
**THE COASTAL SYSTEM OF GORE BAY,
NORTH CANTERBURY, NEW ZEALAND**

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Looking north along Gore Bay, September 2003

Abstract

This thesis examines the coastal system of Gore Bay, North Canterbury, New Zealand. The coastal environment at Gore Bay has not previously been studied in depth and is poorly understood. Effective management of any coastal area requires a thorough description of the entire system, including processes, sediments and morphology. Wind and wave observations, beach profiles, sedimentary analysis, photographic evidence and archival data were used to investigate these three components and unravel the complex relationships within the Gore Bay coastal system.

Gore Bay is approximately four kilometres long and comprises a mixture of both sand and gravel sized sediments. The bay is partially exposed to a high energy swell environment, with the southern end sheltered from the prevailing southerly waves. Two discrete sediment populations were identified in Gore Bay: a pebble mode at around -5ϕ (32mm) and a sand mode at approximately $+2\phi$ (0.25mm). The proportion of sand generally decreases toward the north of Gore Bay, however there is significant temporal variation in sand distribution. Average beach slope is 3.1° in the south, increasing to 8.8° due to a reduction in beach width and increase in beach height toward the north of the bay. These alongshore variations are related to the degree of exposure to the wave environment, which is more sheltered to the south. The beach in the south is backed by a scarp cut into an ancient dune field, on which the village of Gore Bay has been developed. In the north, the backshore slopes landward onto a washover surface and coastal plain, which has an ancient dune field on its landward side.

The morphological response of the beach is dependent on both the characteristics of the wave environment and the distribution of sediments along Gore Bay. The sand and gravel components of the system respond separately to the process environment. Sand moves on- and off- shore as it would on a pure sand beach, while the response of the gravel is dependent upon the permeability of the beach. Beach permeability is affected by grain size, sorting and swash-backwash interactions. Due to the alongshore variation in sedimentary characteristics, the south and north of the bay respond differently to changes in wave conditions. A model of the morphodynamic behaviour of Gore Bay is presented, which takes into account the spatial and temporal variations in beach response.

Gore Bay is a transitional sand and gravel beach, which shows significant variation in morphodynamics to the typical mixed sand and gravel beaches described in the published literature. The presence of a wide surf zone and the onshore-offshore cycling of sediment mean that transitional sand and gravel beaches are a discrete beach type. Management of Gore Bay therefore requires site specific investigation rather than the application of "text-book" coastal principles.

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CHAPTER ONE

INTRODUCTION

1.1 Thesis Statement

This thesis investigates the processes, sediments and morphology of the coastal system in Gore Bay, North Canterbury, New Zealand. A standardised method of coastal investigation is used to provide an in-depth baseline study. Baseline descriptions of coastal areas are essential, both for effective management of the coast and for future studies to build upon. Often in New Zealand, management of coastal areas has been hindered by a lack of knowledge specific to those locations. Kench *et al.* (1999, p.3) states:

While knowledge of the New Zealand coast is rapidly increasing...there is generally poor information on coastal processes (e.g. the height and period of waves occurring in storms and extreme water levels) and coastal dynamics (e.g. the precise history of coastal changes) at most places in New Zealand.

Such knowledge is essential, as management solutions effective at other coastal locations may not be appropriate for locations where processes operate in a different manner. It is also desirable that any coastal research undertaken be comparable to research on similar coastal environments elsewhere. In this way, findings can easily be translated between sites. For this reason, methodologies used in other coastal investigations in New Zealand have been adopted in this study.

1.2 Gore Bay: The Study Area

Gore Bay is located approximately 85 kilometres north east of Christchurch on the eastern coast of New Zealand's South Island (Figure 1.1). The nearest significant settlement is Cheviot, located approximately eight kilometres inland. Gore Bay is the only accessible swimming beach between Amberley Beach and Kaikoura, an approximately 100 kilometre stretch of coastline, dominated by plunging cliffs and

steep, sparsely vegetated slopes. This rugged coastline is broken only at the mouths of rivers such as the Blythe, Hurunui, Waiau and Conway, where limited areas of flat alluvial ground coincide with beaches that are generally wider than those fronting areas of high relief.

