 'significant' events would be experienced each year, and that these events could be studied in conjunction with pre-storm and post-storm beach profile surveys in order to provide information relevant to explaining the beach adjustment in response to high energy events. This was not the case. Few storm events occurred during the study period. Of those that did occur, most were rapid in onset and of short duration, making it difficult to obtain a storm event data set from which conclusive interpretations could be made.

Profile Number

| 1 | 2 | 3 | 4 | 5 | 6 | 7 |

Length of Beach Represented by Profile (m)

|205| 920 | 965 | 535 | 530 | 495 |250|

Net Volume Change (m³.m⁻¹ of beach)

Survey Interval								Total for Study Area (m³)
2/9/87 - 30/7/91	-40	-37	+7	+13	-30	-8	-19	-53140
30/7/91 - 6/3/92	-5	-17	-9	(-16.5)	(-16.5)	-22	-30	-61202
24/4/89 - 28/4/89	+6	+9	-5	-6	-1	+18	-7	+8105
22/2/90 - 1/3/90	+2	-5	-15	-19	-13	+7	1	-32005

Total Study Period   -114452
Average Annual   -25434

Figure 4.12 Net changes in foreshore volume for the Wainono Lowland Coast as represented by the study profiles.

The survey information that was obtained has been analysed in respect of providing information pertaining to medium and short term beach adjustments. Three main methods of analysis were used to identify and describe the beach changes. The first method used basic cross sectional, or profile plots of the horizontal distance across the beach against the change in elevation. Each of the seven profiles was surveyed repeatedly during the study period. Each set of subsequent survey data was overlaid on previous plots giving a display of the changes in profile shape and position. The second method of analysis involved a manipulation of the survey data to give excursion distances for individual contour levels on the foreshore of each profile. Horizontal retreats or advances of the foreshore at different elevations on the profile were obtained. This analysis was extended to standardise and then normalise the horizontal adjustments of the examined contours so that direct comparisons of profiles of different initial shapes and positions in space could be made. The third method of analysis considered changes in beach volume. This was extended to consider total changes in sediment volume for the entire study section.

Periods of erosion and accretion were identified during the course of the field investigations. A major feature of the beach adjustments described was the spatial variability in response to the wave environment, and the temporal variation in magnitude and character of adjustment of individual profiles. The change in shape and form of the beach profile associated with episodes of erosion and accretion was also noted. Erosion caused the beach to become less steep and removed intermediary berms from the profile. Accretion caused the build up of berms and steepening of the foreshore seaward of the berm construction. Overall steepness of the profile from the crest to Mean Sea Level could become less steep due to the progradation of the lower beach and the formation of a landward sloping 'backshore' and crest top on the intermediate berm.

This chapter has provided information that can be used in the examination of three of the questions raised in Chapter One. These questions are:

> What is the significance of high energy events to the beach sediment budget?

> What is the role of high energy events in determining the processes of long term coastal retreat occurring on the study coast?

> What are the short term effects of high energy events on a mixed sand and gravel barrier beach?

In addressing these questions an hypothesis put forward in Chapter One can also be discussed. This hypothesis stated that much of the geomorphic work done on mixed sand and gravel beaches is done during short duration high magnitude events. The conclusions from this chapter indicate that this is the case. The magnitude of the adjustment to the beach over some time period can be a reflection of the magnitude of the processes that have caused the changes. During the study period all of the contours below 5 metres showed adjustment for most survey intervals. Assuming this adjustment was in response to wave processes then a maximum wave height of approximately 3.2 metres would be required to produce run-up to this level. It has also been shown that storm events cause both erosion and accretion of the profile in a short period, and that the magnitude of this change can be as great as the net changes for a much longer period in which no storms occur. Using changes in beach volume as an example, the storm event between 22/2/90 and 1/3/90 although minor, resulted in the net removal of 32,005 m^3 of material from the study area in 7 days. For the nine months between 28/7/88 and 24/4/89 there were no recorded storm events. However there was a net accretion to the study area of 15,500 m^3. This value is made up of 33,325 m^3 accretion to the areas represented by Profiles 3 and 4 and 17,835 m^3 eroded from the remaining areas. It can be concluded that the rate of volume change is appreciably slower during times of low energy processes in comparison to storm event episodes. Therefore the amount of geomorphic work done to the beach during storms appears to be much greater in regards to the movement of sediment, than at other times. By reference to Figures 4.2, 4.3 and 4.4, this can also be seen to be the case in regards to changes in form and shape of the profile.

There are many difficulties in producing a conclusive sediment budget for South Canterbury Coast with the available existing knowledge of the area. Kirk (1987a) and Todd (1988) discuss these difficulties and sediment budgets proposed for the area to date. The work of Kirk and Hewson (1978) has been examined for this study in Chapter Three. The dearth of high energy events during the study period also causes reservations to be placed on defining the significance of such events to the beach sediment budget.

The information from this study is only relevant to the coarse fraction of the sediment budget. Kirk (1987a) noted that there was little information on the variations in proportions of contribution to the sediment budget from place to place along the coast, especially in respect to different coastal types. For the cliffed section of coast just north of the Waitaki River, Kirk noted that 87% of the total cliff retreat from February 1977 to August 1986 occurred between March 1985 and August 1986. The latter time period

included three major coastal rain and coastal storm events. During this period he found that there was an average net sediment loss of 20,068 $m^3 \cdot km^{-1}$ from the Waihao-Wainono lowland beaches. The average annual contribution of material to the sediment budget from erosion of this section of coast was approximately 450 $m^3 \cdot km^{-1}$ (from Kirk 1987a, Figure 10).

The study period was one of net erosion to the Wainono Lowland Coast. Using the mean beach volume seaward of the crest for the study profiles as representing the total study area as in Figure 4.12, the mean total beach volume was calculated to be 542,000 m^3. The average change in volume for the study period was a removal of about 25,500 $m^3 \cdot yr^{-1}$ (an annual average of 6500 $m^3 \cdot km^{-1}$), this amounts to an annual net loss of 5% of the active foreshore. This is much greater than that presented by Kirk and emphasises the variability in the proportion of contribution from different sites along the coast. It is however, less than the removal of sediment possible during one storm episode such as that between 22/2/90 and 1/3/90. It should also be noted here that the removal of sediment from one section of the coast injects sediment into the larger coastal system. This concept is examined further in Chapter Six in relation to the spatial interaction of the adjustment of individual profiles and to the notion of slugs of sediment migrating alongshore.

The second question can be answered with reference to the net horizontal retreat of the beach in profile and to the net change in beach volume. There is little long term information as to trends of erosion for the study section of coast as separate from the South Canterbury Coast. However it is accepted that persistent erosion has occurred for several thousand years (Kirk 1987a). Todd (1988) presents estimates of long term retreat of the 'Waitaki Fan', that range from 0.38 to 1.76 $m.yr^{-1}$. The estimates for the lowland section of coast are between 0.38 and 0.9 $m.yr^{-1}$. For the period between 1953 and 1977, the average annual erosion rate for the Wainono area was 0.38 m (Kirk 1987a). Kirk (1987a) summarised the information collected by the South Canterbury Catchment Board from beach profile monitoring for the coast south of Timaru. The available data set covered only nine years, from 1977 to 1986. The area of interest for this study is included within the 29 kilometre section referred to by Kirk as the Southern Lowland Beaches, which stretches from near Otaio, to south of the Waihao River. There were net sediment gains to the sections of the coast north of Wainono Lagoon and south of the Waihao River, but there was net erosion about Wainono Lagoon. There was also widespread sustained erosional displacement of the beach crests. The mean rates of retreat were slightly less than 1 metre per year. Profile sites 1 and 7 from this study were included in Kirk's analysis but only covered two and three years of data

collection respectively. The average crest retreat of Profile 1 was calculated as 2.7 metres per year, while the average crest retreat at Profile 7 was 6.7 metres per year. The average change in volume for the two profiles was approximately -10 $m^3.yr^{-1}.m^{-1}$ of beach and -11.3 $m^3.yr^{-1}.m^{-1}$ of beach respectively.

The time period of this study is longer than that used by Kirk, and large variations in beach change from year to year have been noted. The average crest retreat for the study period was 0.58 $m.yr^{-1}$. However crest retreat only occurred on Profiles 1, 2, 6 and 7, with a total retreat between 2/9/87 and 30/7/91 of 2.5 metres, 5 metres, 3 metres and 9 metres being recorded respectively. The average change in volume between 2/9/87 and 6/3/92 was -10 $m^3.yr^{-1}.m^{-1}$ of beach for Profile 1 and -10.9 $m^3.yr^{-1}.m^{-1}$ of beach for Profile 7. However, 60% of the total sediment loss from Profile 7 occurred in the last seven months of the study period. It is concluded (with reservations due to the short history of data collection for this section of coast), that the incidence of high energy events maintains the long term coastal retreat. A long period of time without such events can result in net accretion to the coast but this can be offset by just one or two storm episodes.

The third question set out above can be answered by summarising the major responses of the beach to high energy events. The lack of these events during the study period precludes the development of such a summary at this stage. However the question is again addressed in the following chapter, in which the impacts of four storm events on the study coast are examined in detail.

CHAPTER FIVE
HIGH ENERGY EVENTS

5.1 Introduction

Morphological changes to the Wainono Lowland Coast during the study period were discussed in Chapter Four. Episodes of erosion, accretion and change to the profile shape were attributed to varying wave environments at the coast at different times. Specifically, the importance of high energy events in determining adjustments to the upper and middle foreshore was emphasised. The importance of clearly defining what constitutes a storm or high energy event has previously been discussed in Section 1.3. This chapter expands on this discussion through an analysis of recorded storm events on the study coast detailing the common characteristics and the resulting beach responses.

A classification of wave events on the South Canterbury Coast has been made by the Canterbury Regional Council with consideration to the amount of damage that occurred to the beach and to the extent of beach inundation due to wave run-up. Damage has been mainly in the form of erosion, overtopping, breaching or sea-water flooding. The classification terms used by the Canterbury Regional Council are defined in Table 1.3 and are also listed below. They are:

> 'significant' - events yielding sustained overtopping for two or more high tides

> 'moderate' - events that may overtop the beach for a few hours of a tidal cycle

> 'minor' - events that reach the beach crest and may wash over to the landward slope of the beach.

Some events may fail to fit even the 'minor' definition given above but may cause erosion or changes to the beach profile and therefore have an impact on the beach morphology that may significantly alter the ability of the beach to dissipate wave energy. This may be due to some factor other than the wave environment during the event.

Kirk (1987a) also categorised storms at the coast. He separated the impacts at the beach from the oceanographic parameters of the event. He defined events which had maximum wave heights of 3 metres or more as 'storm conditions'. As previously stated in Chapter One, Kirk found from data collected by Hastie (1985), that episodes with wave heights of this order occurred on 75 days of a one year observation period.

However they resulted in only one reported incident of damage at the coast (from Table 1.3). It is assumed that these events contained waves with high energy and must have resulted in some impact to the beach. However the magnitude of this impact and the beach response are unknown. The fact that Kirk found that these are not rare events is also of interest here. However, the nature of weather systems in the Southern Ocean between 1986 and 1990 has been milder than during Hastie's observation period, with for example, only 17 days in 1986 having visual estimates of waves equal to or greater than 3.0 metres in height, and no incidents of beach overtopping or reported damage to the beach.

For the purposes of this thesis a definition of the magnitude of an event will be used that is closely linked to the oceanographic parameters of the storm and to the impact at the beach. A high energy event is considered here as a coastal or oceanographic storm that results in wave process induced changes to the beach morphology such that the form of the beach profile is altered by the removal or relocation of beach material in a short time period. So far, this definition is subjective with no values put on the magnitudes of the storm parameters or the changes to the beach morphology. It also leaves unanswered the definition of what constitutes a 'high energy' event as opposed to 'normal' or low energy processes. The frequency of occurrence of the high energy events is also not addressed as yet. Defining high energy events and the frequency of occurrence are basic problems addressed by this study. However because of the unknown quantities and variables involved in these definitions they may be the end result of the study rather than the starting point for examining beach response. The questions raised in Chapter One that will be addressed in this chapter are:

What are high energy events and how can they be characterised?

How does beach crest lowering occur?

How is breaching initiated, and what conditions predispose its occurrence?

Carrying forward from Chapter Four is also the question:

What are the short term effects of high energy events on a mixed sand and gravel barrier beach morphology?

For the purpose of clarifying the types of events that have been considered for this study as high energy, the following section describes in detail two storm events and their impacts at the beach. Following this will be a discussion of two further storm

events that occurred in quick succession in May 1992. These storms occurred after the field study for this thesis. However they are significant in light of the dearth of high energy events between 1987 and 1991. The Canterbury Regional Council system of monitoring beach response and the assimilation of the data for this study has meant that a late inclusion of this information has both been possible and is relevant to illustrating the nature of, and the beach response to storm events on the South Canterbury Coast.

5.2 Two Coastal Storm Events

Information for this section comes from two reports by the South Canterbury Catchment Board (1985; Canterbury Regional Council 1990), and was augmented by reference to the original storm monitoring observation notes held on file by the Board.

5.2.1 Coastal storm of 27-28 July 1985

Situation

On the 27th of July 1985 the South Canterbury Catchment Board received a storm warning from the New Zealand Meteorological Service, indicating the likelihood of 3 to 4 metre east-south east swells generating from near the Chatham Islands (about 900 kilometres east of Timaru). Figure 5.1 shows a Mean Sea Level Analysis map adapted from those produced by the New Zealand Meteorological Service for the 27th and 29th of July 1985. A slow moving depression centred near the Chatham Islands produced strong south-easterly winds causing high, long period south-easterly swells, which affected much of the east coast of the South Island.

Wave and Water Level Parameters

The Catchment Board made observations of wave parameters including wave height, period, direction of approach and wave run-up at Washdyke, just north of Timaru, in conjunction with high tide times for the duration of the storm as part of their on-going storm monitoring program. High tide observations were made at 10:45am and 11:10pm on the 27th of July, 11:40am and midnight on the 28th of July, and 12:40pm on the 29th of July. High water levels in Washdyke Lagoon cut off access to the beach and prevented wave height observations being made at the beach on the 28th but estimates were made from a close vantage point. Wave data were also obtained from a Ministry of Works 'wave rider' buoy located 100 kilometres north of Timaru and 9.5 kilometres off the Rakaia River mouth. High tide water levels were observed from the
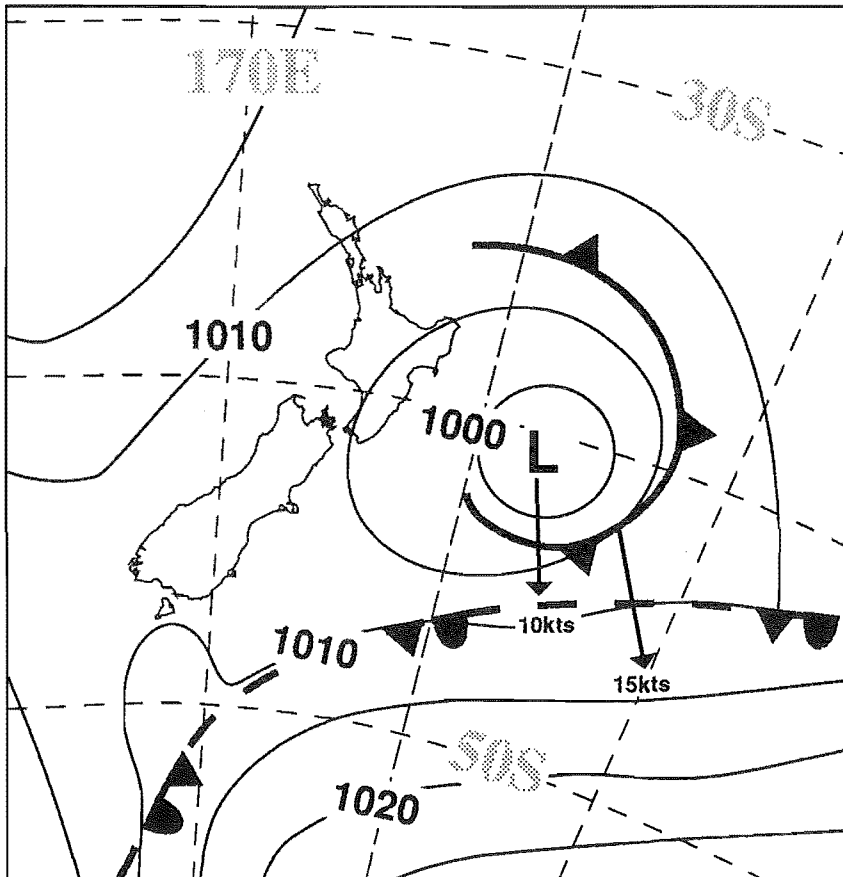
Figure 5.1 Mean sea level atmospheric pressure analysis map; 0600 hours, 29/7/85 (after N.Z. Met. Service Fax. information).

Timaru Harbour Board tide gauge and compared to predicted levels to calculate an approximation of the amount of water level set-up due to the storm.

The wave rider records showed that the maximum 3 hourly mean significant wave height was 4 metres, with a maximum 3 hourly mean wave period of 8.2 seconds. Observations made at Washdyke gave estimates of the significant breaking wave height as 3 metres, a mean wave period of 11 seconds and the wave approach direction as being from the south-east.

Storm duration was calculated from the wave buoy records. A deep water wave height of 2.5 metres was used by the South Canterbury Catchment Board to identify the onset of storm waves. This is a lower limit than the 3.0 metres adopted by Kirk (1987a). The wave buoy records showed that wave heights were above 2.5 metres from 9:00pm on the 27th until 6:00am on the 29th, giving an approximate storm duration of 33 hours. Observations at Washdyke indicated that major overtopping occurred continuously from high tide at 11:10pm on the 27th through to after high tide at 11:40am on the 28th. Overtopping also occurred for approximately an hour coinciding with the peaks of the two subsequent high tides.

Differences between the predicted and observed water levels at the Timaru Harbour Board tide gauge at high tide were calculated for the storm duration. These ranged from 0.1 metres above the predicted level at 10:45am on the 27th, to 0.4 metres at midnight on the 28th. By 12:40pm on the 29th, the observed level was 0.1 metres below the predicted level. These levels were taken inside Timaru Harbour and can only be used as estimates of the storm water level set-up for the open coast. However it can be assumed that they are representative of the order of magnitude of the storm set-up and therefore can be used to estimate the water depth at the critical break point of the mixed sand and gravel beaches south of Timaru.

Breaking wave heights and wave run-up heights were calculated from the wave and water level information using procedures from the Shore Protection Manual (C.E.R.C. 1984). Calculated significant breaker heights were between 3.2 and 5.5 metres. These are higher than the observed breaker heights of 3 metres at Washdyke. Wave run-up heights were calculated for the observed breaker heights using a formula developed by Kirk (1975) for beaches with a similar sediment character and profile shape at Kaikoura. These calculations produced a maximum run-up height of 7.4 metres above mean sea level at high tide.

Impact on the Beach System

There were two sites of major impacts to the beach in the study area. Figure 5.2 locates these sites and shows the area covered by sea water flooding as a result of a breach at survey site Profile 1, and overtopping and beach lowering at survey site Profile 5. The damage to the beach at Profile 1, also known as Waimate Creek or the Waihao Dead Arm, was a major breach of the narrow beach ridge separating the Dead Arm drainage channel from the sea. Figure 5.3a shows profile transects taken at Profile 1 before and after the July storm, while Figure 5.3b shows a contoured plan view of the breached section with the form of the overwash lobes clearly visible. The ridge crest was lowered by an average of 2.1 metres, from a height of 6.8 metres AMSL, over a length of 120 metres. The maximum reduction in height was 3 metres, resulting in the crest being lowered to 3.73 metres AMSL at one point.

Sediment transported landward of the crest by overflowing wave run-up was deposited in the Dead Arm drainage channel reducing the channel area from approximately 370 m² to approximately 90 m² at the southern overwash lobe. At the profile site, nearly all of the material lost from seaward of the beach crest was deposited on the landward side of the ridge. These sediments can still be considered to be part of the barrier beach. However in this position, the material is no longer directly responding to or dissipating the energy of breaking waves other than those overtopping the beach crest. As such it can be considered as lost from the active beach. For the 120 metres of breach a total of 3 828 m³ was lost from the seaward face of the beach, most of this loss being deposited landward of the beach crest.

In a letter to D. Todd of the South Canterbury Catchment Board (10/8/85), Kirk discussed the results of his analysis of three sediment samples from the breach area. He also discussed the implications of the character of the samples in determining the cause of the breach. Kirk noted that the structure of the beach at the breach site - the beach grain size component and the internal stratigraphy - played an important role in the scouring process. Although there was extensive overtopping along the coast, and other occurrences of overwash fans, this was the only site of breaching. Kirk found that the beach sample from near the top of the beach ridge was composed of coarse, very well sorted, well rounded beach gravels which had no interstitial fines. This material was freely permeable and allowed high throughflow velocities within the upper layers of the beach for the dissipation of wave run-up. The throughflow would be mainly in a landward and downslope direction (Kirk 1985). Samples from exposed lower beach sublayers were partly cemented and contained variable amounts of silts and sands. Kirk found that they were not well sorted and contained no strong fine tail to the
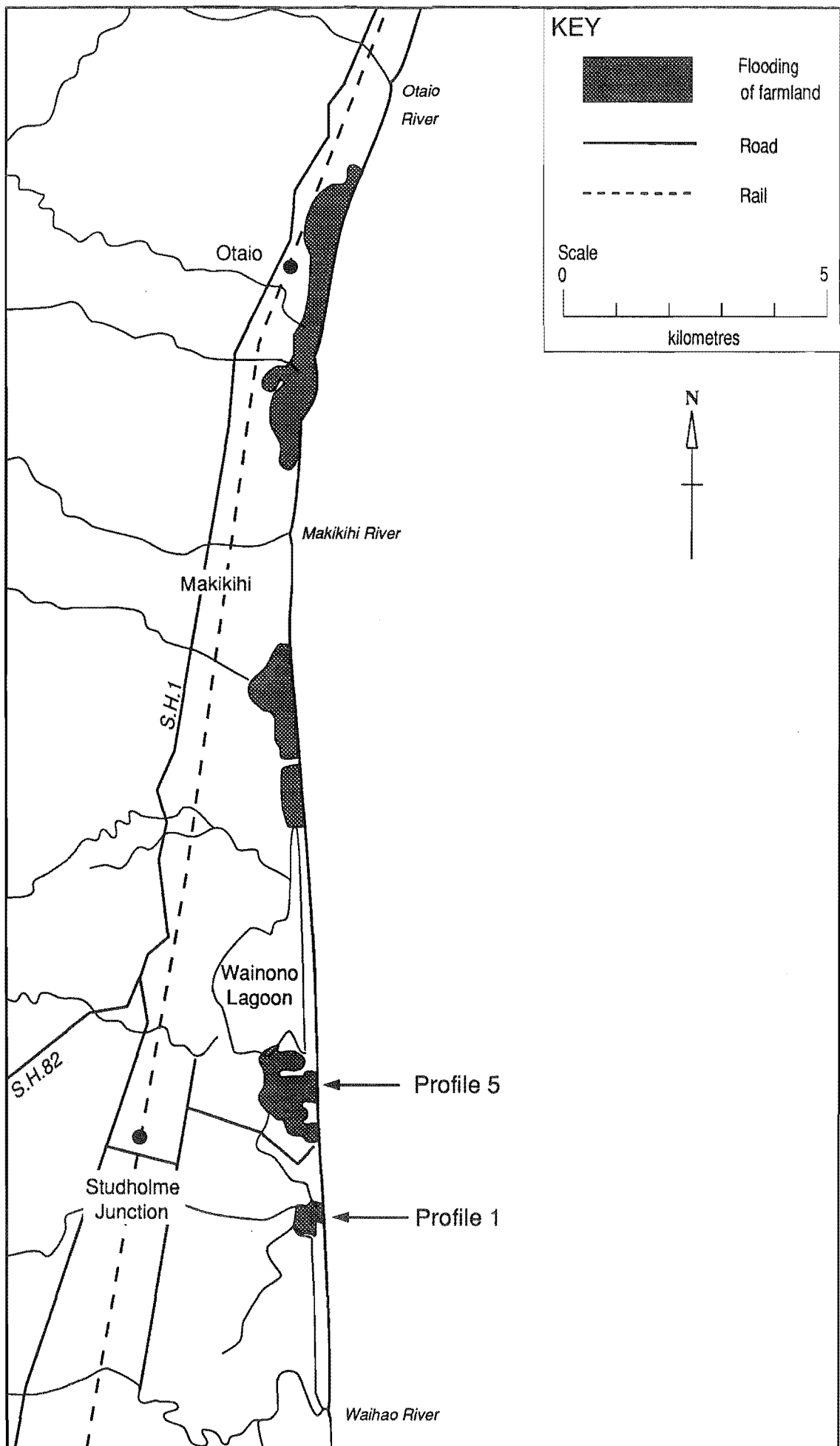
Figure 5.2 Extent of sea water flooding and location of damaged beach sites as a result of the July 1985 storm event.
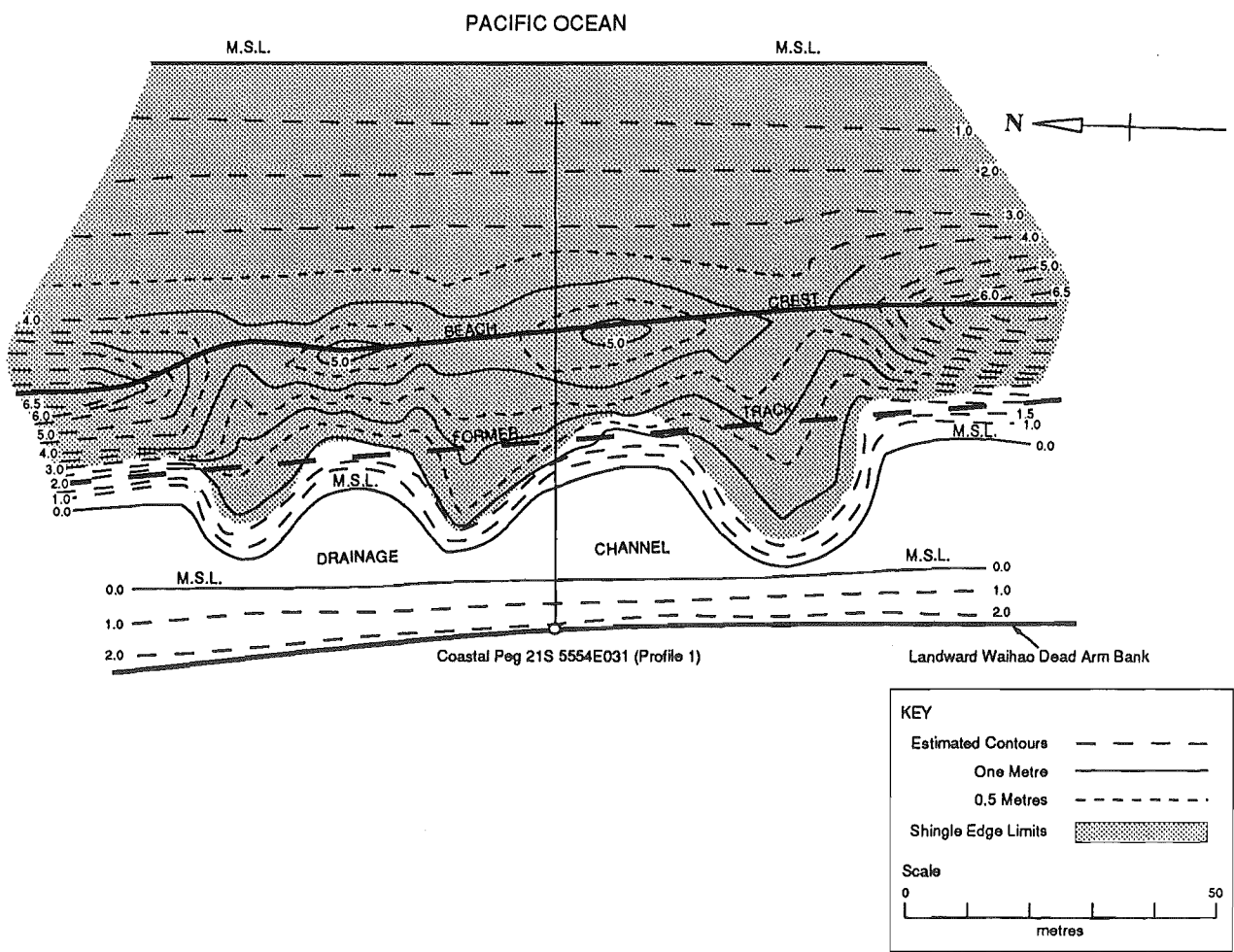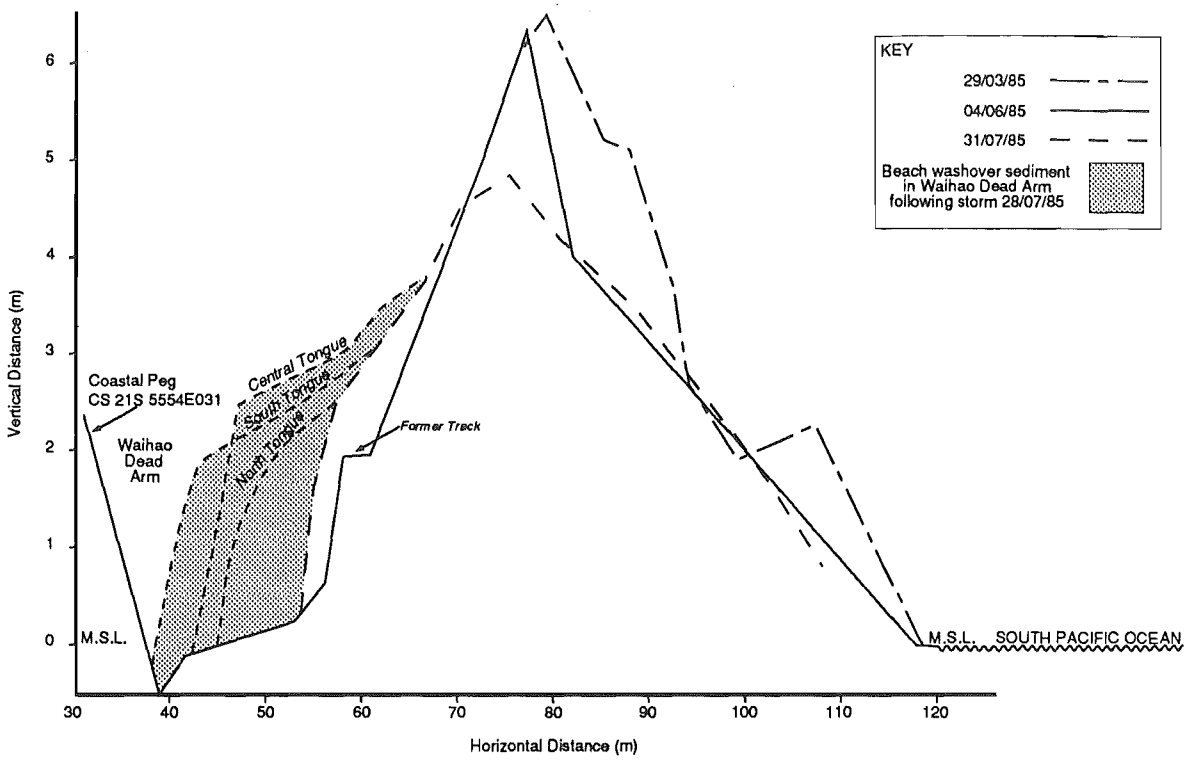
Figure 5.3 Breaching at Profile 1 (source, South Canterbury Catchment Board, 1985)

  a) Beach transects.

  b) Contoured plan view of beach.

sediment size distribution. They were also partly weathered and less permeable than the upper sample. He concluded that they were probably not beach gravels infilled by fines carried into the beach by percolating water, but were likely to be old exposed fluvial deposits. The result of this stratigraphic arrangement is that high volumes of water can be concentrated in the upper layers of the beach, above an effectively impermeable internal layer. This leads to high pressures (heads) and flow speeds generated within the beach, and along the surface causing scouring and displacing of sediment to landward. Kirk concluded that the initial displacement of surface sediments on the crest allowed wave run-up to flow directly over the internal layers. Then, scouring became the main active process widening and deepening the holes through the beach ridge and into the sublayer deposits.

Major overtopping and lowering of the beach crest occurred at survey site Profile 5, adjacent to the southern boundary of Wainono Lagoon as located on Figure 5.2. The cause of the crest lowering was thought to be related to high beach through-flows of swash water percolating from the seaward to the landward sides of the beach ridge resulting in 'pipe-like' failures on the backslope. Wave run-up overtopping the crest of the beach also transported disc and blade shaped gravel down the backslope. This reduced the crest height making it possible for run-up to overtop the crest for a long period and in large volumes resulting in downcutting of the crest and further scouring. Based on an estimate of the throughflow in the permeable upper level of the beach and from run-up heights, peak flows were calculated at approximately 0.12 $m^3 .s^{-1}$ per 1 metre length of beach. This flow rate was used to calculate an estimate of the amount of water that overtopped at Profile 5, assuming approximately 14 hours of overtopping of 150 metres of beach. The resulting 907,500 m^3 of water compared well with visual estimates of the amount of sea water which flooded 80 hectares of farmland adjacent to the overtopped beach, at a depth of up to 1.2 metres (S.C.C.B. 1985).

Figure 5.4a shows a survey of the beach profile at Profile 6. This site is at the northern end of the damaged section of beach as shown in Figure 5.4b and is not a true representation of the total storm impact to the surrounding beach. Figure 5.4b shows a longitudinal cross-section of the damaged site. It can be seen that the major impact was opposite the Wainono Lagoon Stopbank. A beach profile survey site has since been established at this point (Profile 5 in this study) but prior to the storm the only representation of the beach in cross section in this area was from Profile 6. The crest was lowered an average of 1.6 metres over a length of 1.2 kilometres, with the greatest amount of lowering, 2.5 metres, occurring in the centre of the overtopped section. Approximately 4200 m^3 of sediment was displaced. The toe of the backslope moved
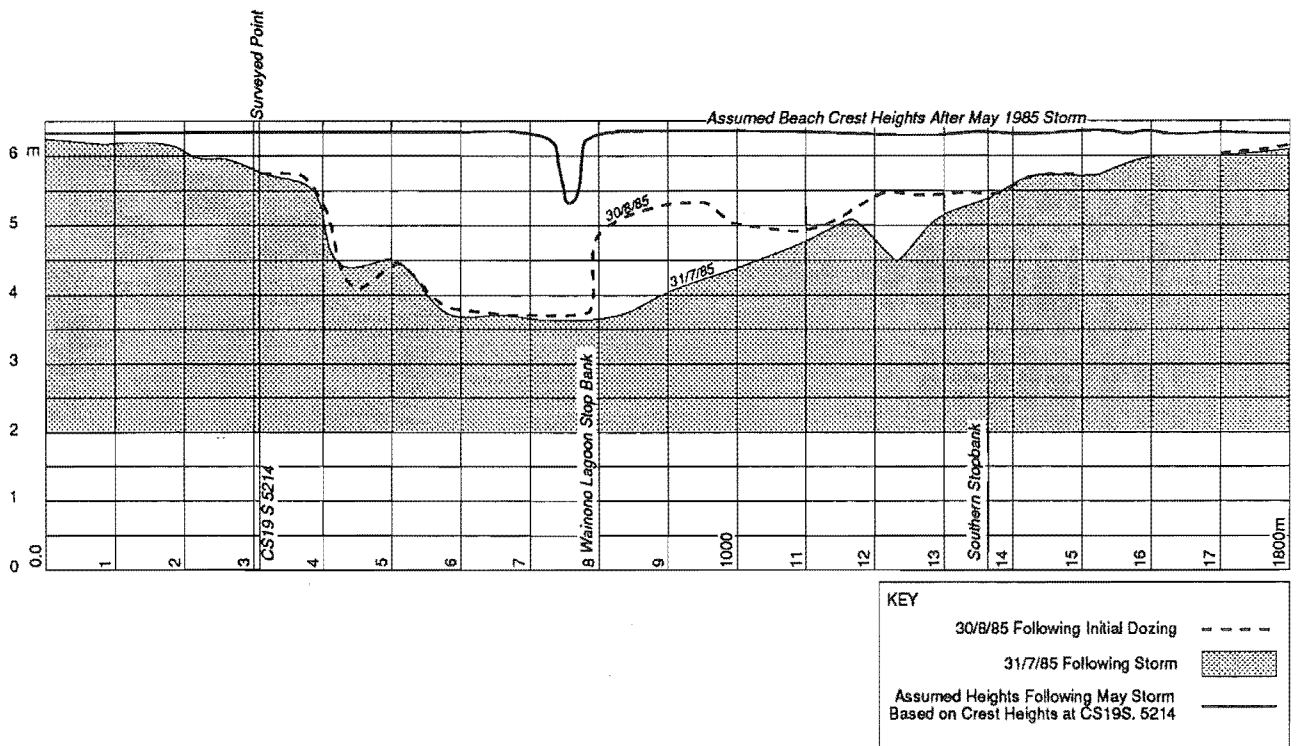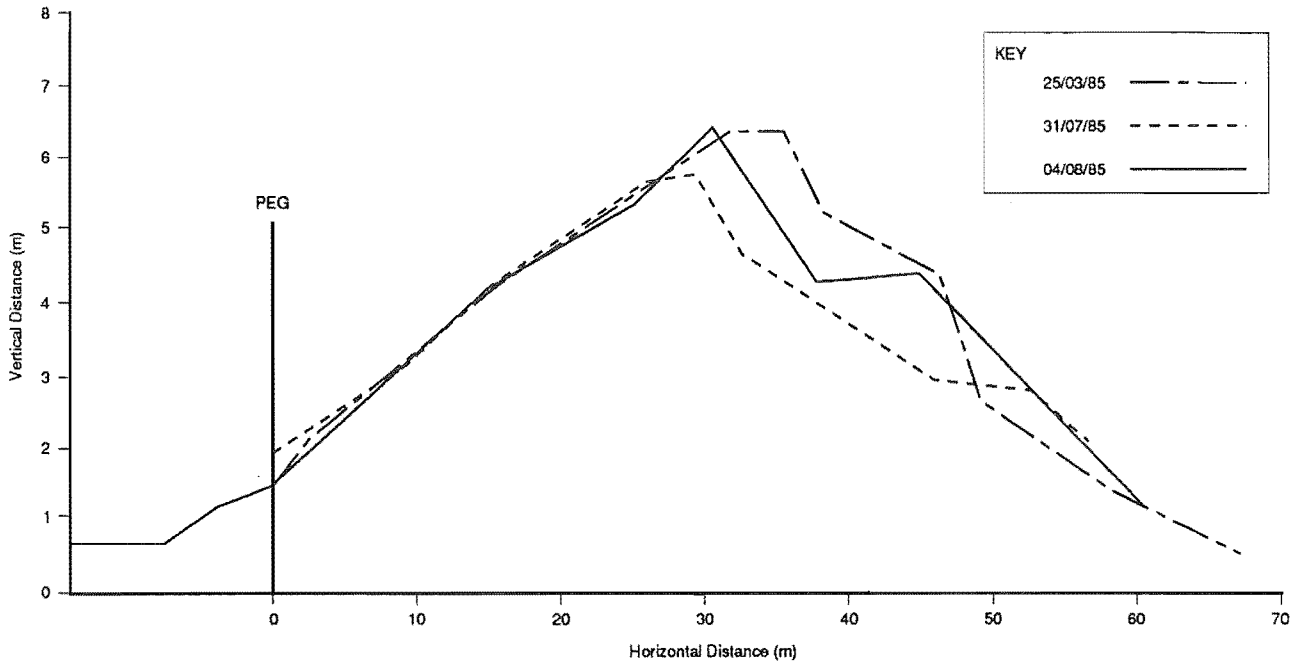
Figure 5.4 Overtopping and barrier crest lowering at Ruddenklau's frontage (Profiles 5 to 6), (source, South Canterbury Catchment Board, 1985).

a) Beach transects.

b) Longitudinal section of beach.

landward approximately 25 to 30 metres as a result of the deposition of material transported from the crest and upper foreshore of the barrier beach . Foreshore slope angles were also reduced, from 7-11° to 2-4°.

The implied difference in beach response to this storm between the Waimate Creek Dead Arm and the Wainono Lagoon stopbank is that at the former site the beach crest was breached by a near instantaneous failure of a section of the beach, whereas the latter suffered damage from wave run-up overtopping and the gradual removal of material from the beach crest to the backshore. It was noted in Chapter Four that there were no offshore features of the sea bed contours that would focus energy at specific sites of the Wainono Lowland Coast. There are also no known previous episodes of breaching or lowering at either of the sites damaged by the July 1985 storm.

Antecedent Conditions

Two storm events had occurred on the South Canterbury Coast shortly before the July event. The first was on the 21st and 22nd of April 1985, and the second on the 14th of May. Both of these storms registered larger waves as recorded on the 'wave rider' buoy, off the Rakaia River, and were longer duration events than the July storm. However the April storm was the first major storm event on the coast since July of the previous year. The interpretation offered here is that the April and May storms considerably weakened the beach system by the removal of foreshore material and steepening of the beach face. Figures 5.3a and 5.4a show the change to the beach in cross section at Profiles 1 and 6 between March 1985 and June 1985. Over 30 $m^3.m^{-1}$ of beach was removed between March and June from Profile 1, the crest was lowered by 0.2 m and retreated landward approximately 2 metres. The beach ridge above the 4.0 metre contour was significantly narrowed and steepened, whereas below this contour the foreshore gradient was less steep in June but more linear, being devoid of any intermediate storm ridges. At Profile 6 the crest retreated approximately 5 metres and there was approximately 10 $m^3.m^{-1}$ of beach removed. In June there was an intermediate storm berm at the 4.0 metre contour and below this there had been deposition of material since March. A narrow blowout was noted after the May storm south of Profile 6, approximately at the position of the Wainono Lagoon stopbank (Figure 5.4b), and was thought to be caused by a localised 'pipe failure' in the backshore. The 'pipe failure' is in the centre of the section lowered in July and was considered to be instrumental in causing the major beach lowering.

With reference to the interpretation offered above, it is considered here that the impacts of the July storm were a result of a combination of the effects of three storms

occurring in quick succession. It can be considered that the lack of storm events on the study coast for nine months prior to April had enabled the beaches to adjust to a moderate or low energy wave environment, establishing a beach profile by March 1985 as shown in Figures 5.3a and 5.4a. The June profile in both cases shows a loss of beach sediment from the upper foreshore and a narrower beach crest than in March. It is argued here that the beach was therefore a less effective barrier to wave attack before the July event.

5.2.2 Coastal storm of 30 May 1990

Situation

The first indication of high energy waves breaking on the South Canterbury coast was received by the Canterbury Regional Council from residents at Washdyke at 7.30am on the 31st of May. Figure 5.5 shows the mean sea level analysis of the situation at 12.00pm on the 31st of May. The large swells reaching the coast were generated by an intensive depression. On the 29th of May, this depression was situated 1300 kilometres south of Timaru and moving eastwards. By noon on the 30th of May it was located 1900 kilometres to the south-east of Timaru. The marine forecast predicted 50 knot southerly winds off the South Canterbury coast. It was noted by the Canterbury Regional Council that these speeds were less than those recorded in the generating area of the storm of July 1985.

Wave and Water Level Parameters

Wave observations at the coast were limited due to the lack of warning of the event and to the event occurring in the evening and early morning. Those carried out were made from Washdyke in conjunction with high tide, at 9.00 am on the 31st of May when beach overtopping was considered to be at a maximum. The mean wave height was estimated at 2.5 metres while the maximum breaking height was 3.5 metres. The average wave period was 16.5 seconds, and the breakers were observed to be spilling offshore and of a collapsing or plunging type at the beach. Wave run-up was measured at Washdyke by the Canterbury Regional Council observer and was found to be in excess of 40 metres across the foreshore. The wave approach angle was from the south with the incident angle of the breaking wave at the beach being 15°. A northward longshore current of 1.3 m.s^{-1} was observed. No other wave observations were carried out until 9.00 am on the 1st of June, at which time the wave height had reduced to a maximum of 2.0 metres and a period of 12 seconds. Wave run-up was measured as 25 metres across the foreshore, and there was no overtopping.
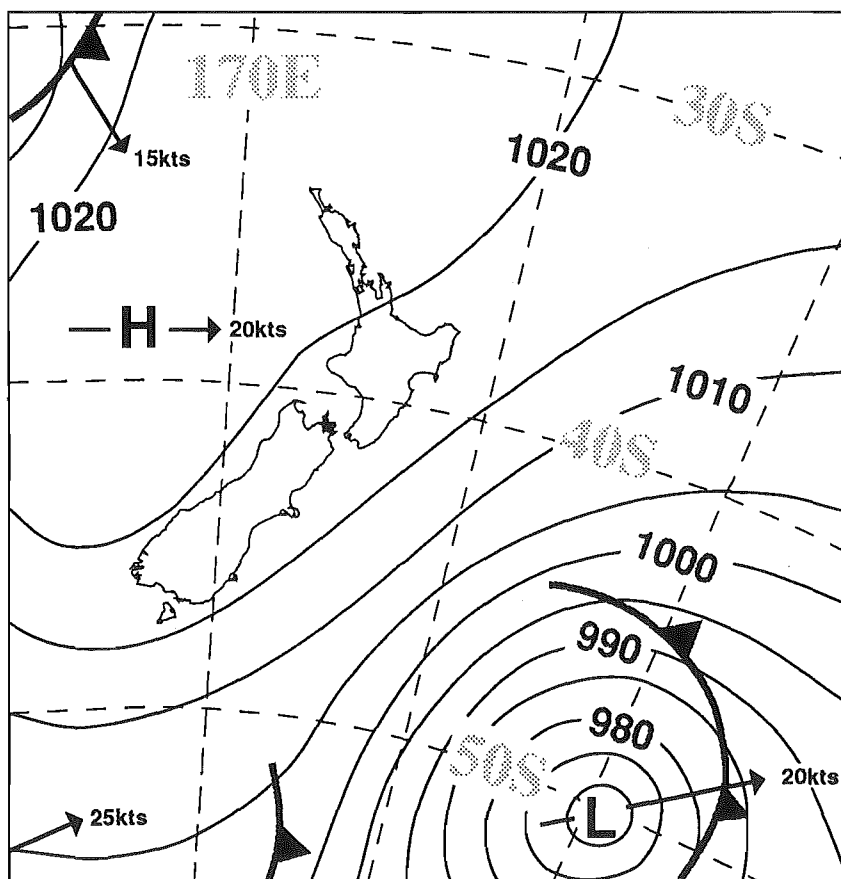
Figure 5.5 Mean sea level atmospheric pressure analysis map; 1200 hours, 29/5/90 (after N.Z. Met. Service Fax. information).

A crude estimate of storm surge equal to 0.2 metres at high tide was made by the Canterbury Regional Council by subtracting the predicted tide level at the Port of Timaru from the actual level as recorded on the Port's tide gauge within the harbour. The event occurred during a period between neap and spring tides. If the event had occurred in conjunction with spring tides, the resultant water levels at high tide could have been 0.5 metres higher than those recorded. This would have resulted in the possibility of higher breaking waves and wave run-up.

Impact on the Beach

The observed impacts on the beach included overtopping at high tide and some foreshore erosion along the 12 kilometre stretch of coast from Washdyke to the Opihi River mouth. The average crest height for this section of coast is 4.5 metres AMSL. A total of 15-17 $m^3.s^{-1}$ of water was estimated to have overtopped the beach crest for a total duration of 9.5 hours spread over two high tides. Material from the crest of the beach was also deposited in drainage channels at the base of the backshore slope in a number of locations.

Further south, along the Wainono Lowland Coast, maximum run-up heights reached the beach crest but did not overtop. It is noted here that the beach crests at this location are an average of 5.5 to 6.0 metres AMSL in comparison to the 4.5 metre crest height at Washdyke. Figure 5.6 shows the beach in cross section at Profile 1 before and immediately after the May 31st event. The impact at Profile 1 involved the net removal of 4.8 m^3 of sediment per metre of beach seaward of the beach crest, and a change in shape of the beach profile. Below about the 4.0 metre contour 10.65 m^3 of sediment per metre of beach was removed from the profile, while above this contour, up to about the 5.5 metre contour, 5.83 $m^3.m^{-1}$ of beach was added to the profile. The stepped profile shape of 1/5/90 was smoothed out and steepened. The average beach slope steepened from 10° to 13°. However, the steep lower foreshore and the lower section of the beach crest slope became less steep, changing from 21° to 10°, and from 36° to 12° respectively. The limit of beach response due to wave run-up was about 5.3 metres above mean sea level.