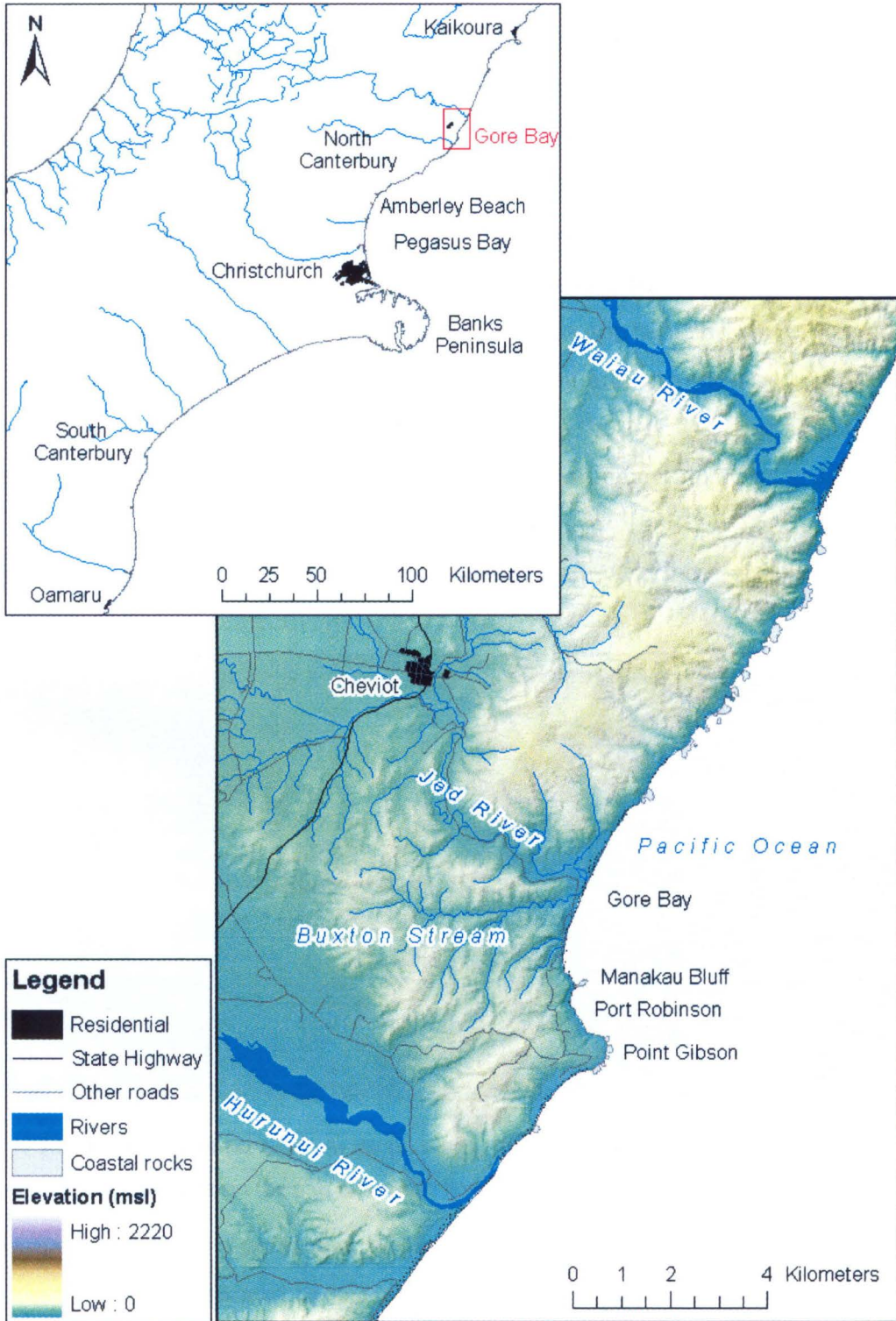


Figure 1.1: The study area including place names and features mentioned in the text.

Gore Bay forms a shallow indentation in the North Canterbury coastline around five kilometres in length and is orientated to the south east. The bay is bounded to the north by a slight headland, formed by a steep rocky coastline which extends almost to the mouth of the Waiiau River. To the south, Manakau Bluff and the associated reef extending north east separates Gore Bay from the adjacent Port Robinson. To the south of Port Robinson lies Point Gibson, a rocky headland, also with a reef extending out to the north east. South of Point Gibson, to the mouth of the Hurunui and beyond, mixed sand and gravel beaches dominate.