Figure 5.7 shows the surveyed cross sections from Profiles 2, 3 and 5 which were also surveyed directly after the May 1990 storm event. Profiles 2 and 3 are very different in shape to Profile 1, in that they were broader and flatter. The volume of sediment for Profile 3 seaward of the crest and above the 1.0 m contour is over twice the corresponding area of Profile 1, approximately 200 $m^3.m^{-1}$ of beach to 87 $m^3.m^{-1}$ of beach respectively for 1/5/90. The volume of Profile 2 at 105 $m^3.m^{-1}$ of beach is much
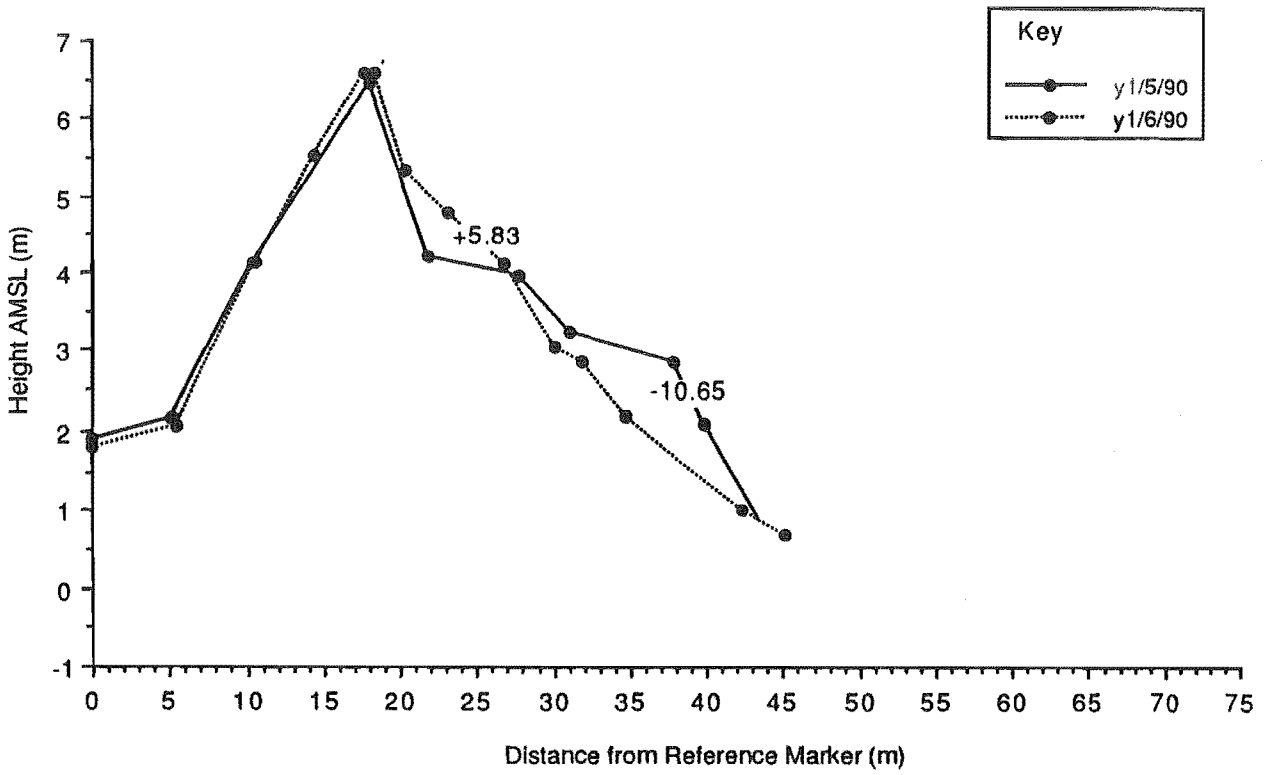
Figure 5.6 Beach profile adjustment at Profile 1 between 1/5/90 and 1/6/90.
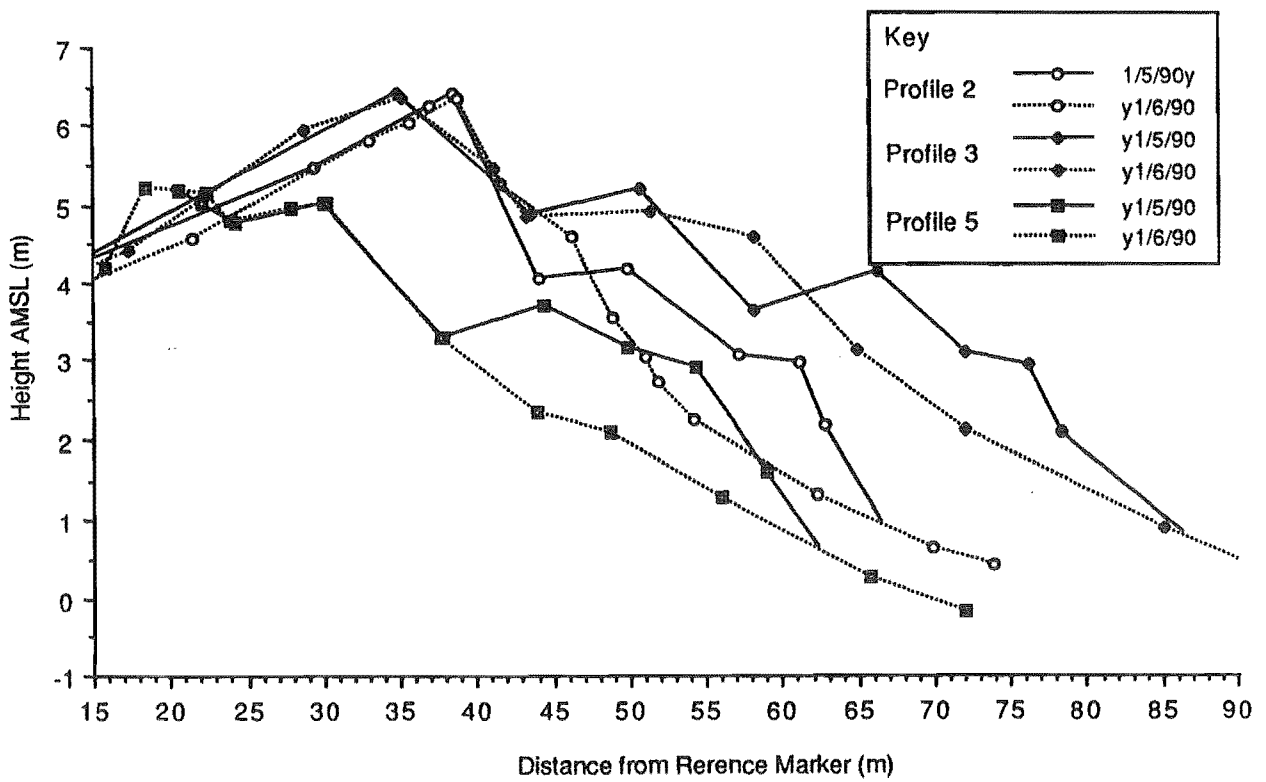
Figure 5.7 Beach profile adjustment at Profiles 2,3, and 5 between 1/5/90 and 1/6/90.

smaller than Profile 3 but is still larger than that of Profile 1. Profile 5 is a modified section of the coast due to beach reconstruction following the overtopping that occurred in July 1985. As such, the crest of this profile is more level and approximately 1 metre lower than the crests of Profiles 1, 2 and 3. From Profiles 2 and 3 it can be seen that the form of the impact of the event was similar to that which occurred at Profile 1, in that the beach profile was generally smoothed and steepened, with material being removed from the lower foreshore and deposited above the 4.0 metre contour. Table 5.1 summarises the volume changes to the profiles. The greatest net change occurred on Profile 5. However this profile exhibited no changes landward of the interberm nadir of 1/5/90 at approximately 3.3 metres AMSL.

Profile	Net sediment change	Change above 4m contour	Change below 4m contour	1/5/90 Vol. from crest to 1m AMSL	% Change 1/6/90
1	-4.82	5.83	-10.65	87.48	5.5
2	-21.21	1.80	-23.01	105.73	20
3	-14.98	2.75	-17.73	199.02	7.5
5	-24.42	NC	-24.42	90.3 (69.21)	27 (35)

Note: All values are in m^3 of sediment per metre of beach.
NC = no change to the profile
The value in brackets is seaward of the limit of the active profile since 1987

Table 5.1   Foreshore volume changes to Profiles 1,2,3 and 5 between 1/5/90 and 1/6/90.

The most noticeable change to the lower foreshore was the removal of the accretionary berm, changing the beach shape from convex seaward to concave seaward. Although the pre-storm profiles are quite different in shape it is also interesting to note the similarities in shape of the lower foreshore on 1/6/90. Due to the sea conditions at the time of the profile surveys, and the unstable character of the lower foreshore and the steep nearshore, the profiles do not extend past the nearshore step to the nearshore bed. However at Washdyke, after a storm event it has been found that the nearshore step can become less steep with the transition from the foreshore to the nearshore being more gradual (D. Todd, Canterbury Regional Council, Timaru 1990, pers. com.).

Antecedent Conditions

Prior to the May 1990 event there had been no major storm events at the coast since August 1986. This was a contributing factor to the limited impact of the storm on the beach (C.E.R.C. 1990), as the beaches were in what could be considered as a 'healthy' condition, whereby the volume of sediment available for the dissipation of wave energy was large enough to withstand the amount of removal of material that occurred over the duration of the storm. This factor can only be acknowledged in hindsight as the storm did not result in breaching or major overtopping although the wave sizes and duration of the event were closely comparable to the damaging July 1985 event. However an informed intuitive 'feeling' for the susceptibility of a beach of this nature to storm damage can be made from direct observation of the beach profile shape and the volume of sediment (D. Todd, Canterbury Regional Council, Timaru 1990, pers. com.).

5.3   Analysis of May 1992 Storm Impact

Two high energy events were experienced on the South Canterbury Coast on 10/5/92 and 21/5/92. They were the first major storm events recorded since May 1990. At the time of writing the storm and oceanographic parameters of these events had not been fully documented or analysed. However some basic information was available. Figure 5.8 shows the Mean Sea Level analysis maps for the two storms. The first storm was generated by an intensifying depression centred about 1500 kilometres east of the South Island, moving slowly to the north-east. Waves approached the South Canterbury coast from east of south-east. The second storm was generated by a strong depression moving from west to east, south of New Zealand. Waves approached the South Canterbury coast from the south. Heavy rainfall was experienced at the coast during each storm. The significant breaking wave height for both storms was estimated as being approximately 3.6 m and both events resulted in overtopping at Washdyke Lagoon.

Profiles 1 and 2 were surveyed in March 1992 as part of the on-going beach monitoring program, and were resurveyed by the Canterbury Regional Council after the second storm event. Plots of these surveys are shown in Figure 5.9. The profile changes shown are clear examples of the beach response that occurs due to high energy events. The antecedent profiles seaward of the crest both have an average gradient from the crest to the lower foreshore of 9° (18.6° landward and 9.7° seaward of the intermediate storm berm) and are generally concave in form. The 25/5/92 profiles show a distinct break between the lower and upper foreshore with different slopes and a change in form from convex to concave respectively. The slope of the adjusted profiles
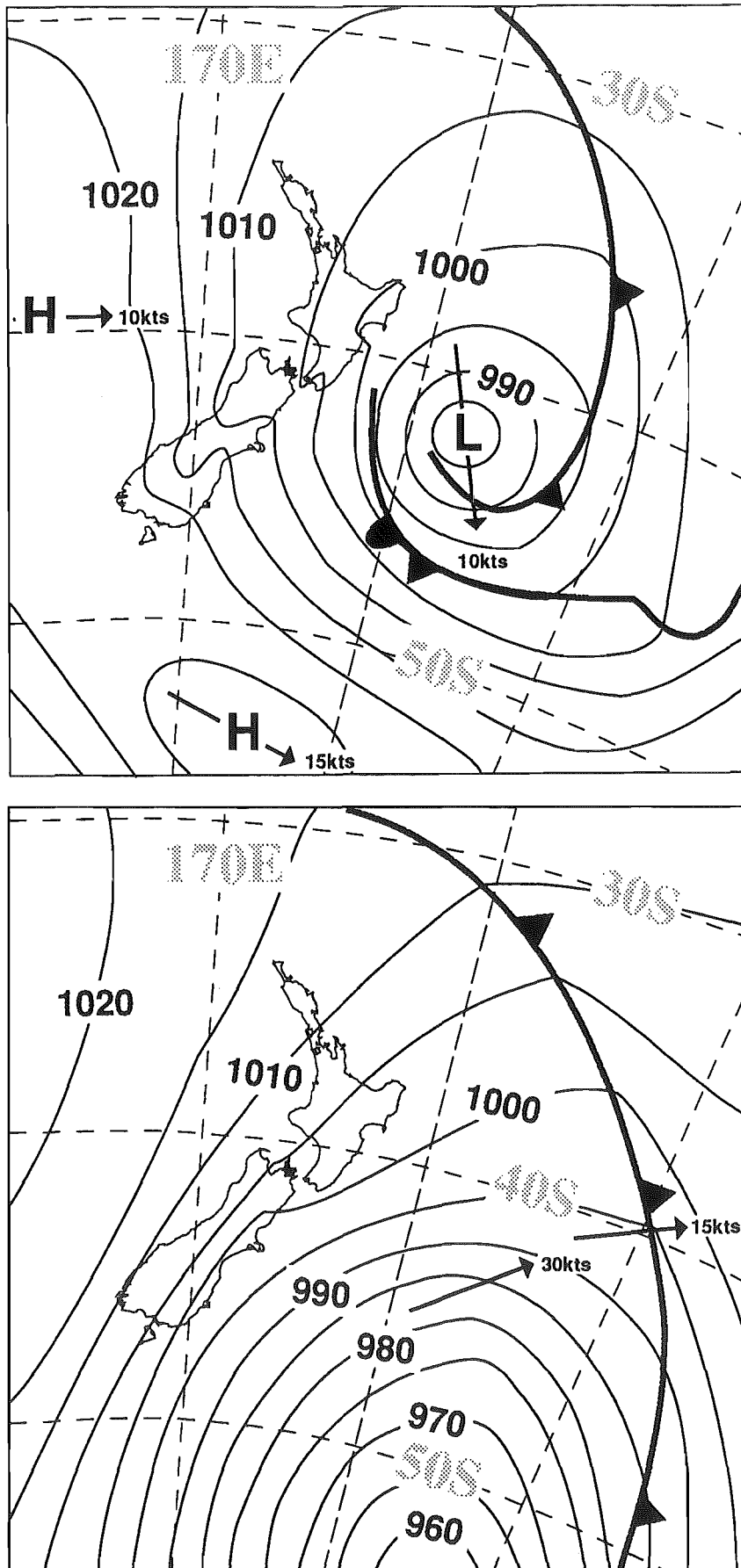
Figure 5.8 Mean sea level atmospheric pressure analysis maps; 1800 hours, 9/5/92 and 1200 hours, 21/5/92 (after N.Z. Met. Service Fax. information).
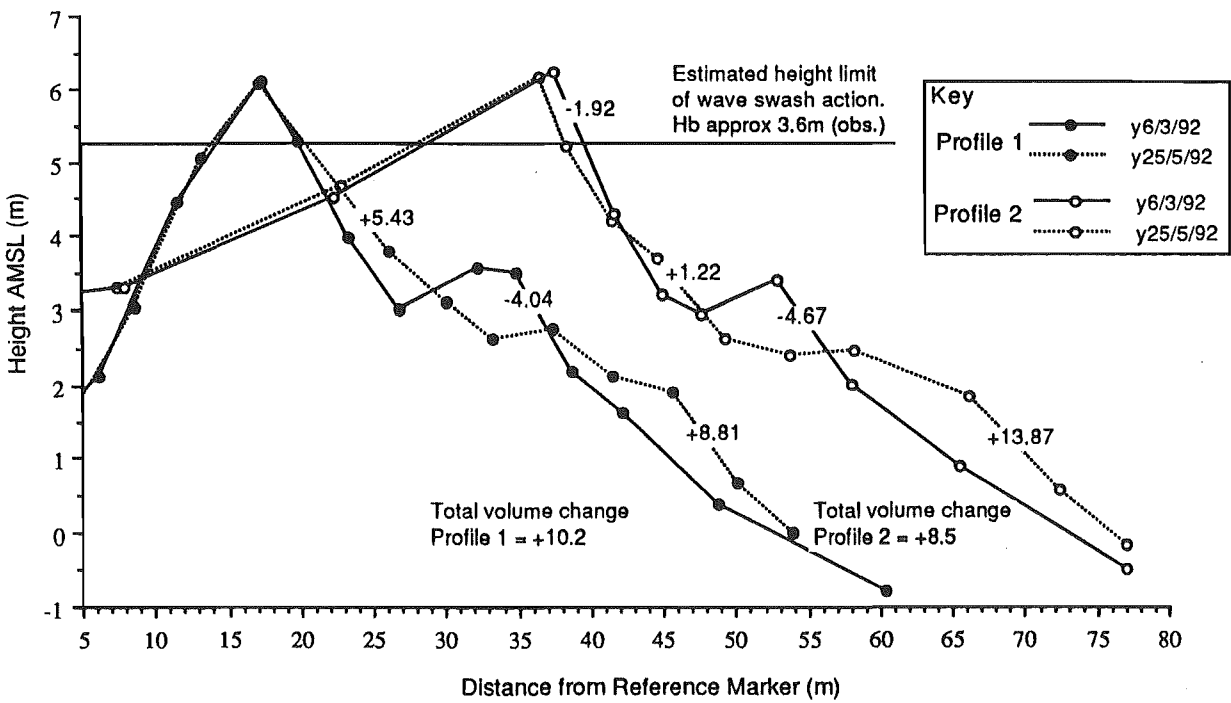
Figure 5.9 Beach profile adjustment at Profiles 1 and 2 between 6/3/92 and 25/5/92. Volumes in $m^3.m^{-1}$ of beach.

from the barrier crest to the interberm nadir is 13°, while the slope from the lower crest to the seaward extent of the survey is approximately 9°. The initial volumes seaward of the crest and above mean sea level are almost the same, at 97.5 m³ .m⁻¹ of beach for Profile 1 and 99.6 m³ .m⁻¹ of beach for Profile 2. The difference is mainly in the size of the intermediate berm. By 25/5/92 for both profiles, the intermediate berm, at 3.5 metres AMSL had been removed, the gradient of the beach had become less steep, and there had been deposition on the lower half of the foreshore. The beach volume changes are noted on Figure 5.9. There are notable differences in the profile adjustment near the crest of the barrier. While there was accretion up to just below the crest on Profile 1, the crest of Profile 2 eroded and retreated 1.5 metres. This may be indicative of differences in the sediment composition of the sites, especially in that Profile 1 was rebuilt after breaching in 1985 and contains reworked overwash material. Observations made at Profile 2 on previous occasions showed that the upper foreshore is composed of layers of large pebbles and small cobbles supported in a matrix of fine material as shown in Figure 5.10. Erosion may have occurred due to destabilisation of the slope below the crest at the limit of wave run-up. Saturation of the beach due to rainfall may also have been a factor in causing the backwash to be effective in removing material downslope.

It should be noted that Figure 5.9 shows the profile adjustments for a two and a half month period, not purely for one storm event. Smaller events would also have caused the profile to adjust between 6/3/92 and the storm of 10/5/92, either by accretion or erosion, or the building up or removal of intermediate swash berms. The changes described above have occurred between two points in time and without other information the process regime must be assumed to be consistent with the idea of two high energy events imposed on a beach adjusted to a moderate or low energy wave environment.

5.4   Characteristics of the Example Storms

The storm events described in the previous sections are assumed to be typical of the types of event and the resulting impacts that occur on the study coast. Of the four storms examined, two types of generating system are in evidence. The events of July 1985 and 10th May 1992 were associated with depressions centred to the east of the South Island, moving slowly south. The approaching waves were from the south-east. The May 1990 and 25th May 1992 storms were generated to the south of New Zealand by intense low pressure systems moving from west to east across the Southern Ocean. All of the storms were rapid in onset although the generating areas were over 1000

Figure 5.10 Matrix supported gravel clasts exposed at the base of the upper foreshore approximately 50 metres south of Profile 2.

     a) Location Photo, taken from Profile 1, looking north to Profile 2.

     b) Detail of exposed section, sunglasses included for scale. This site located at centre of a) above.

kilometres distant. This meant there was little warning time at the coast of possible overtopping or damaging erosion. In two cases the Canterbury Regional Council was first notified of the event by residents at the coast reporting the large breaking waves. The durations of the impact of the storms at the coast varied from 12 hours to 30 hours. The longer duration events were associated with the storms generated from the east of the South Island. The observed maximum breaking wave heights were similar, being between 3.0 and 3.6 metres. The height of the breaking wave at the shore is dependent on the depth of water. For mixed sand and gravel beaches, the nearshore water depth decreases rapidly at the interchange between the fine sand nearshore seabed and the coarse grained beach. It was noted by the Canterbury Regional Council investigator that the waves started to break and spill approximately 50 metres offshore. The plunging breaker at the nearshore step was in some cases the third generation of the initial wave. Although the largest waves occurred during high tide, none of the examined storms coincided with spring tides, reducing the possible wave height.

Impact at the beach included wave overtopping and beach erosion. The July 1985 storm caused by far the greatest amount of damage and change to the beach profile. The beach response to the storms was not uniform. However there were similarities in the overall nature of the response. Common factors include erosion of the upper foreshore and of intermediate berms, deposition in the lower foreshore and retrogradation of the profile. There was not necessarily net erosion of the beach sediment volume. The average beach slope steepened, but only because of the overall shape of the profile changed. Specific areas of the profile steepened, such as the lower foreshore, while other areas such as the upper and middle foreshore became less steep. The major change in profile shape came about due to the removal of any intermediate berms, removing an essentially convex feature from the beach, as can be seen in Figure 5.9.

The antecedent conditions of the beach are an important factor in determining the beach response to a high energy event. An adjusted profile presents the antecedent profile conditions for the next set of waves. The severity of the impact of a storm is controlled by the ability of the beach to dissipate wave energy. The beach is in a 'healthy' state in the role as protection of the coastal hinterland from wave attack, if for the duration of a storm or high energy event, it is considered that the energy of the waves and swash processes can be absorbed or dissipated by morphological responses of the beach without the beach failing, by for example breaching or overtopping. It has been shown that the damage to the coast caused by the July 1985

storm event was in part due to the depleted condition of the beach as a result of two earlier storms (in April and May 1985). The May 1990 storm occurred after a long period of relatively low energy wave conditions, and although of a similar magnitude to the July 1985 event, the damage was not as great. An intermediate berm is present on the foreshores of Profiles 1 and 2 on 6/3/92, indicating that accretionary processes had been at work. However there had been removal of material from the mid-foreshore and accretion on the lower foreshore of Profile 1 and removal of sediment from the lower and upper foreshore of Profile 2 since 30/7/91. The net change in foreshore volume between these dates was erosion of 5 $m^3.m^{-1}$ of beach and 17 $m^3.m^{-1}$ of beach for profiles 1 and 2 respectively. Therefore although these profiles were in a progradational phase in March 1990, the foreshores, especially at the higher elevations, were still steep and narrow in comparison to their form before the May 1990 storm. This may be a reason for the difference in beach response to the two storm episodes. It is evident that a beach that is well nourished or has a high sediment volume, and has undergone a period of accretion, will provide better protection against wave attack than a beach which has a low sediment volume, low elevation and is very steep.

5.5   Discussion

The aim of this chapter is to clearly define the characteristics or parameters of high energy or storm events for the Wainono Lowland mixed sand and gravel barrier beach coast. Four storm episodes have been examined in an attempt to clarify the common storm parameters and the known adjustments of beach profiles in the study area. Only one of these storms occurred during the field study period for this thesis. Due to the lack of storm incidence, the rapid onset and short duration of South Canterbury coastal storms and the isolation of the field area, no field observations were made during this event. This deficiency in data has been overcome by approaching the problem from an analysis of changes to beach profiles. In respect to the questions offered in the introduction to this chapter, the information presented can be used to provide qualitative answers.

5.5.1 Barrier breaching and overtopping

It has not been possible to develop the detail necessary to give a full account of all the factors involved in addressing the specific issues of the mechanics of beach crest lowering and breaching. However examples of this type of damage were discussed in relation to the storm of July 1985. In particular, the breaching of the barrier beach at Profile 1 and the overtopping and beach crest lowering that occurred at the location that was to become Profile 5 were discussed. Kirk (1985) put forward an hypothesis as to

the cause of the breaching at Profile 1. This was a result of an examination of sediment samples taken from sections of the internal stratigraphy of the beach that were exposed during the breach. He found that an effectively impermeable layer of fine sediments from exposed fluvial deposits caused high volumes of water to be concentrated within the upper levels of the barrier. This led to high pressure heads generating high flow speeds of water within the beach and along the surface of the backshore causing scouring and erosion of sediment down the backslope. After the initial removal of surface sediments from the crest, wave run-up flowed directly over the exposed internal stratigraphy. Scouring became the main process in widening and deepening the holes through the beach sediments and into the sublayer deposits. Major lowering of the beach crest at Profile 5 was thought to be initiated by an internal 'pipe failure' in the backshore that occurred during the storm of May 1985. This caused a collapse of the beach above and around the area which was exploited by wave run-up during the July storm. Water flowing over and through the lowered crest gained velocity and transported surface sediments down the backslope.

From observations of the crest during this study, lowering has occurred without overtopping of the crest. It is thought that this is the result of oversteepening of the upper foreshore by wave backwash induced erosion, causing the unsupported crest to collapse seawards. A similar process may also have occurred at and near Profile 2, where an erosion scarp developed as shown in Figure 5.10. Because of the steepness and instability of the slope above the scarp, further erosion could cause the upper foreshore to collapse. Observations of the backshore of Profile 1 seemed to indicate a bulging landwards of the backslope at about 4.5 metres above mean sea level. However, this did not show up in the survey data. Stock tracks forming terracettes were evident further south along the backshore. These may have caused compaction and dislodgement of sediments from the barrier.

5.5.2 Short term impact of storm events

Four main factors have emerged from this study as being important to the way the beach profile responds in the short term to high energy events. These are: -

    a) the slope of the foreshore,

    b) the presence, and dimensions of intermediate berms,

    c) the initial volume of beach sediment seaward of the crest, and

    d) the sediment composition and structure within the foreshore.

It is assumed here that for events that result in overtopping, the morphology of the backshore would be another factor. The first three factors have also been shown to display the main profile adjustments in response to the wave environment. The immediate and short term effects of a high energy event have been summarised in Section 5.4. Commonly, any intermediate berm is removed from the foreshore, the slope of the beach is steepened due to the averaging out of the steep lower foreshore and the often landward sloping section between the intermediate berm and the upper foreshore. The net change in beach volume is not necessarily erosion. However there is a definite redistribution of sediment in reshaping the profile form.

An important feature of the adjustment of the profile is the formation or removal of intermediate berms from the middle foreshore. The formation of these berms is also an important aspect of the morphological mechanics of the mixed sand and gravel beach. Deposition occurs within the swash zone. Therefore the wave processes forming the berms must be of a great enough magnitude to produce run-up to at least 4 metres AMSL at high tide, and they must be of a depositional nature in that the swash dominates the backwash as a geomorphic agent. The horizontal width of an intermediate berm is a function of the time involved in uninterrupted berm construction. For example, a low elevation berm is shown on Profile 3 in Figure 4.3c which formed between 6/9/88 and 17/10/88. The formation of this berm resulted in accretion of approximately 27 $m^3.m^{-1}$ of beach and a maximum horizontal development of about 8 metres. Conversely, the wave processes that remove intermediate berms must be erosional and of sufficient height to affect the entire feature.

Kirk (1970) found that wave steepness was not a good predictive parameter of beach erosion, and that the phase ratio of waves arriving at the shore was a better indicator of the likely foreshore response. He noted that the most significant erosive changes to the beach occurred during periods of high phase differences, whereby there was continual interference between the incoming and outgoing flows. Because of the non-availability of wave data for specific periods and conditions during this study, more work is required to define the wave parameters and phase ratios that produce adjustments on the profile that are damaging to the integrity of the beach function (how well the beach protects the hinterland from the sea).

The short term impact of a high energy event as separate to the immediate or short term response, is in the determination of the morphological characteristics of the profile as the antecedent conditions for the next wave environment. To this extent the impact is dependent on the wave processes experienced after the event. There is a

need for a recovery period between storms, so that the beach can build up to a more protective barrier and dissipate the energy of the next storm event.

5.5.3 High energy events

In characterising 'high energy' events, definitions of storm events as used by the South Canterbury Catchment Board (Todd 1988) and by Kirk (1987a) were offered as examples of the factors that have been considered in the past. Basically, they separated the oceanographic parameters of wave height, period, and direction, water level and storm duration, from the impact of the event at the coast. A qualitative definition was offered for this thesis which maintained the interactive nature of the event and the beach response. This definition states that a storm event could be considered high energy if the wave processes caused a response in the beach morphology such that the form of the beach profile was altered by the removal or relocation of beach material in a short time period. Quantitative values for the magnitude of the storm parameters or changes to the beach were not offered at that stage.

Four storm episodes were analysed in this chapter and the characteristics of these high energy events were discussed. Two types of generating systems were identified. The longer duration events (approximately 30 hours) resulted from storms generated by slow moving depressions east of the South Island. The shorter duration events (approximately 12 hours) were generated south of New Zealand by intense low pressure systems moving eastward across the Southern Ocean. Although both generating systems were over 1000 kilometres from the South Canterbury Coast, there was little warning of the onset of storm waves at the beach. The maximum observed breaking wave heights were between 3.0 and 3.6 metres for the four storms.

In Chapter Four, seven episodes that resulted in adjustment to the beach at high elevations during the study period were noted (Section 4.4.3). These episodes include the May 1990 event discussed in Section 5.2.2. The beach adjustments due to the high energy events discussed in Chapter Four and in this chapter were not uniform. Impacts on the beach included wave overtopping and beach erosion, but the events can result in constructive or erosional adjustments. Erosion or deposition may both occur over the complete profile or on different sections of the profile. Examples have been presented where there has been erosion of the upper foreshore and accretion to the lower foreshore, accretion on the upper foreshore and erosion of the lower foreshore, and accretion on the upper and lower foreshore with erosion of the intermediate region. Three types of beach response can be identified. A classification of these responses which recognises the differences in consequence to the beach function due to different

beach adjustments is proposed. In an effort to reduce confusion with existing classifications the terms used here refer directly to the type of response not to the magnitude. The classification is as follows:

'Destructive' - events that result in overtopping or beach crest lowering with an ensuing loss of material from the coastal system.

'Damaging/Erosive' - events which change the status of the beach from 'healthy' to potentially 'weak' due to a change in foreshore form and the removal of sediment from the profile.

'Damaging/Constructive' - events that result in changes to the foreshore form by net accretion of sediment to the profile.

This classification identifies the short term impact of the storm and the antecedent conditions that are presented to changes in the wave environment. It is also informative in identifying potentially hazardous sites for remedial work or further investigation.

At this stage there are not sufficient quantitative data of the oceanographic components of storms or of event specific beach response to propose a definition of high energy events. From the information presented in this study, a semi-quantitative characterisation of high energy events can be advanced.

Table 5.2 shows values of various characteristics and the beach response for the high energy events identified in this study, in respect to the three classes of resulting beach adjustment. The characteristics used in Table 5.2 are not the only factors that describe storm events or could influence the beach response. Other factors include atmospheric pressure at mean sea level, wind speed and direction, and tidal stage (neap or spring). The variables included in Table 5.2 are those for which comparable data were readily available for the four analysed storm events.

During the study period, the number of high energy events averaged 1.9 per year, with approximately one event each of the 'Damaging/Constructive' and 'Damaging/ Erosive' types. There were no 'Destructive' events during the study period. It has already been noted that the wave conditions during the study were atypical. Therefore the calculated frequency of high energy events should not be used to predict the probability of event occurrence.

There are many similarities in the process variables. The maximum breaking wave heights for the recorded storm events were between 3.0 and 3.6 metres and run-up reached at least 5 metres elevation in all cases. For the six smaller events noted in Chapter Four, for which there were no wave data, the run-up elevations were estimated

| Characteristics | Type of High Energy Event | | |
	Damaging/ Constructive	Damaging/ Erosive	Destructive
Processes			
Max. breaking wave height (m)	3.6	3.5	3
Water level set-up (m)	NA	0.2	0.4
Direction of wave approach	ESE S	S	SE
Duration (hrs.)	18 12	12	33
Runup elevation (m)	min max 3.5 5.2	min max 4.5 5.2	>5
Beach Response			
Volume change (m³ .m⁻¹)	+9	-16.35	-33.5
Excursion dist. (m)			
*Lower 2m	+5.5	-6	+1
Middle 3m	-3.5	-10	-2
Upper 4m	+1.5	+1	-4
Change in crest height (m)	-0.1	0	-1.8
Steepening			
*Lower	more steep	more steep	more steep
Middle	less steep	more steep	more steep
Upper	less steep	less steep	less steep
Antecedent Conditions	One intermediate berm, 7° slope on lower foreshore	Large inter- mediate berms, 18° slopeon lower foreshore	No inter- mediate berms 10° slope on lower foreshore
No. of events considered	5	4	1
Average no. of events per year from 2/9/87 to 25/5/92**	1.1	0.8	0

Note: NA   No data available
   *   Section of the foreshore
   **   Does not include the July 1985 storm

Table 5.2   Characteristics of high energy events.

from adjustment to the profiles. The elevations of run-up ranged from 3.5 metres to over 5 metres. The run-up for the 'Damaging/Erosive' events all reached over 4.5 metres. The minimum run-up elevation for the high energy events identified in this study was 3.5 metres AMSL. This would require a breaking wave height of 3.0 m at mean sea level, or 2.5 m if the water level set-up due to high tide is considered. Therefore wave episodes with breaking wave heights in excess of 2.5 metres can be considered as 'high energy events'.

The main differences in the processes of a 'Destructive' event and the other categories are the storm water levels and the storm duration. For the examples analysed, the storm water level set-up (or storm surge) for the 'Destructive' event was double the set-up for the 'Damaging/Erosive' event. The storm duration is an important variable, in that longer duration storms are more likely to be destructive. A 'Damaging/ Constructive' event could become 'Destructive' if continued erosion of the middle foreshore caused a structural failure of the barrier such as breaching or a 'pipe failure'. The direction of wave approach appears from the storms studied, to have little impact on the magnitude and type of the beach response. However, the direction of approach may be a controlling factor on the duration of the storm. More data are required to verify this proposition.

The major differences in beach response between the types of high energy event are the magnitude and direction of volume change, and the elevation of maximum foreshore retreat. For the destructive events there is steepening of the middle and lower foreshore and erosion at high elevations. 'Damaging/Erosive' events also steepen the lower foreshore, but the erosion of the foreshore occurs mainly at lower elevations. The main factor of the 'Damaging/Constructive' events is that they result in accretion to the upper and lower foreshore, while there is erosion of the middle foreshore.

An important factor in determining the type of beach response is the antecedent condition of the beach profile. The presence of one or more intermediate berms is likely to reduce the amount of damage to the beach by providing a buffer of sediment for wave dissipation and absorption of energy seaward of the barrier crest. The slope of the lower foreshore will also affect the swash processes. A steep lower foreshore will cause a large swash period/wave period phase ratio difference which will cause erosion from this section of the beach.

So far, beach profile change and the response to high energy events in the study area have been dealt with at a site specific level. In effect, this a two dimensional

approach. It has been acknowledged that the area has a strong longshore component to changes in the beach morphology. The next chapter will address the field area as a total coastal system in which the adjustments to one site will be examined in respect to changes to adjacent sites. The notion of slugs of sediment moving along the coast will also be examined in light of the data collected for this study.

CHAPTER SIX

SPATIAL ANALYSIS OF THE WAINONO LOWLAND COASTAL SYSTEM

6.1 Introduction

In Chapter Three the Wainono Lowland Coast and the larger coastal system of which it is a part were described. In Chapter Four individual beach profiles on the coast were examined and the changes observed during the study period were described and interpreted. These examinations dealt with the profiles as specific and separate sites. In this chapter, the study area will be looked at with reference to alongshore and across-shore interactions of morphological change.

The spatial analysis is carried out under three headings, which look at different aspects of similarities and differences between the study sites. The first section will examine the spatial context of changes to the form and shape of the profile sites during the study period. The profile data will be discussed with reference to changes over time having a longshore component. In particular that the adjustment of one profile site will be linked in some way to the adjustments of adjacent sites. The sites are assumed to be subject to the same oceanographic process environment. There are no offshore features of the sea bed contours such as submarine ridges or mounds, that would cause wave energy to be focussed onto specific sites. This assumption has been previously noted with reference to the damage to the beaches at Profile sites 1 and 5 caused by the July 1985 storm and is generally applicable to the study area. Two factors could cause the processes at different sites to vary. The first is the initial form and shape of the profile at a site. It has been noted that the lower foreshore is the 'engine room' of the mixed sand and gravel beach and that beach adjustment is driven by swash and backwash processes. Variation in the shape of the foreshore, especially the slope which is a function of the height and width of the profile will cause variations in the swash and backwash process response. The second factor involves differences in the sediment characteristics of each site which may cause the swash processes especially percolation of water into the beach and therefore the energy dissipation of the waves to vary between sites.

The second direction of the spatial analysis is an examination of the possibility of 'slugs' of sediment moving through the study area in the direction of net longshore transport. The passage of slugs of sediment moving alongshore as put forward by Neale (1987) has been introduced in Section 1.4 and Section 2.6. Two questions were

asked in Chapter One in respect of the passage of these slugs. They were directed at understanding the mechanics of the passage of the slugs along the coast, and to the effect of the passage of a slug on the beach response to high energy events. Aspects of the first question were addressed in Section 2.6. The second question will be addressed in light of the field evidence from this study.

The third part of the spatial analysis of the study area will be an examination of the distribution of sediments. The mean size of sediments in relation to their position on the profile has been discussed in Section 3.5.2. In this chapter the shape of the sediments is discussed in relation to where they are found on the beach profile. In discussing sedimentation of beach gravels in Wales, Bluck (1967) put forward a four part zonation of the beach profile based on the particle shape of surface layers. Bluck's work has been used as a basis of gravel beach zonation and descriptive classification by other authors examining coarse grained and gravel beaches (Benn 1987, Carter et.al. 1990, Forbes et.al. 1990, Postma and Nemec 1990). However there is no equivalent development of ideas for mixed sediment beaches, which are inherently different to pure gravel beaches. The information gathered from this study is relevant to the development of a general model of the spatial distribution of sediments by shape on mixed sand and gravel beaches.

6.2   Spatial Interaction of Adjustments to the Study Profiles

6.2.1 Analysis of longshore variation in Standardised Excursion Distance

Figure 6.1 shows the standardised excursion distance information (SEDA) for the study area plotted for each profile at a specific time against the distance of the profile alongshore. Ten time periods have been displayed in this way. The time interval between each plot varies from one week to thirteen months. These intervals reflect the periods of varying beach responses and adjustments identified in Section 4.4, and can be used to analyse the spatial distribution of beach change at short (or event specific) and medium time scales. Each plot represents a simplified topographical map of the foreshore of the field area at a particular time. The shoreline is also simplified using this method of data display by the removal of any natural curvature or irregularity of the crest. However longshore variations of the foreshore width stand out clearly. For reference to across-shore distances, dashed lines have been included at 0 metres, 15 metres, 25 metres and 35 metres from the datum crest position (as of 24/4/89). For ease of comparison between time periods, the SEDA has been plotted at 1 metre contour intervals. This is at the expense of a loss of some foreshore slope detail. Detail is also compromised by the spacing of the study profiles along the coast. This is
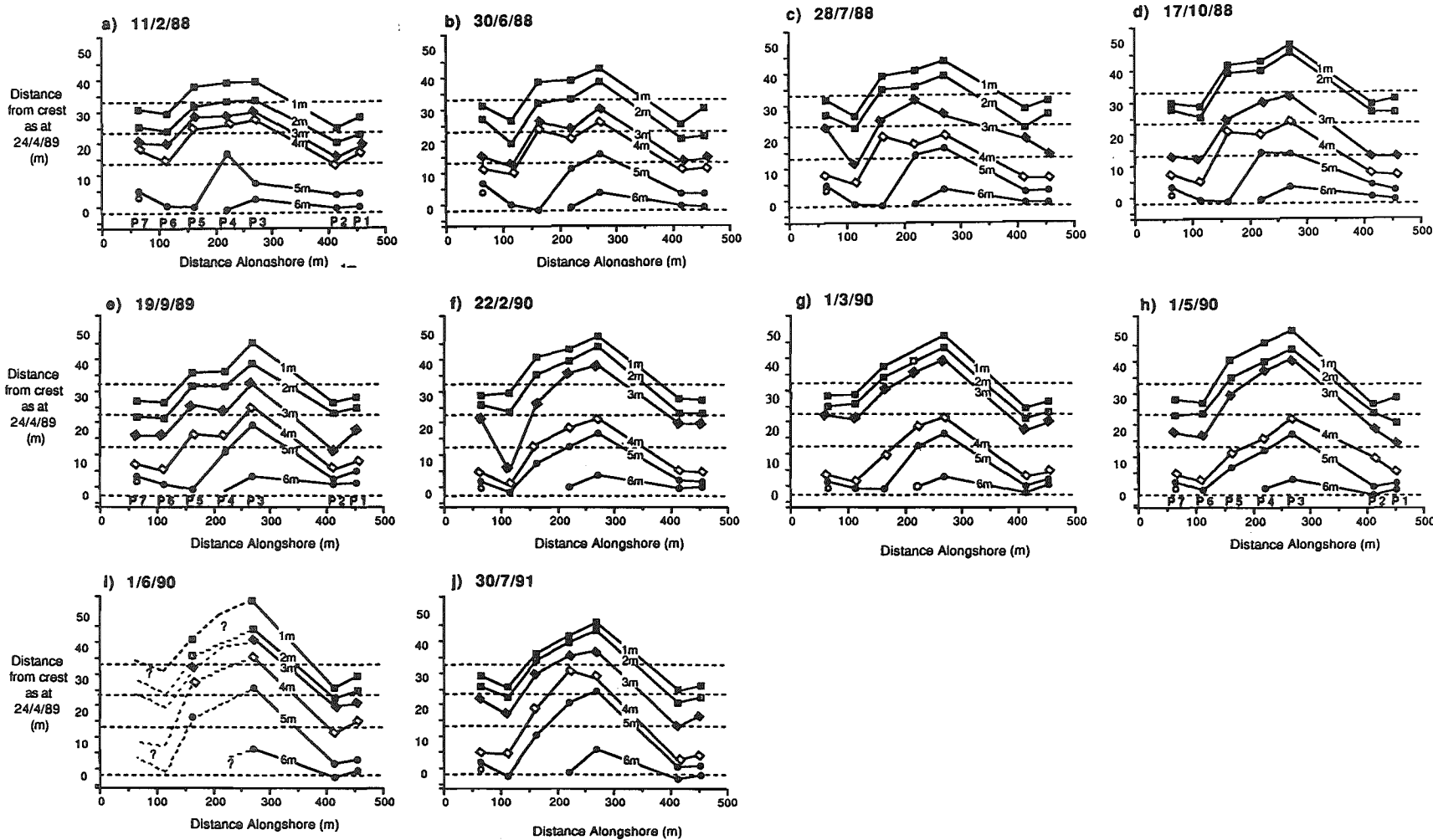
Figure 6.1 Standardised excursion distance analysis of the study area at specific time intervals.

especially noticeable because of the large gap between Profile 2 and Profile 3 at 5513 and 5370 kilometres respectively, and because of the noncontinuation of the 6 metre contour between Profiles 4 and 5 (at 5320 and 5263 kilometres) and Profiles 6 and 7 (at 5214 and 5164 kilometres).

It can be seen from Figure 6.1 that the plan shape of the foreshore in the study area is basically narrow at the end profiles (1,2,6 and 7) and wide in the middle (Profiles 3, 4 and 5). This has been a consistent feature for the total study period. Another consistent feature is that Profile 3 has the widest foreshore and Profile 2 for all surveys bar 22/2/90 has the narrowest foreshore. Further to this, there was very little change to the 6 metre contour during the study period except for retreat of the crest of Profiles 1,2 and 7 from 19/9/89 onwards, and retreat of the 6 metre contour on Profile 4 between 1/5/90 and 30/7/91. Changes between the survey times shown in Figure 6.1 will now be discussed for each interval. The terms erosion and accretion are used to describe a landward excursion or retreat of a contour, or seaward excursion of a contour respectively.

11/2/88 to 30/6/88

As noted in Chapter Four, this was a period of relatively small overall change for the study area. The notable exceptions are the 7 metres of retreat of the 5 metre contour on Profile 4 and the similar magnitude of accretion on the same contour on Profile 3. There was a small amount of retreat of all the 3 and 4 metre contours except for Profile 3. In the lower foreshore, there was accretion of the 1 and 2 metre contours on Profiles 1, 3 and 6 but little change on the other profiles. The overall picture of the beach adjustments for this time interval shows steepening of the upper and middle foreshore but broadening of the lower foreshore, with Profile 3 generally becoming wider.

30/6/88 to 28/7/88

From Figure 4.5 it appears that a small magnitude high energy event occurred during this interval, causing sharp changes to the excursion distances up to the 4.5 metre contour. As with the previous interval there was a steepening of the middle foreshore. There was little change to the 5 metre contour except on Profile 4 where there was approximately 2 metres of retreat. There was general erosion of the 4 metre contour. This is most noticeable for the narrow, end profiles. In general there was accretion to the lower foreshore, with Profile 7 where there was very little change, being the exception. The adjustments to the 3 metre contour show some pattern of longshore

displacement of material. Because there was no change of this contour on Profile 5, it appears that there was a northward displacement of material from Profiles 1, 3 and 6 which display erosion, to Profiles 2, 4 and 7.

28/7/88 to 17/10/88

This was again a period of little overall change, although there was accretion of the lower foreshores on the central profiles. The exceptions are the erosion of the 5 metre contour on Profile 3, which was balanced by accretion to the 4 metre contours of Profiles 3 and 4, and the 10 metres of retreat of the 3 metre contour on Profile 7. From Figure 4.4b, it can be seen that there was some erosion of material from the intermediate storm berm which accounts for the displacement of the 5 metre contour. The accretion to the lower contours can be attributed to the building of a large berm in the lower foreshore. This is shown in Figure 6.1 as a steepening of the beach slope between the 1 and 2 metre contours, and a broadening of the beach between the 2 and 3 metre contours. This is most likely due to a prolonged period of low energy waves directly prior to the survey date.

17/10/88 to 19/9/89

This was a further long period of little change although there was erosion of the lower foreshore on Profiles 4 and 5. There may have been a period of high energy waves as there was a small amount (just over 1 metre horizontal displacement) of erosion of the 3, 4 and 5 metre contours on Profiles 2, 4 and 6, and a small amount of accretion of these contours on Profiles 1, 3, 5 and 7. There was a landward retreat of the 1 and 2 metre contours of approximately 5 metres for all profiles. The middle foreshore became more steep and the lower foreshore became less steep.

19/9/89 to 22/2/90

The beach during this period changed mainly in the middle foreshore. The change was predominantly in the form of accretion which is shown by a 5 metre overall widening of the foreshore on Profiles 4 and 5. However there is some evidence of erosion of the 4 and 5 metre contours on Profiles 1, 3, 6 and 7, indicating that at some stage a high energy event occurred. The small degree of change to Profile 4 at these levels compared to the large amount of accretion to Profile 5 appear to indicate a northward movement of beach material. The general accretion to the 1, 2 and 3 metre contours except on Profile 3, also gives the impression that there is a northward movement of the bulge of sediment in the middle of the study area. The major erosive

feature is the retreat of the 3 metre contour on Profile 6. From Figure 4.2.f, this is associated with erosion of the upper foreshore and the building of an intermediate berm with a crest height of 2.8 metres above mean sea level. Similar changes to the form and shape of the profile occurred on Profiles 5 and 7 but the crest of the intermediate berm was higher than the 3 metre contour. The greater erosion of Profile 6 may be linked to site specific parameters such as the volume of sediment, the sediment characteristics and the permeability of the upper foreshore.

22/2/90 to 1/3/90

For most of the study area there was erosion and steepening of the lower foreshore over this interval. Profiles 2, 5 and to a lesser extent 7, experienced erosion of the upper foreshore, from the 4 metre contour and above. On Profile 5 this included erosion into the wide reconstructed barrier crest from 1985. On Profile 2 there was erosion into the beach crest. However these changes were associated with a broadening of the middle foreshore on Profiles 5 and 6. Foreshore width and volume appear to be the major determinants of different beach responses during this time period, with the narrow steep profiles exhibiting the most adjustment.

1/3/90 to 1/5/90

This was a period of some erosion but mainly there was little change to the foreshore of the study area. The 1/5/90 plot is included to establish the antecedent conditions for the storm of 31/5/90. The main changes between the beginning of March and the beginning of May 1990 were the erosion to Profile 1 up to the 3 metre contour, the accretion of the 4 metre contour on Profile 2, and the retreat of the 3 metre contour on Profiles 6 and 7, making the lower foreshore less steep.

1/5/90 to 1/6/90

The storm event which occurred during this period has been discussed in Chapter Five, as have the beach adjustments to the individual profiles. Generally the event resulted in accretion to the foreshore in the study area. However the form of the profiles changed in that they became more linear with the removal of the intermediate berm, and less steep due to the broadening of the upper and lower foreshore. It is noticeable that the accretion to Profiles 1 and 2 did not result in an increase to the total foreshore width. This may be due to the depleted sediment volume of this section of the coast in comparison with the stretch to the north of Profile 2.

<u>1/6/90 to 30/7/91</u>

This is a further long interval between profile surveys, during which there were no reports of high energy events. However there was erosion of the upper foreshore on Profiles 1, 2, 6 and 7, and steepening of the lower foreshore for the study area except on the southern profiles. Changes to Profiles 4, 6 and 7 may have occurred between 1/5/90 and 1/6/90 as no surveys were made for these profiles for the latter date. The comparatively less retreat of the middle foreshore on Profile 4 than the retreat of 10 metres to the 4 metre contour on Profiles 3 and 5 could be associated with the northward passage of a sediment slug from the section of beach to the south of Profile 3. This will be examined further in Section 6.3.

6.2.2 Analysis of longshore variation at different elevations of the profile

Figure 6.2 displays the Normalised Excursion Distance (NED) plots for the study area grouped together by elevation for each of the profiles. Note that the NED shows the proportional change of the contour position in respect to the initial distance of the contour from a fixed datum. In this case the initial position is that of 2/9/87. Note also that the manner of display in Figure 6.2 does not show the proportional longshore distances between the profiles. The graduations on the vertical axis are in 0.2 units and represent a difference in the position of the contour that is 20% of the initial distance from the fixed datum. This method of display has been used to examine the beach adjustments for variations alongshore at different elevations on the beach profile. For example if the adjustment as shown by the NED is the same then it could be concluded that the response to the wave environment from one site to another was the same. If there is a difference in the NED then this may represent a longshore component to the beach response, or the significance of some other factor such as foreshore slope or sediment volume in determining the beach response. Changes will now be discussed for the different elevation groupings shown in Figure 6.2.

<u>1 and 2 metre Contours</u>

Changes at this elevation show a similar pattern for the study area except for slight variations due to the availability of data for the 1 metre contour for some surveys. The most significant differences come about for the period after approximately 1000 days (19/9/89). Profiles 1 and 2 show an increased rate of erosion until the last interval between surveys when there is accretion. The other profiles show accretion and then erosion for Profiles 3 and 6, and a slower rate of accretion for Profiles 4, 5 and 7.
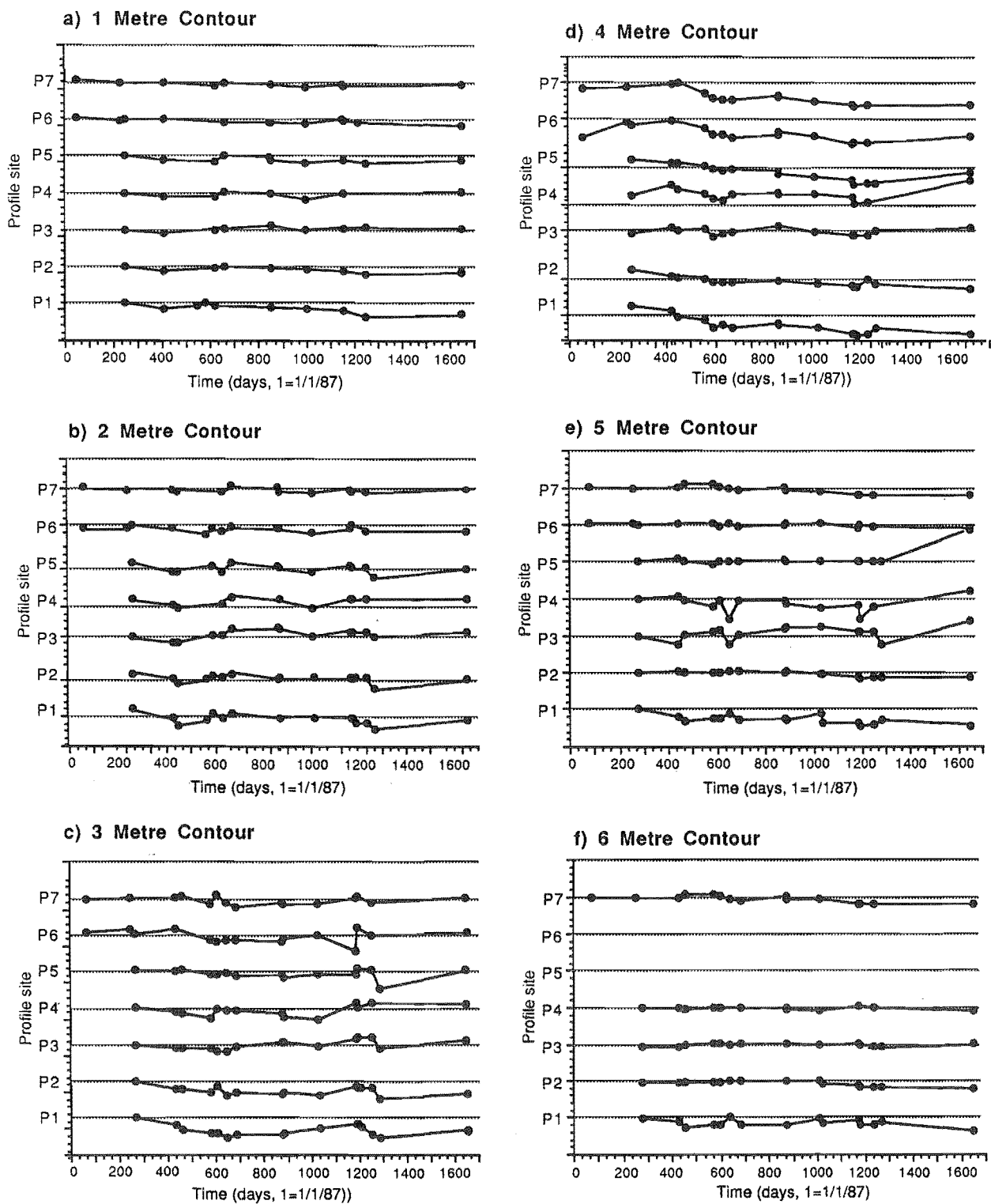
Figure 6.2 Normalised excursion distance analysis of like elevations on the study profiles.