The beach at Gore Bay comprises a mixture of sand and gravel sized sediment, the exact composition varying both spatially and temporally, but in general the sediment is coarser in the north (Figure 1.2). The beach in the northern part of the bay is also steeper than in the south. This variation in sediment and morphology indicates that some variation in processes is also occurring along the bay. Coarse sediment and steep foreshores usually indicate a higher energy environment than fine sediment and gently sloping foreshores (Finkelstein 1982; Komar 1998). The variation in processes, sediments and morphology at Gore Bay are described further in Chapters Three, Four and Five respectively.

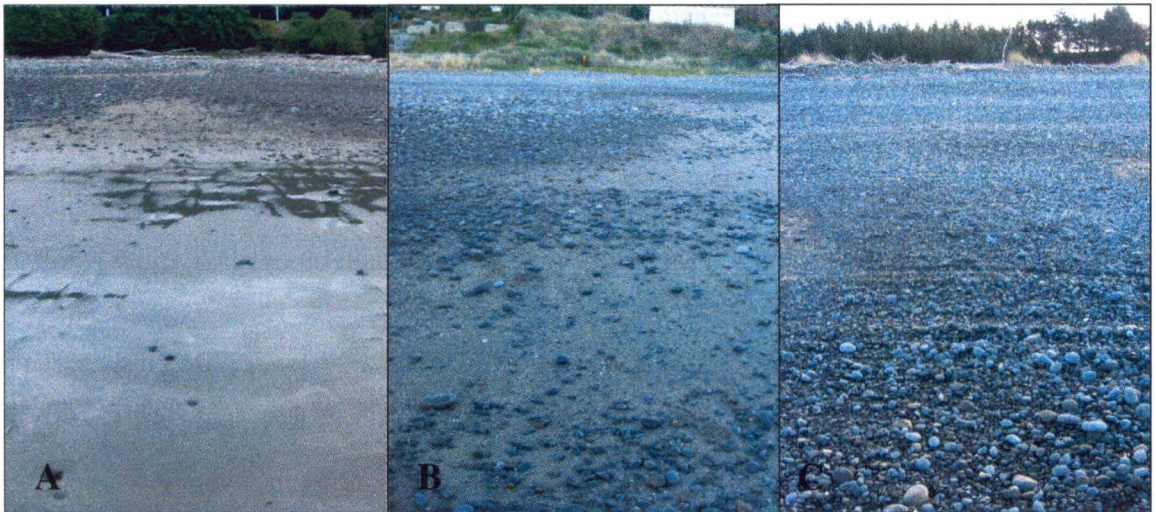


Figure 1.2: The nature of the beach in the (a) south, (b) centre, and (c) north of Gore Bay. Photographs are taken from the mid tide water level, looking landwards.

Gore Bay contains two permanent waterways, the Jed River and Buxton Stream, the mouths of which are located in central Gore Bay, north of the village. In the south of the bay, the Tweedies and Cathedral Gullies contain small ephemeral streams, which flow only after periods of heavy rainfall.

The township of Gore Bay contains approximately 80 dwellings, most of which are small holiday homes and baches, built in the post-war years, when coastal holiday homes all over New Zealand were popular. Sixteen of the houses are permanently inhabited by residents, most of whom are retired or semi-retired. The village is confined to a narrow strip, roughly parallel to the road, south of Buxton Creek. In the last ten years, an area of land between the original village and Buxton Creek has been subdivided and a number of large modern houses built.

1.3 Conceptual Context

1.3.1 Current state of knowledge

The predominant rationale for this thesis is that the Gore Bay coastal system has not previously been studied in depth and is poorly understood. There have been few studies of the Gore Bay coastal environment in the past and studies that have been completed are relatively simple. De Groot (1979) studied beach profiles surveyed at Gore Bay in 1936, 1948 and 1979, concluding that the rate of backshore retreat averaged approximately 500mm/year. Five years later, a resurvey of these profiles found that erosion between 1979 and 1984 was minimal, while some progradation had occurred in the upper beach (Slark 1984). Yetton and Garland (1988) prepared a Coastal Environmental Planning report for the Cheviot County Council, which included a coastal hazard map of Gore Bay. They concluded that historical erosion patterns were likely to be repeated and that further study of Gore Bay be encouraged.

The above studies have focused mainly on the erosion hazard at Gore Bay, with only brief descriptions of the coastal environment and little insight as to how the system operates. A more integrated approach, such as that suggested by Pye and Allen (2000) is needed at Gore Bay, whereby the interactions between changes in environmental forcing factors, hydrodynamic processes, sediment transport processes, morphological changes, human activities and feedback between these factors are investigated.