There is also a similar pattern of response for the 2 metre contour except for the period between days 850 and 1150 (28/4/89 to 22/2/90). During this period there was an episode of erosion followed by accretion for all of the profiles except Profiles 1 and 2 which display no change. The interval between the last two survey dates was one of accretion for all profiles except Profiles 4 and 6 which have no net change in position.

3 and 4 metre Contours

These contours display more variation and complexities over time than those of the lower foreshore. On the 3 metre contour there was generally erosion up to day 575 (28/7/88) at varying rates. However on the 4 metre contour there was accretion on Profiles 3, 4, 6 and 7. Between days 575 and 615 (6/9/88) there was erosion of the 3 metre contour on Profiles 3 and 6 but accretion on the other profiles, and erosion of the 4 metre contour on all of the profiles. There is more disparity in the beach adjustments up to day 850 (28/4/89) where for the 3 metre contour there was accretion on Profiles 3, 5 and 7 and erosion on Profiles 2, 4 and 6, and for the 4 metre contour there was accretion on all profiles except Profile 5. There was generally accretion of the 3 metre contour between days 850 and 1217 (1/5/90) except for a period of erosion on Profile 6. During this period there was erosion on the 4 metre contour for all of the profiles. The response for the May 1990 storm shows as erosion for the 3 metre contour but accretion or no change for the 4 metre contour. The last interval was one of accretion for all of the profiles except for the 4 metre contour on Profiles 1 and 2. The most marked changes were on Profiles 3 and 4.

5 and 6 metre Contours

These profiles show the least amount of variation and excursion. This is to be expected as these elevations would only be adjusted during high energy events. However there are more disparities in the direction of change of the contours than for those at lower elevations on the beach. Up to day 407 (11/2/88) there was erosion on Profiles 1 and 3 and accretion on the other profiles at the 5 metre level. Between 11/2/88 and 7/3/88 there was erosion on Profiles 1, 2, 4 and 5 for both elevations and accretion on Profiles 3 and 7. There are major excursions of the 5 metre contour between days 575 and 656 (28/7/88 and 17/10/88) on Profiles 3 and 4, and again for Profile 4 between days 1150 and 1217 (22/2/90 and 1/5/90). From Figure 4.2.d, these changes can be seen to relate to the destruction and rebuilding of the crest of the intermediate berm that is intersected by the 5 metre contour on the seaward face and on the backslope of the berm. The last interval shows major changes to the 5 metre contour on Profiles 3, 4 and 5 in the form of accretion in relation to the initial horizontal

position of the contour. Profiles 1, 2 and 7 display the most variation for the 6 metre contour. This is due to the narrow width and steep slope of the foreshore on these profiles presenting less beach surface for the dissipation of wave energy.

Long Term Trends

The general trend for the study area over the total study period appears to be one of erosion across most of the foreshore. Profiles 1 and 2 which are steep, and narrow in width from the barrier crest to the nearshore exhibit an erosive trend at all elevations. Profiles 6 and 7 which are similar in shape to Profiles 1 and 2 are also mainly erosive. However this is not consistent across the profile. They both have slightly seaward excursions of the 3 metre contour while the lower contours are only slightly erosive. This has caused a change in shape of the profile with the lower foreshore becoming steeper and the middle foreshore becoming broader and flatter. Profiles 3 and 4 are nearly totally accretional over the study period. The exception is the upper foreshore of Profile 4. Profile 5 has a trend of both erosion and accretion, with the lower foreshore retreating and the upper foreshore prograding. This has also caused the lower foreshore at this site to become steeper while the middle and upper foreshore has broadened and become less steep. It is not known how the beach adjustments at this site have been affected by the barrier reconstruction of 1985, although it is clear that the replacement of overwashed material from the backshore onto the beach crest (and therefore made available for wave energy dissipation) has not been detrimental to the beach function.

6.3   The Passage of Sediment Slugs Through the Field Area

6.3.1 Testing for the presence of sediment slugs

Neale (1987) developed a concept of longshore sediment transport involving the movement of 'slugs' of material along the beach. The idea of a 'slug' or collective movement of beach sediment rather than sediment spread evenly through the coastal system is linked to the injection of discrete masses of material into the system from major events such as coastal cliff slumpage or river mouth barriers breaching from the landward side. These sources of material are both present south of the study area (updrift of the dominant longshore transport direction), in the form of the Morven-Glenavy Cliffs and the Waitaki River mouth. Neale identified the existence of pulses of sediment passing through the field area and gave estimates of their magnitude and average rate of passage (as discussed in Section 2.6).

The presence or absence of a slug of material at a site was identified by Neale from variations about the mean of the foreshore volume. This is displayed diagrammatically in Figure 2.12. A hypothetical passage of a slug of material through the study area is shown in Figure 6.3. The longshore distance between the profiles is plotted on the 'x'-axis while the foreshore of the study area represented by the volume of sediment at each site is plotted on the 'y'-axis. The line T_1 joins these points for the volumes of the study sites as of 2/9/87 (the start of the study period for this study). Lines indicating the mean foreshore volume for the study area for this point in time (M_t) and the volume of each profile for the study period (M_p) are also plotted. The bulge of volume above the mean may indicate the presence of a sediment slug passing through the area. The region of the T_1 curve above the mean volume (M_t) is the position of the maximum accretional effect of the slug (or the slug crest) while those areas below the mean volume line indicate the trough between slugs. Following Neale's concept, as the slug passes through the area, the bulge moves (northwards in this case) so that at another point in time the volume distribution along the coast would appear as for T_2. Neale found that the average rate of slug movement through the Wainono Lowland coast was 1.15 km.yr-1 (Neale 1987, p213). If this rate was applicable during the study period then the slug would move approximately 4.25 kilometres, therefore passing completely through the field area.

Lines joining the profile volumes for five different times at approximately one year intervals (labelled T_1 to T_5) during the study period have been plotted in Figure 6.4. The initial volume curve is similar in shape to the initial SEDA curve of Figure 6.1. This general pattern is maintained for the total study period. Between T_1 and T_2 there was a loss of sediment from all of the profiles, with the largest losses being from Profiles 1, 2, 3 and 5. The net volume change of the north and south profiles of the study area was minimal between T_2 and T_3, but there was accretion on Profiles 3 and 4 over the same time period. Erosion from Profiles 1, 3 and 7 between T_3 and T_4 occurred while there was an increase in volume on Profile 2 and negligible change on Profiles 4, 5 and 6. Net increases in volume occurred on all of the profiles except Profiles 2 and 3 over the last interval (T_4 to T_5). The magnitude of the changes can be seen from Table 6.1. Note from Table 6.1 that variations in volume over the shorter time periods are in some cases greater than the net long term change. Therefore it is difficult to imply any long term trend of volume change.

The mean volume of sediment in $m^3.m^{-1}$ of beach above 1 m AMSL for the total length of the study area for each time period is also given in Table 6.1. These values are plotted as horizontal lines on Figure 6.4, and show that there was net erosion from
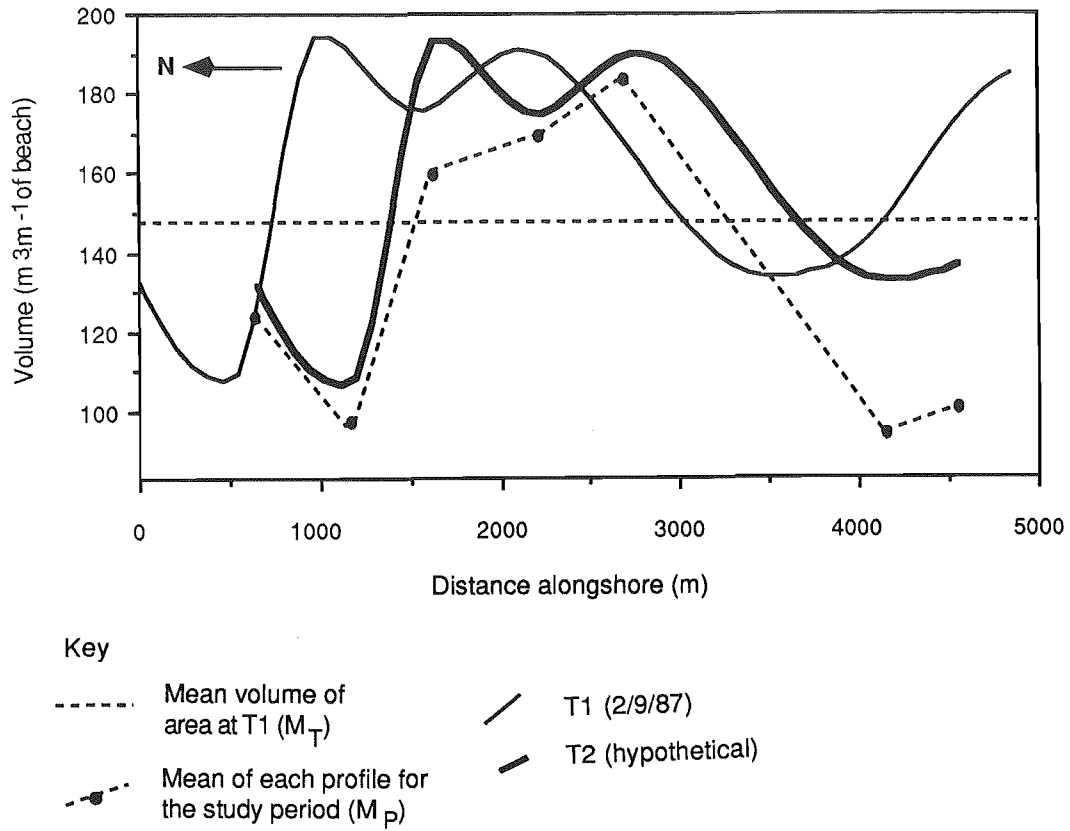
Figure 6.3 Hypothetical movement of a 'slug' of sediment through the field area.
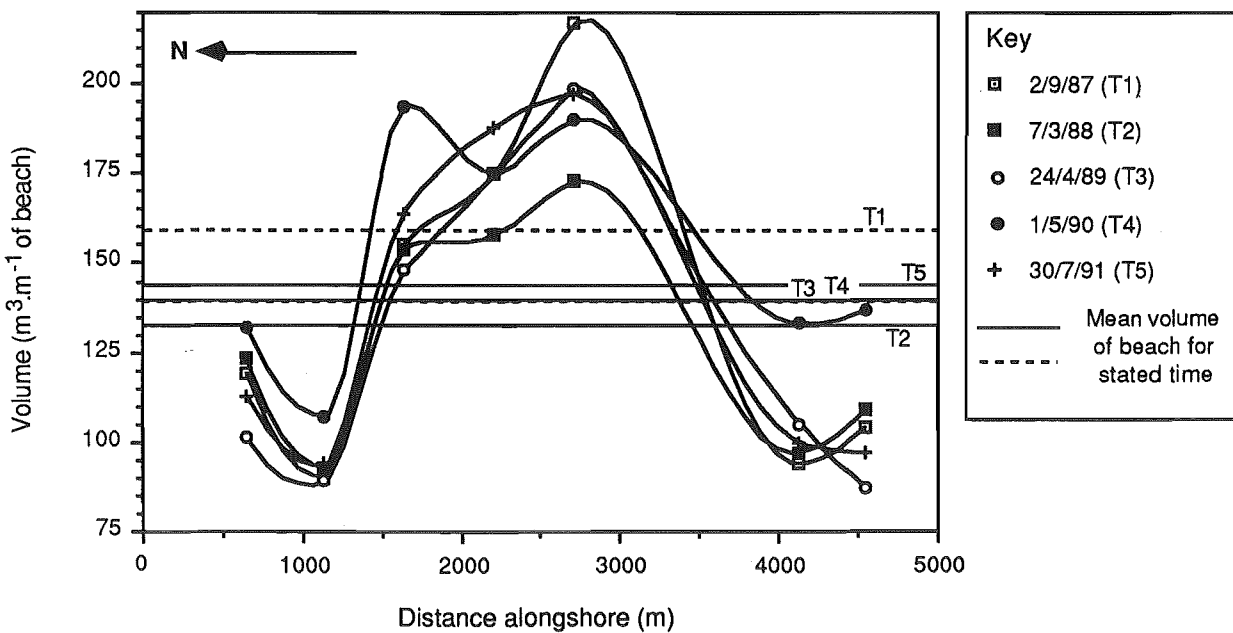
Figure 6.4 Changes in foreshore volume for the study area, interpolated from profile volumes.

	2/9/87	Net Change	7/3/88	Net Change	24/4/89	Net Change	1/5/90	Net Change	30/7/91	Total Net Change
Profile 1	137	-28	109	-5	104	-17	87	10	97	-40
Profile 2	133	-36	97	-3	94	11	105	-5	100	-33
Profile 3	190	-17	173	44	217	-18	199	-2	197	7
Profile 4	175	-17	158	17	175	0	175	13	188	13
Profile 5	194	-40	154	1	155	-7	148	16	164	-30
Profile 6	107	-14	93	-3	90	-1	89	5	94	-13
Profile 7	132	-9	123	-4	119	-18	101	12	113	-19
Mean Volume	158	-24	134	11	145	-5	140	5	145	-13

Table 6.1 Foreshore volumes and net volume changes for each profile at different times during the study period (all values in $m^3 . m^{-1}$ of beach).

the foreshore over the four years of the study period. There was a major loss of volume in the six months from 2/9/87 to 7/3/88 with a net change of -24 $m^3 .m^{-1}$ of beach. However for the second and last intervals there was a net gain to the beach volume.

Figure 6.4 shows no obvious longshore temporal pattern to the volume change such as that shown in Figure 6.3. The changes that are evident indicate the possibility of an onshore offshore component or of both northward and southward littoral components to changes in the beach morphology as represented by foreshore volume. The effect of short term changes to the long term character of the beach adjustments can be seen to be significant.

To further test for the presence or passage of sediment slugs in the study area, the methodology used by Neale (1987) was applied to the field data. Neale identified the troughs and crests of sediment slugs by plotting the standardised volumes of profiles along the South Canterbury Coast as shown in Figure 2.13a. This method of analysis and plotting was carried out for the volume data of this study. The standard volume is calculated using equation 2.1, shown below:

$$B_z = (B_t - B_x)/B_x \qquad\qquad eq.2.1$$

To recap, B_z is the standardised foreshore volume, B_x is the mean of the measured volumes at a given profile (in $m^3 .m^{-1}$ of beach above 1 m AMSL), and B_t is the volume of the profile at time 't' (in $m^3 .m^{-1}$ of beach above 1 m AMSL). Volumes below the average have negative values while volumes above the average have positive values. The average volume B_z is equal to 0.

The standardised values for the study profiles have been plotted in Figure 6.5. An interpolated curve has been fitted to the data using the Cricket Graph graphing package on a Macintosh computer. This system uses the Stineman method of interpolation (Stineman 1980). The volumes are standardised for individual profiles and so the amplitudes of change shown in Figure 6.5 are not comparable between profiles. However the position in time of the peaks and troughs can be compared. The mean volume for each profile is noted on the graph and is also shown as a dotted line about which the standard area varies. These lines have been positioned on the 'y'-axis in respect to the relative distances of the profiles along the coast with north being at the top of the graph. The graduation marks on the 'y'-axis represent 10% variation from the mean. Below average volumes are below the dotted line while above average volumes are above the line.

Short term fluctuations in the foreshore volume caused by high energy events can have an effect on the long term interpolations. Variations to the volume of a profile can be as much as 18% of the profile volume during a single event. For example, during the period between 22/2/90 and 1/3/90 the average absolute change in volume for the study profiles represented 7.3% of the mean total foreshore volume. In Figure 6.5 this value is represented by less than 1 unit on the 'y'-axis. Recorded changes in volume between observations were up to 30% of the mean, while the interpolated curve shows a maximum deviation of 80% (for Profile 2). This interpolated variation is not a true representation of the volume change as seen from field evidence but is a feature of the interpolation method for the long time period with no field data, and is a function of the large change in volume between 1/5/90 and 1/6/90 on Profile 2.

From Figure 6.5 it can be seen that there is a large amount of fluctuation about the mean foreshore volume for each profile. The variations have been placed into seven time interval groups. The first interval is from 2/9/87 to 7/3/88. All of the profiles except for Profiles 3 and 5 have an initial standard volume above the mean. The standard volume reduces over this time period. For the second interval to 28/7/88, the interpolation indicates that the change in volume reaches a turning point and increases to a short term high volume content. There is then a short period of decrease in volume for all of the profiles except Profile 1. The fourth period from 17/10/88 to 24/4/89 shows variations in the volume change for the different sites. Profiles 1, 2 and 6 all show a tendency towards a decrease and then an increase in standard volume, while the other profiles have an increase in volume remaining above the mean and then decreasing towards the end of this interval. This is mainly due to the direction of the short term change in volume between 24/4/89 and 28/4/89. The fifth interval (to 22/2/90) shows a
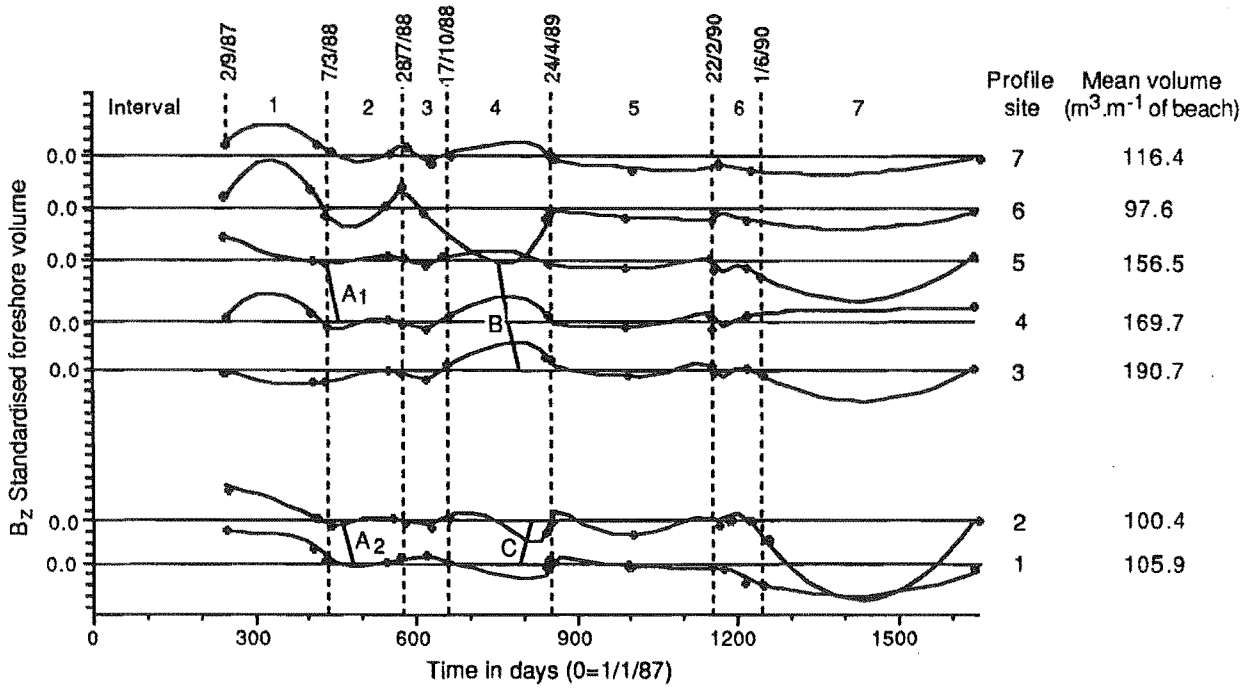
Figure 6.5 Changes in standard volume about the mean foreshore volume for the study period.

general tendency of lower than average volumes which increase towards the end of the period. The sixth interval shows a period of response to two high energy episodes, between 22/2/90 and 1/3/90 and between 1/5/90 and 1/6/90. The first event caused erosion on Profiles 2, 3, 4 and 5, but there was an increase in volume on Profiles 1, 6 and 7. The second event was associated with erosion on all the profiles surveyed on 1/6/90. No data were available for Profiles 4, 6 and 7, but it is assumed that these sites were also subject to net erosion. The effect of these events on the standardised volume curve is to add irregularities to the longer term pattern. The final interval break shows a pattern of erosion and then accretion. This agrees with the interpretation from the SEDA analysis which showed retreat of the profiles although there was steepening of the foreshore.

The clear long term patterns found by Neale are not evident from this field study. This may be due to the relatively short data collection period and the short term averaging of the foreshore volume. Neale's average volumes for Profiles 1, 2 and 5 were 132, 196 and 166 $m^3.m^{-1}$ of beach respectively. In comparison, the average volumes for those profiles over the period of this study were 106, 100 and 156 $m^3.m^{-1}$ of beach respectively. Neale's work does show that a long period slug trough should be passing northward through the study area (see Figure 2.13b). From the differences in the calculated average volumes this may be the case. However the passage of the trough and the subsequent slug crests before and after the trough have had short term variations in volume superimposed on them. These variations are a response to short term changes in the wave environment.

The rate of passage of the slug given by Neale is based on linkages between the positions of slug troughs and peaks for different sites along the coast at different times, as shown in Figure 2.13b. The rate of movement is measured from the gradient of the linkage lines. Because the passage of the slugs is driven by the longshore component of wave energy arriving at the beach, the average rate of slug movement must be a function of the average longshore component of the wave environment, which for Neale's case covered the time period between 1977 and 1987.

Linking positions of high and low volume on different profiles to suggest a movement of the slugs alongshore does not appear to be applicable for the study area. In most cases suggested linkages infer that a trough or crest of a slug is affecting more than one profile at the same time. This could be the case, as the absolute magnitudes of change are not shown on this graph. However linkages could be applied at a smaller scale, as shown by A_1, A_2, B and C on Figure 6.5. These links indicate rates of

movement of small slugs of sediment at approximately 6 km.yr^{-1} or more. It is significant that the direction of movement of the small slugs is not uniformly to the north. For the cases of A$_1$, A$_2$ and B, the inference is of a southward movement of the small troughs and crests of sediment. It is assumed that this is a direct response to the wave environment for that period of time.

From the spatial and temporal analysis of beach foreshore volumes it can be seen that there are variations in volume along the Wainono Lowland Coast at any point in time. It is concluded that these variations during the study period indicate the presence of a slug of beach sediment in the field area. The 'crest' of the slug is situated about Profile 3 and the 'troughs' are approximately adjacent to Profiles 2 and 6. The slug has remained quasi-stationary in that although it was present in generally the same position of the study area during the study period, there was some variation in the spatial distribution of the sediment volume. The average difference in volume between the slug crest (approximately at Profile 3) and the slug trough (at Profile 2 and Profile 6) is 101 m^3.m^{-1} of beach. This equates to 50.5 m^3.m^{-1} of beach change in volume about the mean beach volume for the area. This is close to the average maximum volume change of 45 m^3.m^{-1} of beach given by Neale.

There is no evidence from the field data of a net northwards passage of the slug through the field area therefore no long term rate of translation alongshore can be calculated. The lack of noticeable longshore movement of the slug is consistent with the atypical nature of the wave environment during the study period, but emphasises the importance of a net northwards component of the wave environment in maintaining the northerly passage of the slugs of sediment.

6.3.2 The effect of sediment slugs on beach response to high energy events

> How does the passage of slugs affect the response of the beach to high energy events at different sites along the coast and at particular sites over time as the slugs pass through?

The above question was asked in Chapter One in relation to the function of the beach, in particular to how variations in the sediment volume could cause the beach to no longer be protection for the coastal hinterland against wave processes. It was noted that the long term maintenance of the profile shape required the input of beach materials to offset the losses. This is also the case in the short term.

The presence of a slug of sediment plays an important role in determining the antecedent profile morphology that is available to dissipate wave energy. Whether the crest or trough or the flanks (that area between the crest and trough) of the slug is

present at a specific site will determine the amount of foreshore sediment volume in the site. In the study area, the variation in foreshore volume can amount to 40% of the mean volume for this stretch of coast. Therefore it can cause significant changes to the profile shape, especially the width of the foreshore (between 15 and 20 metres difference in width for the crest and trough) and the number of intermediate berms between the barrier crest and the swash zone. The profile adjacent to the slug crest presents a much healthier protection against wave attack than the profile adjacent to the trough, in that there is more sediment available during episodes of erosion and more beach surface area between the breaking wave and the barrier crest to dissipate or absorb swash energy, therefore minimising overtopping. The profile adjacent to the slug trough is more susceptible to erosion of the barrier crest and/or to overtopping by wave run-up and the possibly damaging consequences to the barrier.

Passage of a slug past a site will cause a net increase in sediment volume as the trough moves away and the crest moves onto the site. If a slug remains stationary or quasi-stationary then the susceptibility to detrimental morphological impact at the slug troughs, such as erosion of sediment and retreat of the barrier crest during high energy events increases over time. This is especially significant if there is a net loss of volume from and/or a landward retreat of the upper foreshore as a result of a storm episode. At the slug crest, the net increase in sediment volume results in the development of a buffer of protection for the barrier crest and the hinterland.

6.4   Spatial Distribution of Beach Sediments

6.4.1 Longshore variations of sedimentary characteristics

The slug is a spatial feature on the coast but it is not known whether the spatial distribution and location of the slug reflects variations in sediments or whether the slug has a definite sedimentary structure, especially in displaying differences between the slug crest, trough and flanks. The descriptive characteristics of the mixed sand and gravel sediments on the Wainono Lowland Coast were discussed in Section 3.5.2 (see also Figures 3.6, 3.7 and 3.8). It was noted that the mixed sediments are difficult to analyse because of the wide range of sizes and sorting properties exhibited by samples of beach material. It was also noted in this study that there were no longshore trends in sediment size and shape but there were large across-shore variations that displayed similarities between the positions on the profiles at different sites. These conclusions are consistent with those put forward by Kirk (1967), McLean (1970) and Benn (1987) and show that longshore variations in morphological adjustments are not explained by

longshore variations in sediment characteristics. These conclusions do not preclude a link between the presence of slugs and the spatial distribution of beach sediments alongshore.

The lack of longshore variation in sedimentary characteristics may mask differences in the across-shore distribution of sediments between different sites along the beach. Therefore it can be asked whether the crest, trough or flanks of a slug display a definite across-shore pattern of sedimentary structure.

6.4.2 Across-shore zonation of sediment characteristics

McLean (1970) noted an across-shore zonation of sediment characteristics on mixed sand and gravel beaches. He attributed this to zonation of the hydrodynamic processes, and a preferential deposition of certain sizes which produced "...distinctive textural zones parallel with the shore..." whereby "...large variations in size and sorting values across the beach may result." (McLean 1970, p158). However it can be noted from Chapter Two that there is no descriptive model of the spatial distribution of the sediment characteristics on mixed sand and gravel barrier beaches.

From an examination of beaches in south Wales, Bluck (1967) subdivided the gravel beaches of his study area into four zones. These zones were based on differences in particle shape of surface layer sediments across the foreshore and their hydrodynamic properties. The applicability of these zones has been assumed for gravel beaches in general by other authors including Benn (1987) in examining the mixed sand and gravel beaches of the Washdyke-Seadown coast, north of Timaru. It was shown by McLean (1970), Benn (1987) and for this study, that the concept of across-shore zonation is applicable to the mixed sediment beach, but it is not known if the Bluck model of zonation is appropriate.

Bluck suggested that local hydrodynamic conditions (swash, backwash and percolation) combined with the settling velocities of different particles were responsible for the across-shore zonation. However Bluck was also concerned with lithological differences in the sediments present in his study area. Krumbein and Pettijohn (1938) stated that lithology was only one of the factors that could cause variation in particle shape. These factors include the original shape of the particle, the structure of the particle, the exposure to wave energy and the time the particle had spent in the wave environment. The lithology of sediments on the Wainono Lowland Coast is predominantly greywacke, whereas the South Wales beaches studied by Bluck contain four lithological types. Benn (1987) noted that the sediments of the Washdyke coast

were comprised of young, basically sound pebbles which contained few fractures or planes of weakness such as schistocity, cleavage or bedding. Sediments in the Wainono area are similar, while those examined by Bluck were more weathered and more mature. Therefore it cannot be assumed that Bluck's zones for gravel beaches would be the same as those on mixed sediment foreshores.

Bluck (1967) used a zonal sediment sampling method in recognition of the distinct morphological features on his study beaches. Particle shape was classified according to the Zingg classification (in Blatt et al. 1980). Figure 6.6 is a composite diagram presented by Bluck and shows the distribution of zones across the beach. The defined zones and a description of the particle shapes found within each of these zones are listed below.

Large Disc Zone - Upper foreshore; clast supported framework of cobble sized discs. High proportion of disc shaped grains in the larger size classes, spherical and rod shaped fragments almost confined to the lower size ranges.

Imbricate Zone - Seaward faces of berms; mainly imbricate disc-shaped pebbles. High proportion of disc shaped grains in all sizes.

Infill Zone - Spherical cobble frame infilled with mainly spherical and rod shaped pebbles in all sizes.

Outer Frame - Cobbles seaward of the gravel bar margin, comprised of mainly spherical grains. (after Bluck 1967, and Postma and Nemec 1990)

Figure 6.7 shows the frequency shape distribution by particle size for the identified zones on one of the beaches studied by Bluck. It can be seen that there is a large percentage of spherical particles on the beach although the dominant shape is discoid.

Shape information from this study was combined for the samples from equivalent positions on the five beach profiles sampled. The samples from position 6 were selectively examined for shape by measuring the a-, b-, and c-axes of the fifty largest clasts in each sample (fifty particles being the minimum recommended sample size for Zingg analysis (Blatt et al. 1980). Using the fifty largest particles also gives a measure of the maximum hydrodynamic forces acting on this section of the beach. The frequency of occurrence of different shapes (using the Zingg method of classification) was plotted against size classes. This information is presented in Figure 6.8. The particle sizes are in millimetres and the particles were grouped in 20 mm classes

STORM BEACH : SKER POINT
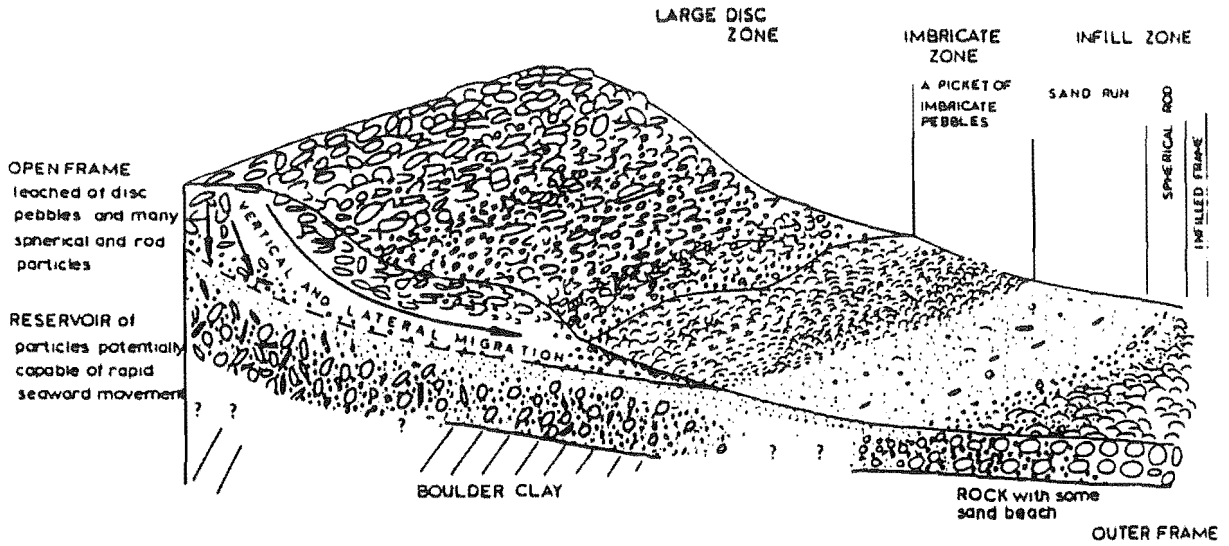
Figure 6.6 A composite diagram showing a part of Sker Point storm beach (from Bluck 1967, Figure 26).
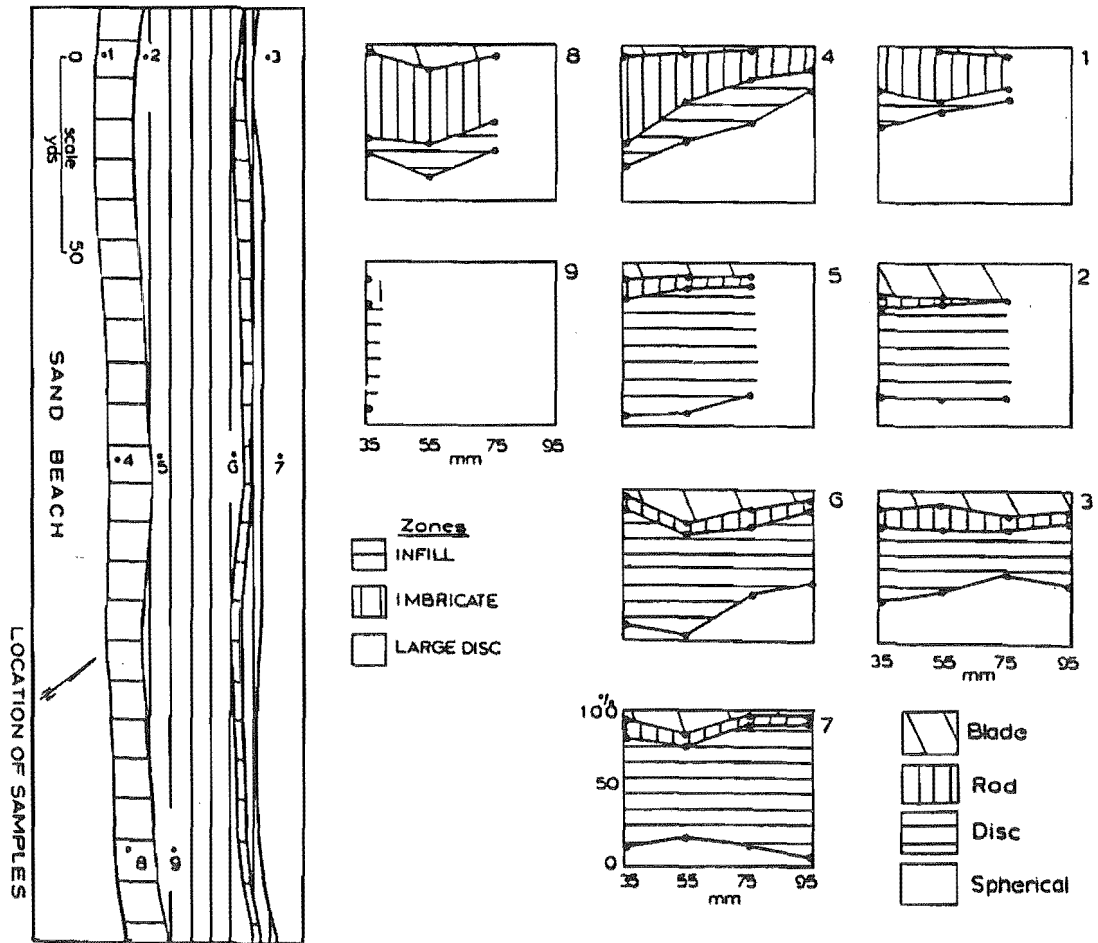
Figure 6.7 Distribution of particle shapes and zones of the Newton beaches (from Bluck 1967, Figure 4).
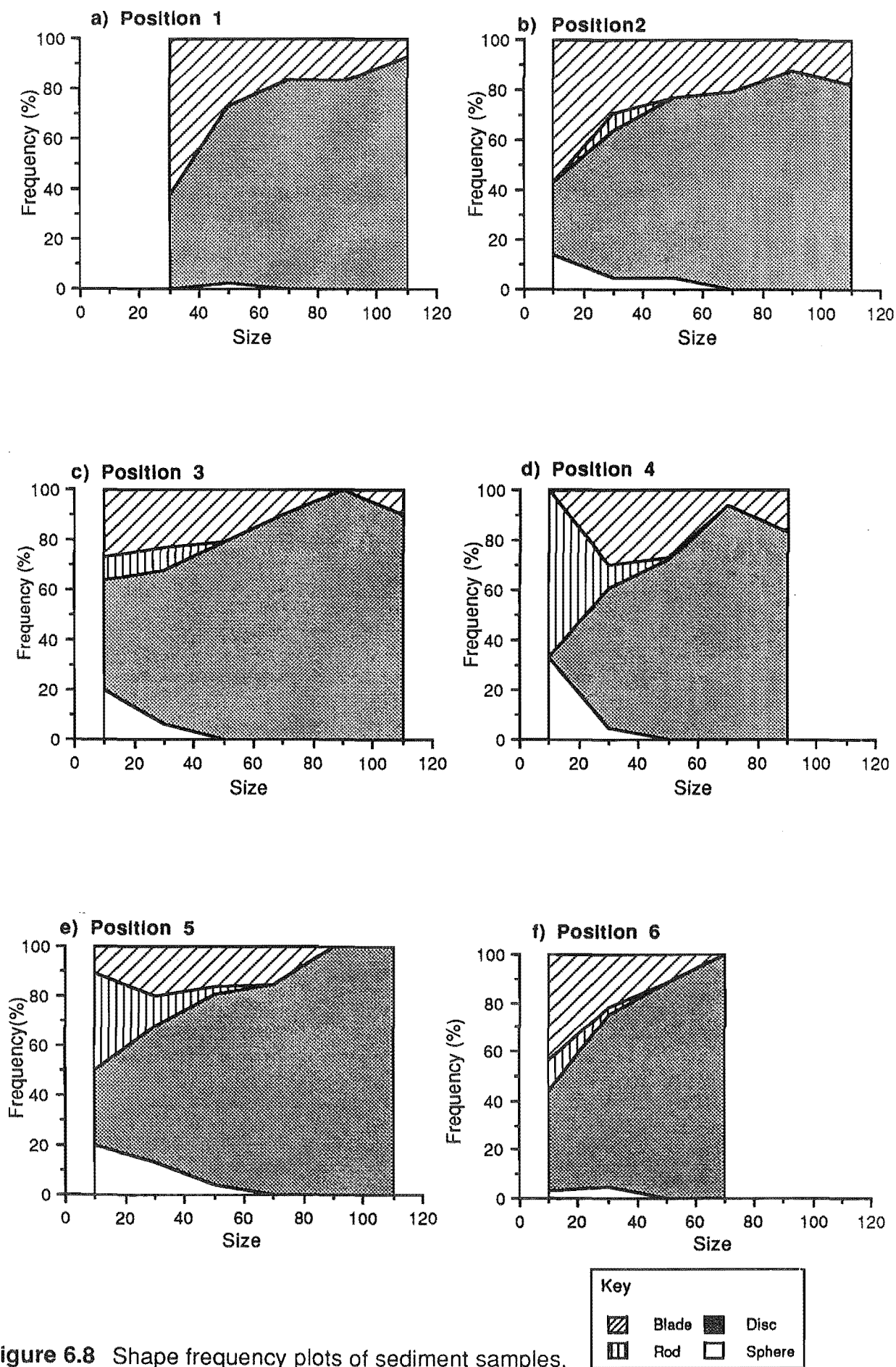
Figure 6.8 Shape frequency plots of sediment samples.

according to the b-axis measurement. Figure 6.9 shows the size frequency with the proportion of various shapes in each size class. This gives an estimate of the distribution of sizes in each position on the beach.

The patterns of size and shape distribution across the beach show distinct variations between the five positions. The initial subjective zonation of the beach in choosing the sample collection positions (as discussed in Section 3.5) appears justified from these results. Because of the transient nature of the intermediate berms, the number of zones present at one time may vary. However the division shown is applicable for the majority of the profile surveys carried out for this study. A description of the sediment particles found in each zone as shown in Figures 6.8 and 6.9 follows.

Position 1: Backshore

The backshore is comprised mainly of large disc shaped particles. Particles from the surface sample range in size from 20 to 120 mm across the b-axis. The mean size is 70 mm while the modal class is between 60 and 80 mm. Although the shapes are dominated by discs, there are blades present in all the size classes but mostly in the smaller sizes. In this zone the deposition occurs as a result of swash overtopping the barrier crest. There is a definite distinction between the large discs on the surface and the sediments just below the surface layer which are comprised of sands and small pebbles that have settled into the spaces between the larger clasts.

Position 2: Barrier Crest

This zone is also dominated by disc shapes with blades and some spherical and rod shaped particles in the smaller size classes. It differs from the backshore zone in the size distribution. There is a complete range of sizes present in the samples from this position. The mean size is 45 mm and the modal class lies between 20 and 40 mm. The distribution of sizes is skewed towards the smaller size classes. The disc particles are imbricated on the seaward facing slope of the crest and at or near the angle of repose for the range of sediment sizes present. The surface sediments are not cohesive and the slope collapses easily. Material is deposited in this zone under swash and backwash processes. During episodes of erosion the subsurface sediments may become exposed as shown in Figure 5.10.

Position 3: Upper Foreshore

The shape distribution in this zone is similar to that found on the barrier crest. There are more discs present in the smaller size classes and the surface sediments can
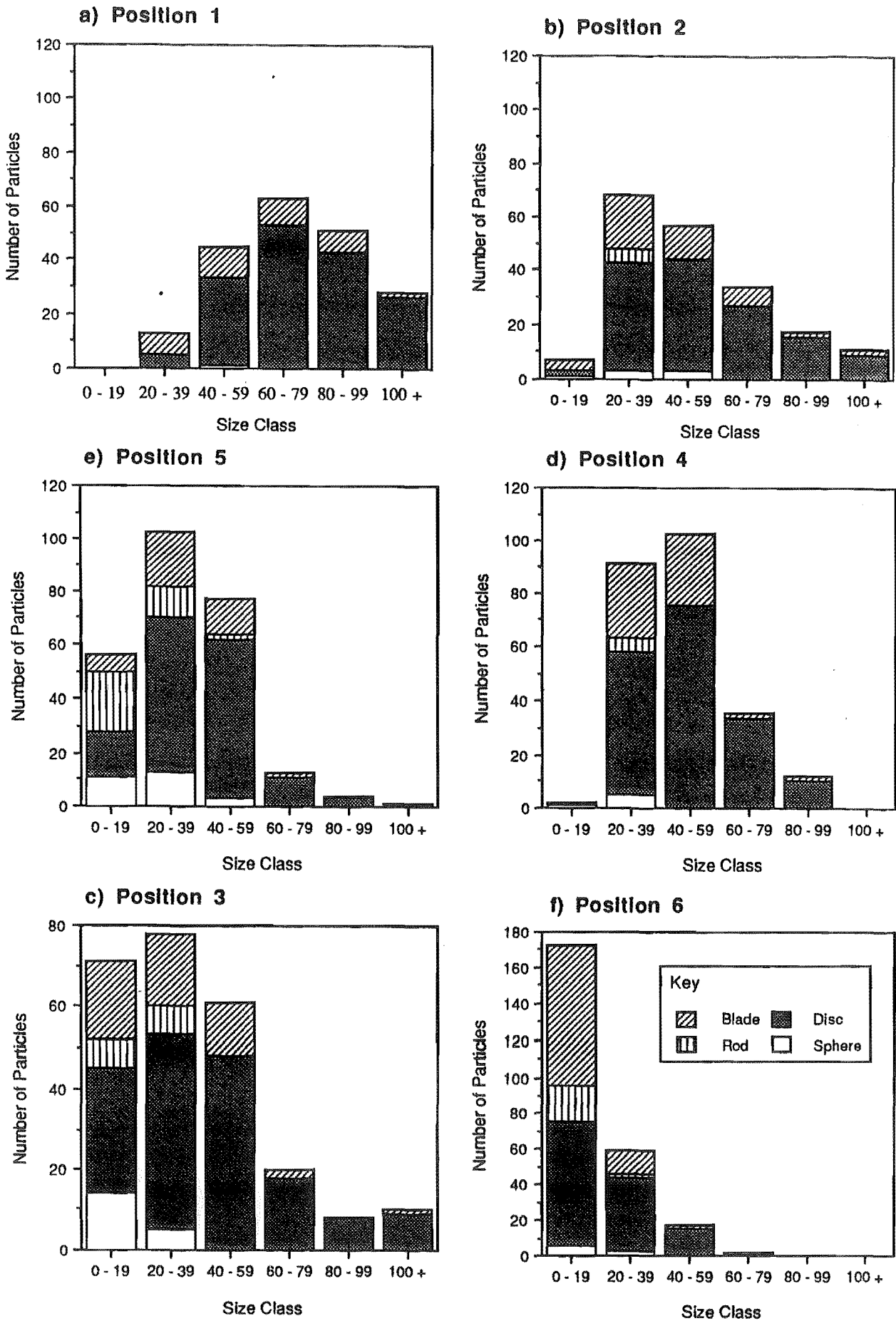
Figure 6.9 Number and shape of particles classed by size (size class based on b - axis measurement).

be infilled with fine particles. The complete range of sizes is present with the mean size equal to 30 mm and the modal size range being 20 to 40 mm. This zone contains the greatest percentage of particles within the smallest class (below 20 mm) for all of the zones above the lower foreshore.

Position 4: Intermediate Berm

The mean size of particles in this zone is 40 mm and there are few particles over 80 mm or under 20 mm across the b-axis. The modal size range is between 40 and 60 mm. The dominant shape is discoid and there is a larger proportion of blades than in the other zones. The increase of rods and spheres on the shape frequency graph is due to the small number of particles found in the small size class. The processes at work in this zone are similar to those of the upper foreshore and the barrier crest except that the energy content of the swash and backwash is much smaller. This is reflected in the differences in sediment sizes present in zones 1 and 3.

Position 5: Low Energy Swash Limit - Interberm Nadir

The range of sizes in this zone is concentrated in the three smaller classes of size (under 60 mm across the b-axis), although large particles are present. The modal class is 20 to 30 mm and the mean size is 30 mm. The large sizes are dominated by disc shaped particles but this is again a factor of the small number of particles in these size classes. This zone has the greatest shape range in the small sizes, with the proportion of rods and discs almost equal. Blades and spheres are also present. This zone is at the limit of swash during episodes of low wave energy. The interberm nadir can also be infilled by fine sediments and was observed to contain a large sand lag deposit on some sections of the study coast.

Position 6: Swash Zone - Lower Foreshore

The overall mean size of the samples taken from Position 6 was approximately 5 mm, and were composed mostly of granules and coarse sand. The samples were of two types. Those taken from Profile 2 and P10 had a high proportion of large particles (nearly half of the sample by weight) whereas the samples of Profiles 3, 5 and 7 were more uniform in size. The mean size of the 50 largest clasts for the two types of sample are 29 mm and 10.6 mm respectively. The mean b-axis measurement for all of the clasts measured for shape is 18 mm. The modal size is in the 0 to 20 mm class. The range of sizes is predominantly less than 40 mm with only 19 of the particles greater than 40 mm including 2 particles greater than 60 mm. The dominant shapes are discs and blades with some rods and spheres in the smallest size class. The hydrodynamic

processes are similar to those in Position 5 higher up the foreshore, except the swash and backwash are more turbulent and breaking waves can cause saltation of sediment particles.

Interpretation

From the across-shore zonation described above it can be illustrated that processes of different magnitudes act on different parts of the foreshore. This is a function of the energy of the processes and the translation or dissipation of energy into sediment movement and foreshore adjustment. Higher energy events will move larger sediments and affect the beach to higher elevations on the profile than episodes of low energy. The properties of the different shaped particles under various wave conditions determine their behaviour. For example, discoidal particles are more easily entrained than spheres with a similar b-axis, and when they are in suspension they have a lower settling velocity than other shaped particles. Therefore they are carried further up the beach by the wave run-up and deposited near the swash limit as the water percolates into the beach or the swash velocity drops.

Disc shapes are predominant in all but the smallest sediment size class for each position on the beach. The mean particle size is progressively greater towards the limits of swash of higher energy events. The exception is Position 3 which has a large proportion of finer material, including a large number of spherical particles. These sediment characteristics may be the result of a mixture of processes with the large discs deposited during the formation of the intermediate berm, and the smaller spheres being a lag deposit from a higher energy event.

6.4.3 A more detailed shape classification

The Zingg method of shape classification used so far for this study follows the methodology used by Bluck (1967). Benn (1987) noted that this is a coarse method of describing particle shape as it is limited to only four shape classifications, discs, blades, rods and spheres. A more detailed method of shape classification was put forward by Sneed and Folk (1958). The Sneed and Folk method distinguishes ten shape types. These are shown in Figure 6.10. Because of the computer generation of shape plots for this study, a rectangular display of shape distribution has been used in favour of the triangular display used by Sneed and Folk. Plots of the distribution of Sneed and Folk shape classifications for the study samples are shown in Figure 6.11.