The poor quality of knowledge about many of New Zealand's coastal systems is of concern to those involved in coastal planning, as effective decisions cannot be made based on sporadic information. This thesis seeks to fill a small part of this void, by providing a thorough description of the processes, sediments and morphology of the Gore Bay coastal environment.

An understanding of coastal processes, sediments and morphology is essential for resource management purposes. As beaches closer to Christchurch become increasingly developed, greater pressure will fall on Gore Bay by holiday makers. Preludes to this can already be seen in the northern part of the township, where a number of large, modern holiday homes have been recently constructed. Under the Resource Management Act (1991), applications for resource consent are required to include an assessment of environmental effects. In order to be able to adequately assess the possible effects of any activity, it is essential that a thorough description of the environment exists, against which any change can be measured.

The Resource Management Act (1991) also requires the identification and assessment of coastal hazards. This requires knowledge and understanding of the coastal environment. There is a long history of coastal erosion and associated problems at Gore Bay, which are detailed further in Chapter Three. The most dramatic erosion events have occurred during periods of higher than normal wave conditions, in the 1930s, 1950s and 1970s (Yetton & Garland 1988). Previous studies (de Groot 1979; Yetton & Garland 1988) have indicated that erosion is likely to be an ongoing concern at Gore Bay. Despite this concern, little or no erosion has been documented at Gore Bay since the 1980s. Whether this lack of erosion is due to the protective works built by local residents or because wave conditions have been conducive to accretion rather than erosion is unknown. Nevertheless, the Gore Bay Ratepayers Association are concerned about the stability of the coast and have set aside funding for future protection works. If any such works do eventuate, a thorough understanding of the coastal system will help ensure that the most appropriate solution for the Gore Bay environment is chosen.

1.3.2 The distinct nature of Gore Bay

Gore Bay is also of interest to coastal scientists because of the variation in both sedimentary and morphological characteristics. These variations, both spatial and temporal, make it difficult to classify Gore Bay as a particular “type” of beach, or even to succinctly describe the nature of the beach. For example, de Groot (1979) described Gore Bay as being a “sand beach backed by a shingle ridge” in the south, and as being “predominantly shingle” in the north. However, Gore Bay has also been described as a “mixed sand and gravel beach” (Slark 1984) and as a “mainly sandy beach” (Yetton & Garland 1988). Local residents (Sorenson 2003, pers. com.; Wilson 2003) tell that the beach near the village (i.e. the southern end) is predominantly sandy most summers, but that winter storms result in more gravel being present on the beach.

From the above descriptions, it can be seen that Gore Bay is neither purely sand nor purely gravel, but rather, contains varying amounts of both sand and gravel sized sediment. Beaches containing gravel are relatively rare worldwide, except in areas of Canada, Ireland and New Zealand, where they are a common feature of the landscape (Mason *et al.* 1997). Jennings and Shulmeister (2002) presented a field based classification scheme for gravel beaches, including those with a mixture of sand and gravel sized sediments. Their scheme is based on a simple visual classification that can be applied globally in the field and is underpinned by morphodynamic differences between the beach types. The three beach types identified are: pure gravel, mixed sand and gravel, and composite gravel.

Mason *et al.* (1997) distinguished two types of mixed sediment beach, which can be linked to Jennings and Shulmeister’s (2002) classification. The first is described as a broadly homogenous mix of sand and shingle with some grading across and along shore, which is equivalent to a mixed sand and gravel beach. The second type of mixed beach is equivalent to a composite gravel beach and is described as having a wide sandy intertidal terrace flanked by a shingle ridge. It is commonly noted (Dawe 1997; Pescini 2000; Single & Hemmingsen 2000) that the majority of New Zealand’s mixed sediment beaches fall into the mixed sand and gravel beach type, an exception

being several beaches on the west coast of the South Island, which are regarded as composite beaches (Jones 1992; Jennings & Shulmeister 2002).

Most of the early research on New Zealand's mixed sand and gravel beaches was undertaken on the South Canterbury coast (Kirk 1969, Kirk 1975, McLean & Kirk 1969; McLean 1970). As a result, the majority of mixed sand and gravel terminology and characteristics are based on these beaches (Kirk 1980). However, this section of coast is part of a 240 kilometre stretch of mixed sand and gravel shoreline, extending from Oamaru to Banks Peninsula (Figure 1.1), which is subject to high energy from an east coast swell environment (Davies 1964). The coast is in chronic erosion and subsequently, the alluvial coastal cliffs are a major source of sediment to the beach system. Several studies have shown that there is little or no longshore variation in grain size or sorting, despite strong longshore currents to the north (McLean & Kirk 1969; Hewson 1977).