COMPACT

C

.7

CP · CB · CE

.5

.80

$\frac{S}{L}$

.90

Ψ_p

P · B · E

.3

.70

VP · VB · VE

.60

.50

.40

.30

PLATY · 33 · BLADED · .67 · ELONGATE

$$\frac{L-1}{L-S}$$
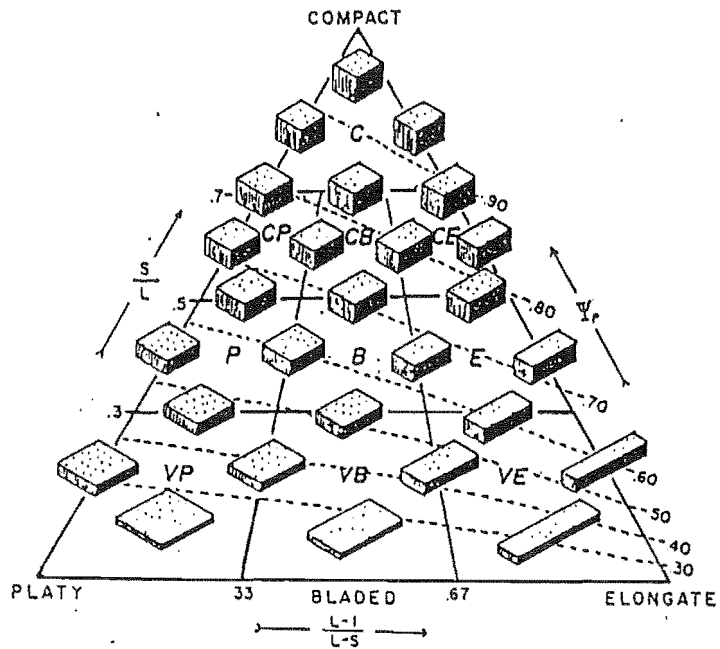
	Legend
C =	Compact
CP =	Compact Platy
CB =	Compact Bladed
CE =	Compact Elongated
P =	Platy
B =	Bladed
E =	Elongated
VP =	Very Platy
VB =	Very Bladed
VE =	Very Elongated

Figure 6.10 Shape triangle (after Sneed and Folk 1958, from Benn 1987, Figure 3.2).

It can be seen from Figure 6.11 that most of the samples are clustered among the platy, very platy, bladed and very bladed shapes. Elongated and compact elongated sediments are present to a lesser extent. From Figure 6.11a it can be seen that there is no easily defined longshore variation in shape distribution indicating that there are no definite patterns of sediment structure for different sections of the sediment slugs. From Figure 6.11b, it can be seen that there is distinctive clustering of sediments from different positions on the beach. The distinctive shape classification distributions for each sample position (or zone) can be seen clearly from the shape frequency histograms shown in Figure 6.12. For comparison to the Zingg shape classification, both methods are shown. The following discussion looks at the shape histograms for each position on the profile as a group.

From the Zingg shape histograms it can be seen that the dominant shape for all of the positions on the beach is discoid, varying from 50% to 80% of all the shapes present. For all positions except Position 5, blades are the next most prevalent shape. The most even balance between discs and blades occurs in Position 6, with spheres and rods present but to a lesser degree. Position 5 is an exception to the disc over blade dominance in shape type, as there is a fairly even proportion of spheres, rods and blades with the discs being singularly dominant.

The dual shape prevalence is also apparent from the Sneed and Folk shape histograms. For all of the positions except Position 6 - the lower foreshore -, very platy/ platy and very bladed/bladed shapes dominate. However each position has a distinctive 'skyscraper' pattern to the histograms. On the backshore, Position 1, the two dominant types stand out alone with the more very platy and very bladed shapes being present than platy and bladed. There are a small number of elongated shapes but no compact shaped particles. At the barrier crest, Position 2, very bladed/bladed shapes stand out above the very platy/platy shaped particles, and there is a complete range of the shape types present .

There is also a complete range of shapes at Position 3, the upper foreshore, although the very bladed and very platy shapes are less dominant. There is a noticeable presence of the other shapes with about 4% by number of each shape. There are slightly more elongated particles. In Position 4, on the intermediate berm, the proportion of platy and bladed shapes is slightly higher than in Position 3, and there are fewer particles of the other shapes especially of the compact/compact platy/compact elongated types.

Profile 2

Profile 3

Profile 5

Profile 7
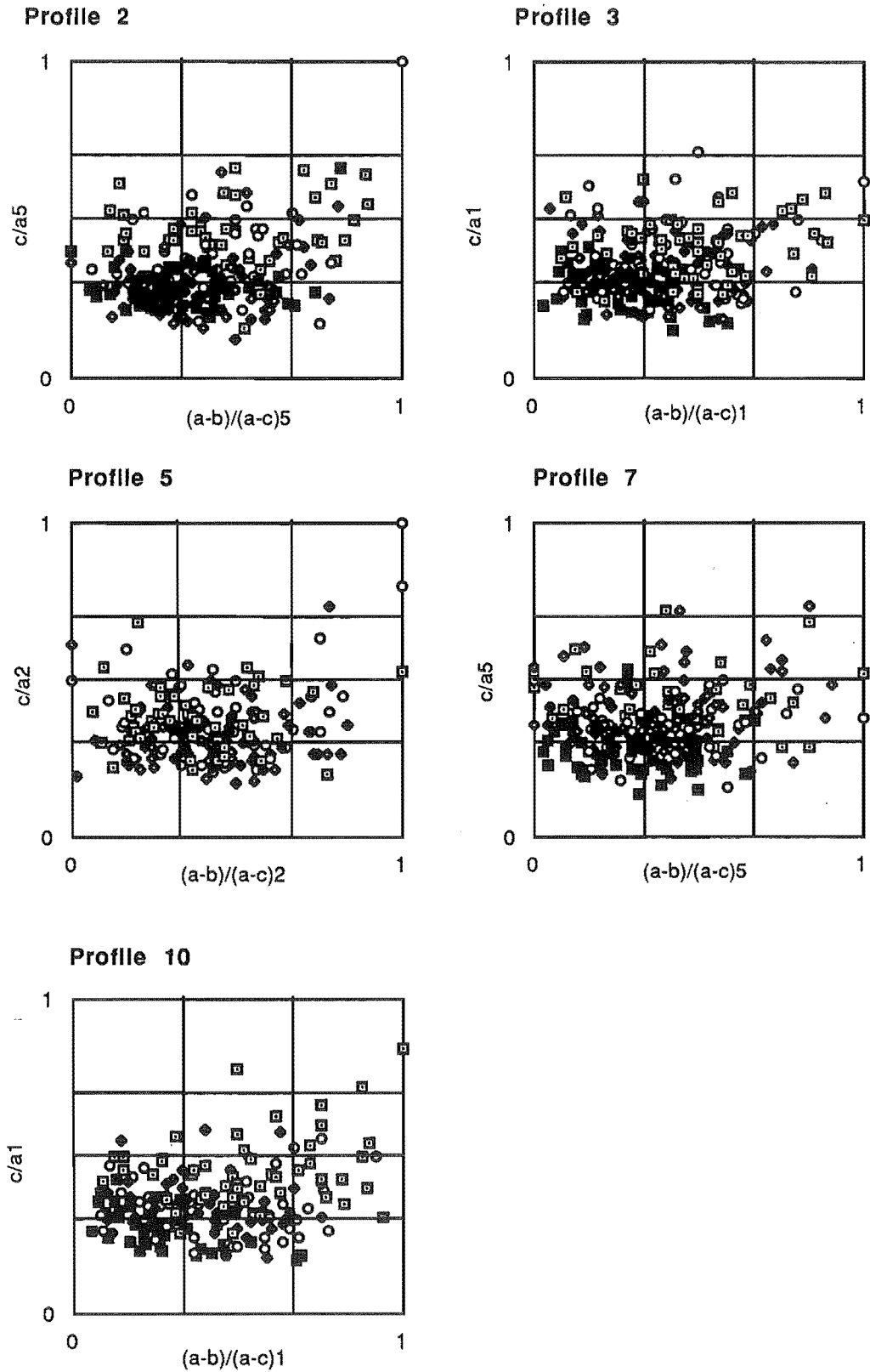
Profile 10

Figure 6.11 Plots of Snead and Folk shape classifications for the samples of this study.

a) All sample positions for each profile.

Position 1

Position 2

Position 3

Position 4
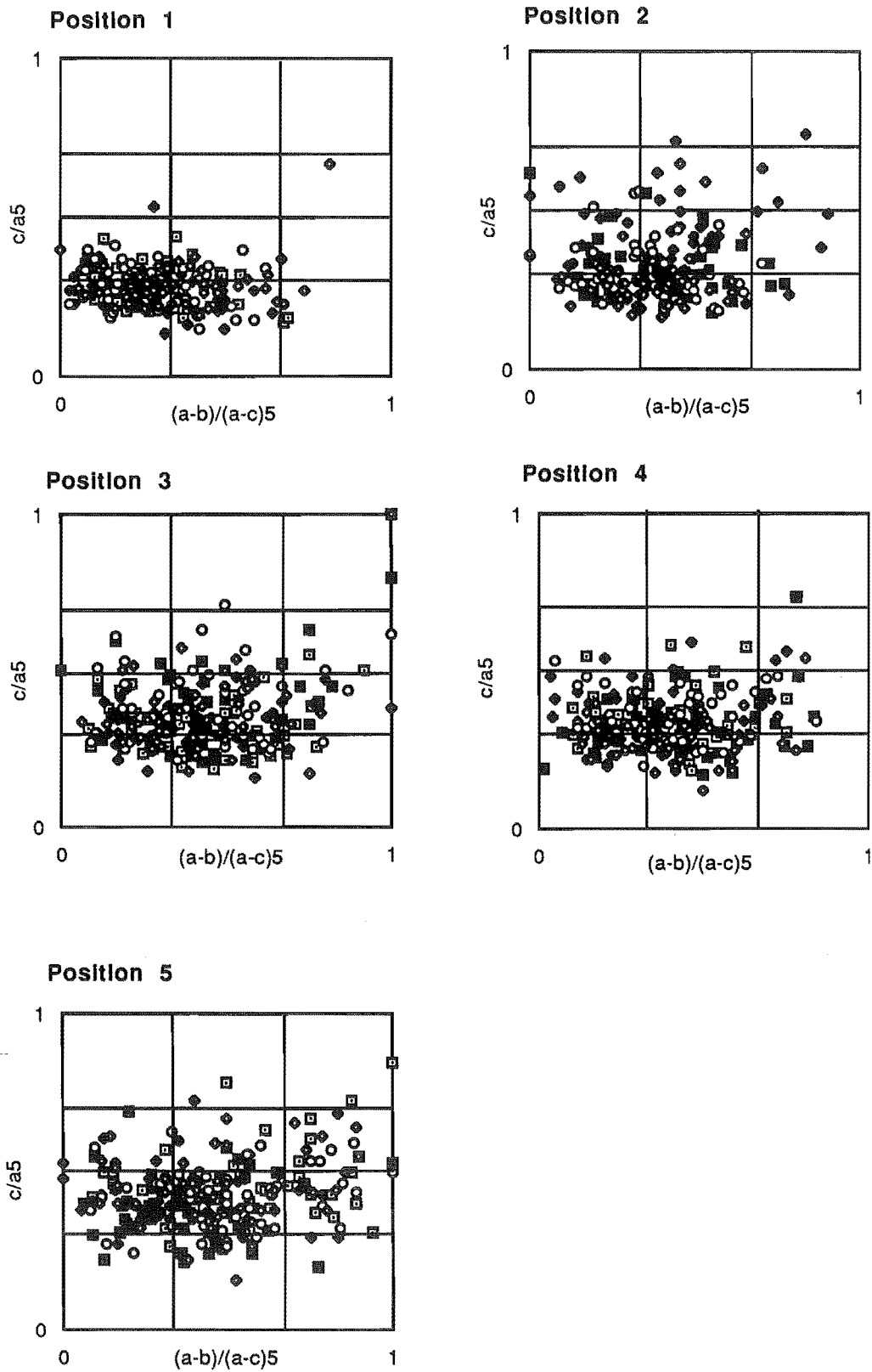
Position 5

Figure 6.11 Plots of Snead and Folk shape classifications for the samples of this study.

b) All profiles for each across-shore position sampling.

Figure 6.12 Zingg and Sneed and Folk shape classification histograms for the samples.
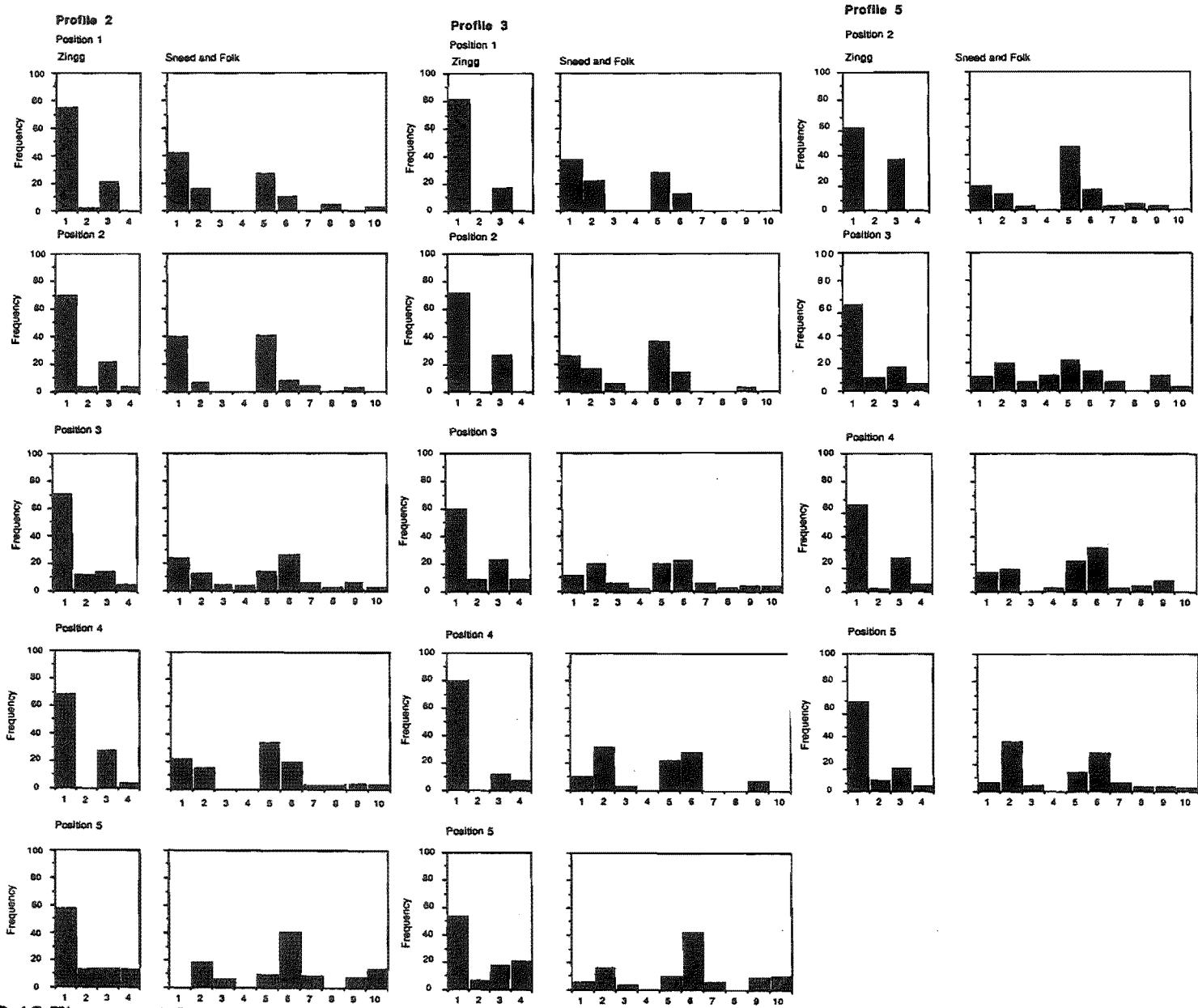
Figure 6.12 Zingg and Sneed and Folk shape classification histograms for the samples.
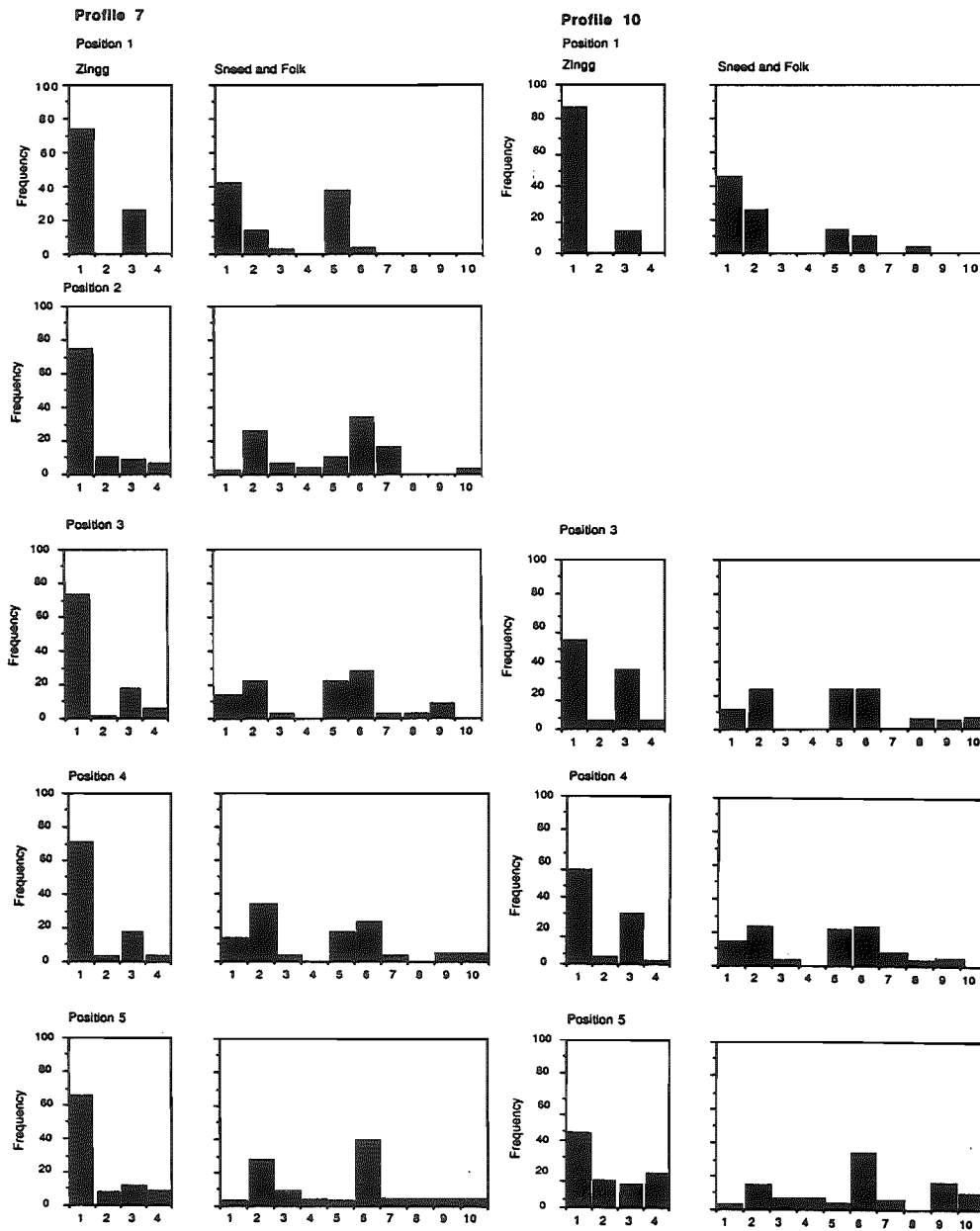
Classes

Zingg 1 Disc
2 Sphere
3 Blade
4 Rod

Sneed and Folk 1 Very Platy
2 Platy
3 Compact Platy
4 Compact
5 Very Bladed
6 Bladed
7 Compact Bladed
8 Very Elongated
9 Elongated
10 Compact Elongated

There are only two definite peaks in the shape histogram for the interberm, low energy swash limit zone, Position 5. These occur for the bladed and to a lesser degree for the platy shapes. However there is a nearly even distribution of the other shape classes except for the very platy, compact and very elongated shapes. There is a more even distribution of the shape classes in Position 6, the swash zone or lower foreshore. The shapes are dominated by blades only and there are proportionally more very elongated and elongated shaped particles.

The Sneed and Folk shape histograms have distinctive patterns for the different sample positions across the beach profile, and these differences in pattern are more definite than on the Zingg shape histograms. The Sneed and Folk histograms could be interpreted as a zonal signature such that the across-shore position of a sediment sample could be traced according to its shape distribution and the shape histogram produced.

6.4.4 A model of across-shore zonation of sediment characteristics

It can be seen from a comparison of Figures 6.6, 6.7 and 6.8 that the sediment characteristics of the study area are very different to the gravel beaches examined by Bluck. The variation in the number and description of identifiable zones on the two types of beach also indicate that Bluck's zonal breakdown of gravel beaches is not applicable to the mixed sand and gravel barrier beaches of the Wainono Lowland Coast. There is no outer frame to the mixed beach, the break between the coarse beach and the fine sand nearshore bed is always seaward of the breaking waves. There are also more small particles present at and near the surface of the sand and gravel beach emphasising the mixed nature of the sediments.

The descriptive information from Sections 6.4.2 and 6.4.3 can be used to develop a model of the sediment characteristics of the across-shore zonation of the mixed sand and gravel barrier beach. This model is presented in Figure 6.13. As noted earlier, the zonation for a specific site is subjectively determined, and is dependent on the profile morphology at the time of investigation. The limits of the zones are loosely positioned in Figure 6.13 as there are no definite boundaries between one zone and another on the beach. It is more likely that there is a progressive but gradual change in the sediment character along the profile surface. The shape histograms presented follow the Sneed and Folk (1958) shape classification based on the ratio of size difference of the measured axes, and have been determined from an amalgamation of the sediment sample data from this study. The zonal description of the sediment characteristics of each zone follows those given in Sections 6.4.2 and 6.4.3. These are listed below.
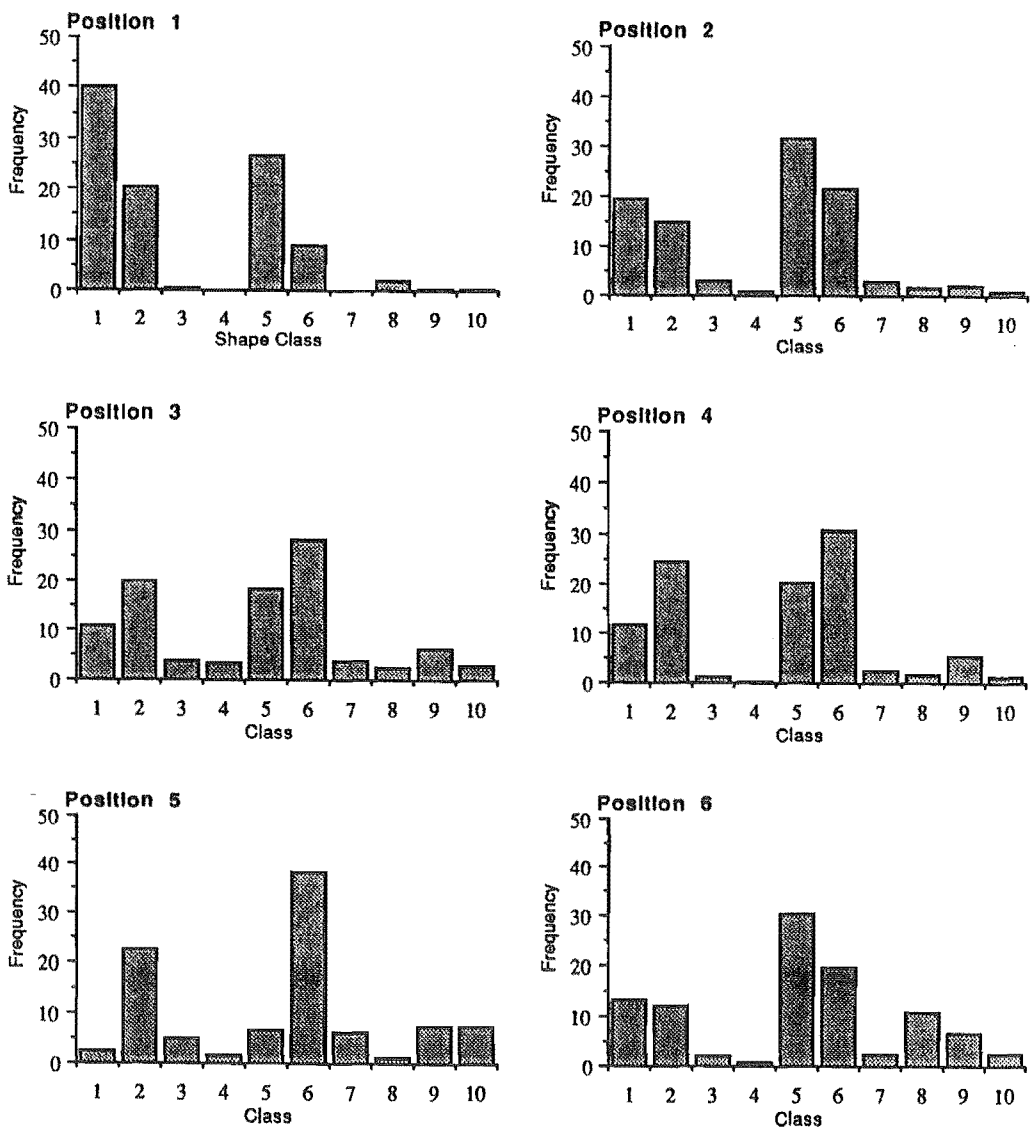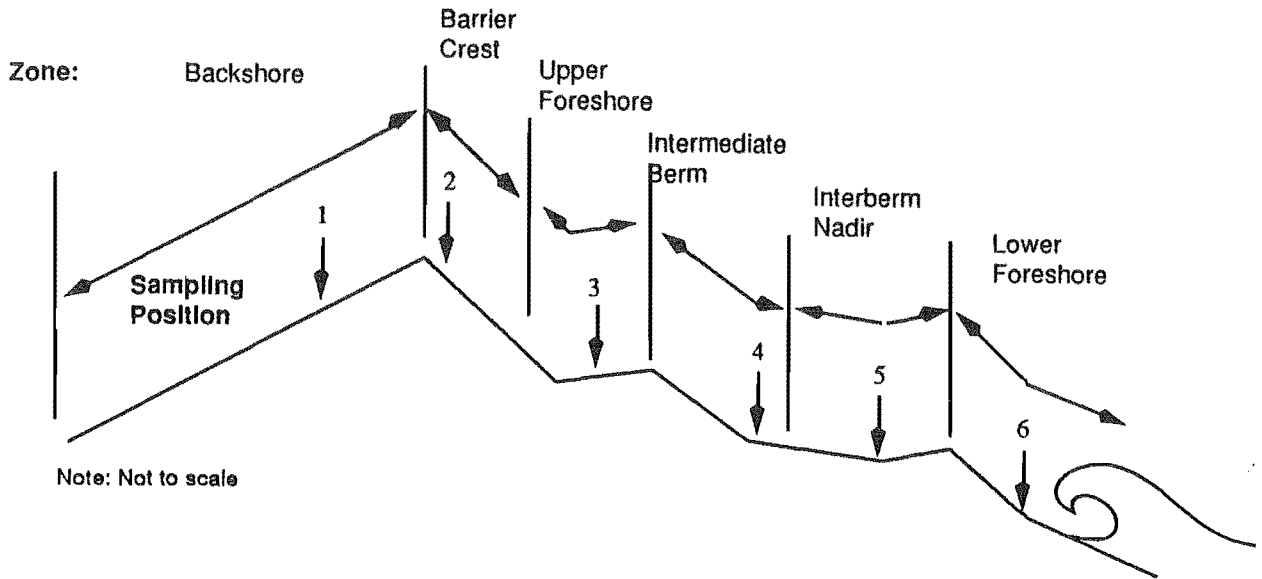
Figure 6.13 A zonation model of sediment shape characteristics for mixed sand and gravel barrier beaches.

a) Across-shore zonation.

b) Shape signature.

Backshore -   Large discs (mean size 70 mm) dominate this zone
                     with the disc shape being very platy or very bladed.
                     The surface layer is two or three particles in depth
                     and fine and sand sized material is dispersed
                     amongst the larger clasts.

Barrier Crest -   Very bladed and bladed dominate over platy
                     shaped particles although there is a complete
                     range of shapes present. Imbrication of the
                     particles on the seaward facing slope is well
                     defined. The mean particle size is 45 mm.

Upper Foreshore -   The complete range of shapes is also dominated by
                     bladed and platy shapes and is a result of a
                     combination of process magnitudes. This also
                     leads to a mixture of sediment sizes with the mean
                     size being 30 mm.

Intermediate Berm - There is a narrower selection of particle shapes in
                     this zone, similar in shape to the backshore but
                     smaller in size (mean size 40 mm) although there
                     are few particles smaller than 20 mm.

Interberm Nadir -   The dominant shapes are bladed and platy
                     although there is an even spread of the rest of the
                     shape range. This zone is also active in a range of
                     process magnitudes and can be covered in a lag
                     deposit of sand sized particles. The mean size is
                     slightly less than 30 mm.

Lower Foreshore -   This zone is bimodal in size range with a mixture of
                     sand to granule sized particles (mean size 3-5 mm)
                     and pebble to cobble sized particles (mean size 18
                     mm). The dominant shape of the larger clasts is
                     bladed but tends towards the platy end of the blade
                     range of axis ratios (a-b/a-c slightly more than 1/3).

6.5 Discussion

6.5.1 Longshore variations

Spatial variations of morphological characteristics of the Wainono Lowland Coast
were examined in this chapter. Alongshore variations in morphology were identified.
These included differences in foreshore width and foreshore volume for the different
profile sites. The pattern of variation alongshore was examined with reference to the
presence of slugs of sediment moving along the coast as collective units of material,
and whether the presence of slugs could be identified from the field data. A sediment

slug was found to be present in the study area from the general longshore shape of the foreshore width and longshore distribution of profile volume. In both cases, a bulge was evident from the data. The bulge was represented by narrower foreshore widths and smaller foreshore volumes on Profiles 1, 2, 6 and 7 (the profiles at each end of the study area) than on Profiles 3, 4 and 5 (the profiles in the central region of the study area).

6.5.2 Across-shore zonation

The question was raised as to whether the morphological variations alongshore were reflected in variations of the sediment characteristics. It was found that there was no inherent feature of the beach that caused variations in the morphological response. No alongshore patterns of sediment character could be identified from the sediment samples. However, there were patterns of similarity in sediment shape characteristics for samples taken from equivalent positions across the beach profile for all of the sampled sites. These patterns appear as vertically separated bands running alongshore, and the foreshore has a distinctive across-shore structure. The bands running parallel to the shoreline were identified as being in separate, process-determined morphological zones at different elevations across the foreshore. The pattern of zonation was noted to be different to that described by Bluck (1967) as distinctive for different zones across gravel beaches in south Wales. Bluck's model is therefore not applicable to this mixed sand and gravel barrier beach. No descriptive model of sediment distribution on mixed sand and gravel beaches exists. This lack of an applicable model has hindered effective description and comparison of mixed sediment beaches from different parts of the world.

A model of across-shore zonation of sediment shapes for the mixed sediment beach was developed from the data collected for this study. This model provides a baseline against which other mixed sand and gravel beaches can be compared. It represents the first step in providing a comprehensive understanding of sediment behaviour and distribution on the mixed sand and gravel beach.

Six zones running parallel with the shoreline were identified subjectively in the field and subsequently found to have distinctive sediment shape distributions which reflect the process environment for a given section of the profile. These zones are the backshore, the barrier crest, the upper foreshore, the intermediate berm and interberm nadir (positioned in the middle foreshore), and the lower foreshore. Sediments were sampled from each zone and measured to determine the shape of each particle. The Zingg shape classification method (Zingg 1935) was found to be too coarse to identify

the difference in shape properties clearly. The shape classification presented by Sneed and Folk (1958) was applied to the sediment samples and found to adequately distinguish differences between the across-shore zones. It is considered that materials from each zone possess a unique sediment signature as represented by the Sneed and Folk shape histogram. The proposed model presents the across-shore zonation of the mixed sand and gravel barrier beach with the sediment signature for each zone.

6.5.3 Variation in beach response to high energy events

The beach response to high energy events was discussed in detail in Chapters Four and Five. Responses to events were not uniform for all sites in the field area. It has been noted that there are no features offshore of the study area that would concentrate wave energy onto one site more than any other. It has also been noted that there is a quasi-stationary slug of sediment positioned on the Wainono Lowland Coast. From the spatial analysis of the area and the sampled sediments, it has been shown that there is a distinctive structure to the foreshore. This structure is the same for all of the area and does not differ between the slug crest, trough or flanks. Therefore, it is concluded that the structure is not a determining factor in whether or not barrier breaching, overtopping or crest erosion occurs during a high energy event.

The characteristics of the event are the dominant control on how much of the profile (especially its elevation) is affected. The key factor in determining beach response is the available sediment volume in the foreshore, which is presented to the event. It was shown in Chapter Five that the beach response varied with volume. Greater volume is reflected in a wider foreshore and the presence of intermediate berms. These act as a buffer of protection for the barrier crest. Although material may be removed during a high energy event, sites with large intermediate berms, wide foreshores and high volumes are less likely to sustain damage to the barrier crest.

Those study profiles that sustained damage to the crest had a foreshore volume less than 130 $m^3.m^{-1}$ of beach and a foreshore width of less than 35 metres. These are not offered as definite limiting values for determining whether a site response to high energy events will be 'Destructive'. However, they can be used as guidelines for determining the 'healthiness' of the beach in respect of the beach function as protection for the hinterland from the sea.

CHAPTER SEVEN

CONCLUSIONS

7.1 Summary of Major Findings

This thesis considered the role of high energy events in determining beach morphology on a mixed sand and gravel barrier beach. Morphological adjustments of seven beach profiles were examined over a four year period, in the area near Wainono Lagoon, on the South Canterbury Coast. A number of questions were proposed for consideration. These questions are listed below.

1. What are 'high energy' events, and how can they be characterised?

2. What are the short term effects of high energy events on a mixed sediment barrier beach?

3. What is the role of high energy events in determining the processes of long term coastal retreat occurring on the study coast?

4. How does beach crest lowering occur?

5. How is breaching initiated, and what conditions pre-dispose its occurrence?

6. What is the significance of high energy events to the beach sediment budget?

7. What are the mechanics and component variables of the passage of slugs, how big are they, what drives them and how fast do they move along the coast?

8. How does the passage of slugs affect the response of the beach to high energy events at different sites along the coast and at particular sites over time as the slugs pass through?

9. Does the magnitude and frequency concept (as proposed by Wolman and Miller 1960) apply to the South Canterbury coast, if so how, and if not why not?

10. What thresholds exist in the function of a mixed sand and gravel beach system?

In addition to these specific questions, the morphological examination of beach changes has highlighted the incompleteness of understanding of processes and responses on mixed sand and gravel beaches.

The major findings of this study contribute to three general areas of knowledge of the mixed sediment beach process/response system. The first area concerns the characterisation of high energy events on the South Canterbury Coast. The second area deals with the beach response to these events. The third general area contributes to describing the spatial variations of mixed sand and gravel beach morphology. The conclusions reached in respect of the ten questions asked above are set out below.

7.1.1 High Energy Events

Question 1: Characterisation of High Energy Events

The impacts of high energy events on human use of the coastal environment on the South Canterbury Coast are both physically and economically important. It is therefore difficult to separate the magnitude of the processes of the event from the resulting impacts at the coast. The significance of the event to the human use system is proportional to the type and amount of beach adjustment or sea water encroachment that occurs, rather than to the magnitude of the oceanographic variables, such as wave height, period, direction of approach and storm duration. Defining what constitutes a high energy event involves a circular argument. It is necessary to define the type of beach response that occurs during high energy events for the definition to be of use to the users of the coastal environment. It is also necessary to define a boundary for the magnitude of the process variables to separate high energy or storm processes from low energy or 'normal' process conditions. The position of this boundary is reflected by the type of beach response that occurs as a result of different process environments.

From an examination of the field data for this study, it is concluded that there are three types of beach response to what is nominally assumed to be high energy events. These are classified as follows:

'Destructive' - events that result in overtopping or beach crest lowering with an ensuing loss of material from the coastal system.

'Damaging/Erosive' - events which change the status of the beach from 'healthy' to potentially 'weak' due to a change in foreshore form and the removal of sediment from the profile.

'Damaging/Constructive' - events that result in changes to the foreshore form by net accretion of sediment to the profile.

The study period was considered as atypical in respect of the process regime. There were fewer storms during the study period than were expected after a consideration of documented event occurrence such as presented in Table 1.3.

However, high energy events that did occur during the study period were identified by evidence of the types of beach response described above. Seven episodes of high energy processes were noted. Three events were of the 'Damaging/Constructive' class, and four events were of the 'Damaging/Erosive class. In addition, three other storm episodes were examined. These events occurred outside the study period but were included as examples of the types of event that are possible. Of these storms, two were considered to be 'Damaging/Constructive' and one resulted in 'Destructive' beach adjustments at two sites within the study area.

A definition of high energy event processes could not be proposed because of insufficient quantitative data describing the oceanographic components of each event or the parameters of beach adjustment due specifically to the event. From an examination of the beach response to the seven high energy episodes during the study period and to the three other storm events, a semi-quantitative characterisation of high energy events was advanced.

Wave episodes with breaking wave heights in excess of 2.5 metres can be considered as 'high energy events'. This is less than the 3.0 metre definition of storm waves adopted by Kirk (1987a). The lower breaker height is applicable as events of this magnitude can produce wave run-up to a minimum elevation of 3.5 metres AMSL. This elevation is over half the height of the barrier beaches in the study area. 'Damaging/ Erosive' events during the study had run-up reaching at least 4.5 metres AMSL. The 'Destructive' event produced run-up to over 5 metres AMSL, with observed breaking waves heights of 3.6 metres. The main differences in process between the 'Destructive' event and the other categories are greater storm water levels and a longer storm duration. The 'Destructive' event resulted in storm water levels of 0.4 metres above the predicted water level. Long duration events (in excess of approximately twenty hours) are more likely to be 'Destructive'. The wave approach direction does not appear to influence the type of adjustment to the beach, but may be a controlling factor to the storm duration.

7.1.2 Beach response

Question 2: Short Term Effects

Four factors, important to the way the beach profile responds in the short term to high energy events emerged from this study. They are:

a) the slope of the foreshore,

b) the presence, and dimensions of intermediate berms,

c) the initial volume of beach sediment seaward of the crest, and

d) the sediment composition and structure within the foreshore.

The three classes of beach response to high energy events (as discussed above) are differentiated by the magnitude and direction of the volume change, and the elevation on the profile at which maximum foreshore retreat occurs. 'Destructive' events result in steepening and net removal of sediment from the foreshore. The sediment may be removed offshore or displaced from the foreshore to the backshore, removing it from the active beach, and therefore no longer available as protection against wave attack. 'Damaging/Erosive' events also result in steepening of the lower foreshore and removal of sediment from the upper and middle foreshore. These events do not cause adjustments to the barrier crest. 'Damaging/Constructive' events cause the shape of the foreshore to change. The lower foreshore is steepened while the overall gradient of the rest of the profile is made less steep. The net effect is an increase in the volume of sediment in the upper and lower foreshore, and erosion of sediment from the middle foreshore.

All of the high energy events result in the removal of any intermediate berms that may be present. This section of the foreshore is the swash zone under large breaking wave conditions, and is 'graded' by the action of swash and backwash. The upper foreshore is a deposition zone during 'Damaging/Constructive events, but undercutting and destabilisation of the seaward slope of the barrier crest can occur during 'Damaging/Erosive' events.

Most of the foreshore adjustment occurs in the middle and upper foreshore during high energy events. The antecedent condition of the foreshore is therefore an important control on the type of response. Sediment volume present in this part of the profile will provide a buffer for wave dissipation and absorption of wave energy, and will be a source of material for erosion. In the study area, profiles with foreshore volumes over 130 $m^3.m^{-1}$ of beach, and foreshore widths greater than 35 metres sustained less damage to the barrier crest than those with lesser dimensions.

Question 3: Long Term Effects

The short documented history of beach changes and the large variations in beach adjustment from year to year make it difficult to interpolate the effect of high energy events on long term trends of beach behaviour. During the study period, crest retreat occurred on four of the seven study profiles. Retreat varied from 2.5 metres to 9 metres. The average net changes in foreshore volume for the study period were ·

approximately -11 $m^3.yr^{-1}.m^{-1}$ of beach. However, during an episode of high energy waves between 22/2/90 and 1/3/90, the change in volume ranged from -19 to +7 $m^3.m^{-1}$ of beach for the study profiles. It follows that the average changes over a long period with few high energy events, such as the study period, can result in changes to the beach that can be offset by one or two storm episodes.

The major effect of high energy events on the long term beach morphology of the South Canterbury Coast comes about through 'Destructive' events, where there is a loss of material from the active beach system due to overtopping, barrier crest lowering or breaching. This causes retreat of the barrier crest and a change in the position of the beach with reference to some fixed datum. Because there is a deficiency in the supply of sediments to the beach, this retreat is irreversible without some human intervention such as beach reconstruction or renourishment.

Questions 4 and 5: Mechanics of Crest Lowering and Breaching

Examples of barrier crest lowering and breaching were discussed in Chapter Five in respect of the consequences to the beach morphology of the storm of July 1985. However, as there were no incidents of this type of beach response during the study period it has not been possible to develop the detail necessary to explain the mechanics of barrier crest lowering and breaching. During the course of this study, small magnitudes of crest lowering occurred between survey dates, although there was no evidence of overtopping. It was thought that the crest lowering was caused by oversteepening and/or undercutting of the upper foreshore by wave backwash induced erosion, resulting in collapse of the unsupported seaward facing slope below the crest.

Question 6: Significance of High Energy Events to the Sediment Budget

The information from this study is only relevant for the coarse fraction of the sediment budget. High energy events can add material to the sediment budget through rapid injection of material into the sediment transport system from the upper foreshore or backshore, including unconsolidated sediments at the base of coastal cliffs. These events can also remove sediment from the active system, both by transporting material offshore beyond the narrow zone of longshore transport of coarse particles, and by relocating material beyond the barrier crest and into the backshore zone.

During the study period there was an annual net loss of 5% of the active foreshore (6500 $m^3.km^{-1}$). This is a greater value than the 450 $m^3.km^{-1}$ presented by Kirk (1987a) as the annual average contribution to the sediment budget by erosion of the Waihao-

Wainono Lowland beaches. It is however, less than the possible removal of sediment from the beach during one storm episode. As there were few high energy events during the study period, reservations are held as to the significance of such events to the long term sediment budget.

Questions 7 and 8: Sediment Slugs and Longshore Variations in Beach Response

The notion of 'slugs' of sediment moving along the coast as collective units was put forward by Neale (1987). Field data from this study were examined in an attempt to determine if these slug forms were present in the field area, and if so, how their passage through the area affected the beach response to high energy events.

The component variables, and the mechanics of sediment slug formation and movement along the coast were discussed in Chapter 2. The slugs reflect episodic supply of sediment from the Waitaki River and coastal cliff erosion to the beach system. They move along the shore in the direction of dominant longshore transport, and are measurable as protrusions to the beach morphology. They also represent variations in the spatial distribution of beach sediment volume. In plan view (see Figure 2.12) they have a wave-like form, and can be described as having a crest - the area of greatest seaward protrusion, and a foreshore volume in excess of the mean volume over time -, and a trough - the area between crests, which has less than the mean volume over time. Neale calculated the average maximum volume change caused by the passage of a slug past a site on the coast to be 45 $m^3.m^{-1}$ of beach, and the average rate of passage to be 1.4 $km.yr^{-1}$.

It was concluded from the field evidence of this study, that alongshore variations in foreshore volume indicated the presence of a slug of beach sediment in the field area. The crest of the slug was situated near Profile 3, and the troughs of the slug were approximately adjacent to Profiles 2 and 6. The slug remained quasi-stationary during the study period. The average difference in volume between the slug crest and the slug trough is 101 $m^3.m^{-1}$ of beach, which equates to 50.5 $m^3.m^{-1}$ of beach change in volume about the mean volume for the area. There was no evidence of a net northwards passage of the slug through the field area, and no long term rate of longshore translation of the slug could be calculated.

The presence of a slug at a site on the coast plays an important role in determining the antecedent morphology of the profile that is available to dissipate wave energy. Whether the crest or the trough of the slug is present at a specific site will determine the amount of foreshore sediment volume. The profile adjacent to the slug

crest presents a much 'healthier' protection against wave attack than the profile adjacent to the trough. This is because there is more sediment available during episodes of erosion, and more beach surface area between the breaking wave and the barrier crest to dissipate or absorb swash energy. This reduces the risk of barrier breaching or overtopping. The profile adjacent to the trough has less foreshore sediment volume and a narrower foreshore. It is therefore more susceptible to erosion of the barrier crest or overtopping by wave run-up. Passage of a slug past a site will change the profile dimensions, including volume. If a slug remains stationary or quasi-stationary, the susceptibility to damage to the barrier crest during high energy events at the slug troughs increases over time. At the slug crest, the net increase in sediment volume results in a buffer of protection for the barrier crest.

Questions 9 and 10: Applicability of the Magnitude Frequency Concept and Thresholds

The principles of magnitude and frequency, and thresholds have not been specifically discussed with reference to the field evidence of this study. However the underlying theme of the study has taken into consideration the notion that the interaction of processes and geomorphic responses is reflected in the beach being a constantly adjusting system, both responding to, and affecting the nearshore wave and run-up environment.

Wolman and Miller (1960) proposed that some moderately high magnitude events of moderate frequency accomplish most of the geomorphic 'work' on beaches. They acknowledged that some types of work can only be done by high magnitude events, but they did not distinguish between changes to the form and changes to the position of the beach when considering the beach equilibrium. Their conclusions are only partially applicable to the South Canterbury Coast. There are variations in the beach response to processes of different energies. However on these mixed sand and gravel barrier beaches, the form and shape of the beach profile, and its position, are determined by high energy wave processes. Low energy process episodes adjust the shape and position of only the lower portion of the beach profile. High energy events will obliterate the morphological work done by low energy episodes.

The detail necessary to develop a full discussion of the interaction between beach adjustments on the South Canterbury Coast, and the frequency of events of differing magnitudes is not yet available. More long term information is needed on the wave environment, including wave parameters, storm duration and the frequency of events. During this study, the frequency of high energy events was approximately 2 per year. This was considered to be 'calm' in comparison to historical records of storm

occurrence. Temporal variability is not addressed in the magnitude frequency concept. From this study it is concluded that the year to year variability of the frequency of storm incidence is an important factor in determining the beach response to high energy events. A number of storms in quick succession (as occurred during 1985) can have a more damaging impact than a single event of a larger magnitude. This is due to the importance of the antecedent conditions of the beach morphology, especially foreshore volume, as controls of the beach response.

The concept of geomorphic thresholds is applicable to the coastal environment. Descriptive thresholds have been offered for distinguishing damaging impacts of high energy events from 'destructive' changes to the beach morphology. However more work is necessary to determine specific threshold parameters in both process variables and the beach morphology that separate different types of beach adjustment. The process variables include wave height and period, the phase ratio between the breaking wave period and the swash processes, storm water level and set-up, and storm duration. The geomorphological thresholds include beach width, volume and height.

7.1.3 Across-shore zonation

Slugs are indicative of an alongshore variation in the beach morphology. This study identified vertically separated across-shore variations in the profile morphology and the sediment shape characteristics. These variations illustrate that processes of different magnitudes act on different parts (or elevations) of the foreshore. Higher energy events will move larger sediments and affect higher elevations on the profile than episodes of low energy. Different entrainment, transportation and deposition properties of sediments of different shapes were also illustrated. The pattern of variation was different to that proposed by Bluck (1967) for gravel beaches, and suggested that there was a distinct zonal character for mixed sand and gravel barrier beaches.

The data from this study provided a base for the development of a new model of across-shore zonation of sediment shapes for mixed sediment beaches. Six zones were subjectively identified in the field. These zones have distinctive shape characteristics which reflect the process environment for a given section of the profile. Materials from each zone possess a unique sediment signature, which is represented by a frequency histogram of sediment shapes using the Sneed and Folk shape classification (see Figure 6.13). The zonal descriptions of the sediment characteristics and the process environment are listed below.

Backshore -   Large discs (mean size 70 mm) dominate, with the
                  disc shape being very platy or very bladed. The
                  surface layer is two or three particles in depth and
                  fine material is dispersed amongst the larger clasts.
                  Deposition occurs as a result of swash overtopping
                  the barrier crest.

Barrier Crest -   Bladed shapes dominate over platy particles
                  although there is a complete range of shapes
                  present. The mean size is 45 mm. Imbrication is
                  well defined. The surface sediments are not
                  cohesive and the slope is unstable. Swash and
                  backwash processes affect this zone during high
                  energy events.

Upper Foreshore - A complete range of shapes is present but
                  sediments are dominated by bladed and platy
                  shapes. There is a large range of sediment sizes,
                  with the mean size equal to 30 mm.

Intermediate Berm - Mean particle size is 40 mm, and there is a narrow
                  range of shapes and sizes with few particles over
                  80 mm in diameter and few under 20 mm. Discs
                  are the dominant shape, and the processes are
                  similar to those in the barrier crest and backshore
                  but of a smaller magnitude.

Interberm Nadir - This is the limit of low energy swash. The zone is
                  active in a range of process magnitudes. The
                  mean sediment size is slightly less than 30 mm and
                  the dominant shapes are bladed and platy. Sand
                  sized material can accumulate as a lag deposit in
                  this zone.

Lower Foreshore - This zone has a bimodal size range, with a mixture
                  of sand to granule sized particles (mean size 4 mm)
                  and pebble to cobble sized particles (mean size 18
                  mm). The dominant shape of the larger clasts is
                  bladed, but tends towards the platy end of the
                  bladed scale. Processes are similar to the
                  interberm nadir except swash and backwash are
                  more turbulent.

7.2   Suggestions for further research

At the outset of this study, an integral part of the research involved analysis of the oceanographic processes that impact upon the South Canterbury Coast. Unforeseen circumstances - including the loss at sea of a submersible bottom mounted wave recorder, and the rapid onset, short duration and low incidence of storm events during the study period - prevented this analysis from being carried out.

A full understanding of the interaction between wave processes and beach morphology requires information about both factors. More offshore wave height and period, and breaking wave height and period data are required to provide the detailed process information necessary to develop quantitative definitions of high energy events. This data needs to be integrated with short term , or event specific beach adjustment information. There is also a need for more detailed beach morphology information, especially about the internal sediment composition and structure of the barrier. This would be useful in developing explanations of the mechanics of barrier crest lowering and breaching.

More detailed information is also needed to expand the investigation of the magnitude and frequency concepts in coastal science, for the development of applicable general principles. It should also be possible to make quantitative statements about geomorphic thresholds in the mixed sand and gravel beach system. This is especially significant for delineating the magnitudes of the oceanographic components for high energy episodes that result in beach adjustments of different types and magnitudes. The oceanographic or process variables include wave height and period, the phase ratio between the breaking wave period and the swash processes, storm water level and set-up, and storm duration. The geomorphological thresholds include beach width, height and volume.

The proposed model of across-shore zonation of mixed sand and gravel barrier beaches developed from field data from the Wainono Lowland Coast could be tested against data from other mixed sediment beaches, and either verified or modified to make it more generally applicable.

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