In comparison, Gore Bay is less than four kilometres in length, surrounded by cliffed, hard rock coasts, which provide little sediment to the bay. The bay is sheltered from the south and there is a strong variation in the nature of the beach from one end to the other. Therefore, it seems likely that the processes acting at Gore Bay will be different to those reported in the literature and that the principles of mixed sand and gravel beaches, as described for South Canterbury, may not apply.

More recently, several studies undertaken on the nature of beaches in northern Pegasus Bay (Hall 1995; Pescini 2000) have found some variation from the typical mixed sand and gravel beach described in Kirk (1980) and Single and Hemmingsen (2000). Pegasus Bay is situated approximately 50 kilometres south west of Gore Bay, on the east coast of New Zealand's South Island (Figure 1.1). The southern two thirds of the bay is a pure sand beach system, which grades into a mixed sediment beach in the northern third. This transition is due to the different sediment inputs from rivers within the bay (Shulmeister & Kirk 1997). The beaches of northern Pegasus Bay are often described as "mixed sand and gravel" beaches (Siemelink 1984; Shulmeister & Kirk 1993; Pescini 2000), however there are distinct differences to the mixed sand and gravel beaches of South Canterbury. Hall (1995) distinguished the beaches of northern Pegasus Bay as "a new type of mixed beach" and constructed a

morphodynamic model for them (discussed further in Section 2.4). Although the model was not intended for application outside northern Pegasus Bay, strong similarities between the beaches of Gore Bay and northern Pegasus Bay make it worthwhile to investigate further.

It is of interest then, whether the classification system of Jennings and Shulmeister (2002) can be applied to Gore Bay and whether Gore Bay adheres to the principles of a “typical” mixed sand and gravel beach (Kirk 1980). Does the Gore Bay coastal system operate in the same way as the transitional sand and gravel beaches of northern Pegasus Bay or is it more like the composite gravel beaches of the west coast of the South Island? It is important to determine how the Gore Bay coastal system operates, so that knowledge gained from studies of beaches of a similar nature can be used in the management of Gore Bay.

1.4 Aims and Objectives

The primary aim of this thesis is to provide a thorough description of the Gore Bay coastal system, so that those involved in the management of coastal resources have an understanding of the environment and a benchmark to compare future studies to. The secondary aim is to determine whether Gore Bay fits into one or more classifications of mixed sediment beaches, so that knowledge gained from similar beaches can be utilised in the management of the Gore Bay coastal system.

In order to achieve these aims, the following objectives have been set:

- To identify and describe the processes operating within the Gore Bay coastal system.
- To describe and interpret the nature of the sediment in Gore Bay.
- To describe and interpret the morphology of Gore Bay.
- To identify and describe the interaction and feedback mechanisms between these three components.
- To compare the characteristics of Gore Bay to those of various “beach types” described in the literature.

These aims and objectives will be met by conducting a thorough investigation of the Gore Bay coastal system, based around the conceptual frameworks explained below.

1.5 Investigative Frameworks

In any study, a conceptual framework on which to base the research is essential. There are many such frameworks utilised in current coastal literature, including the process-response model (Krumbein 1963), the sediment budget model (Miller & Zeigler 1958), and the morphodynamic model (Wright & Short 1984). These models provide a simplification of reality, under which a particular research problem can be effectively addressed.

The conceptual framework used in this study combines a model developed by McLean and Kirk (1969) with the process-response model of Krumbein (1963). McLean and Kirk’s (1969) model demonstrates how the variables influencing beach morphology interact. It was termed an *ordered control model* by Lauder (1987), due to the distinction made between first and second order controls (Figure 1.3). Foreshore slope is identified as the ultimate response element of the beach, dependent on all other variables. The model identifies source area characteristics and hydraulic factors as independent variables, both of which have an initial control on the textural characteristics of the beach materials.

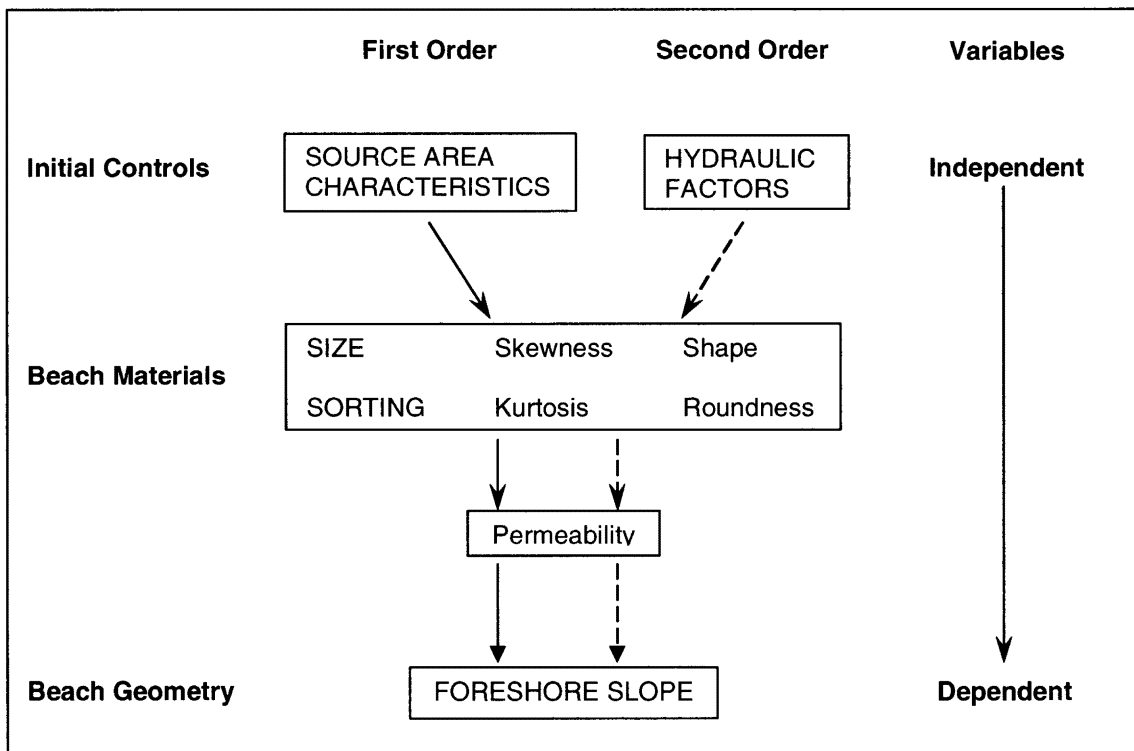


Figure 1.3: The ordered control model relating initial controls, beach materials and beach geometry. The level of dependency increases from top to bottom. First order controls are indicated by solid arrows, second order by dashed arrows. From McLean & Kirk (1969).

Source area characteristics refer to the nature and composition of the material supplied to the beach. For example, if the main source area for a particular beach is a gravel bearing river, the characteristics of the beach materials will be different from a beach where the main source area is coastal sandstone cliffs. Hydraulic factors include the wave environment (height, period, direction and refraction), wind environment (speed and direction), currents (speed and direction) and tidal influences. Hydraulic factors work on the material supplied to the beach from the source area, often modifying the properties of the beach materials. However, it is the source area characteristics which have a first order control on beach materials, and hydraulic factors a second order influence. This is in agreement with Folk (1965), who stated:

If a coastline is made up of outcrops of soft, fine grained sands, then no matter how powerful the waves are, no sediments coarser than fine sands will ever be found on the beach. If a coastline is made up of well-jointed, hard rocks which occasionally tumble down during rains, then the beach sediment will be coarse no matter how gentle the waves of the water body.

In an environment where little is known about the source area characteristics and hydraulic factors, the ordered control model can be used to determine them, on the basis of the morphological and textural variations in the beach (Mason & Folk 1958). This approach was successfully used by Dawe (2000) in his study of North Beach, Kaikoura. By working backwards through the model, variations in beach materials and morphology allowed the identification of a previously unknown source of material to North Beach. Using both the normal and reverse approaches of this model, the initial controls, beach materials and beach geometry of Gore Bay will be investigated.

The ordered control model (McLean & Kirk 1969) is based on the idea that foreshore slope is the ultimate response element, controlled by all other factors. However, the process-response model shown in Figure 1.4 recognises that all parts of a beach system interact with each other to result in an environment that continually adjusts to try to attain equilibrium (Krumbein 1963).

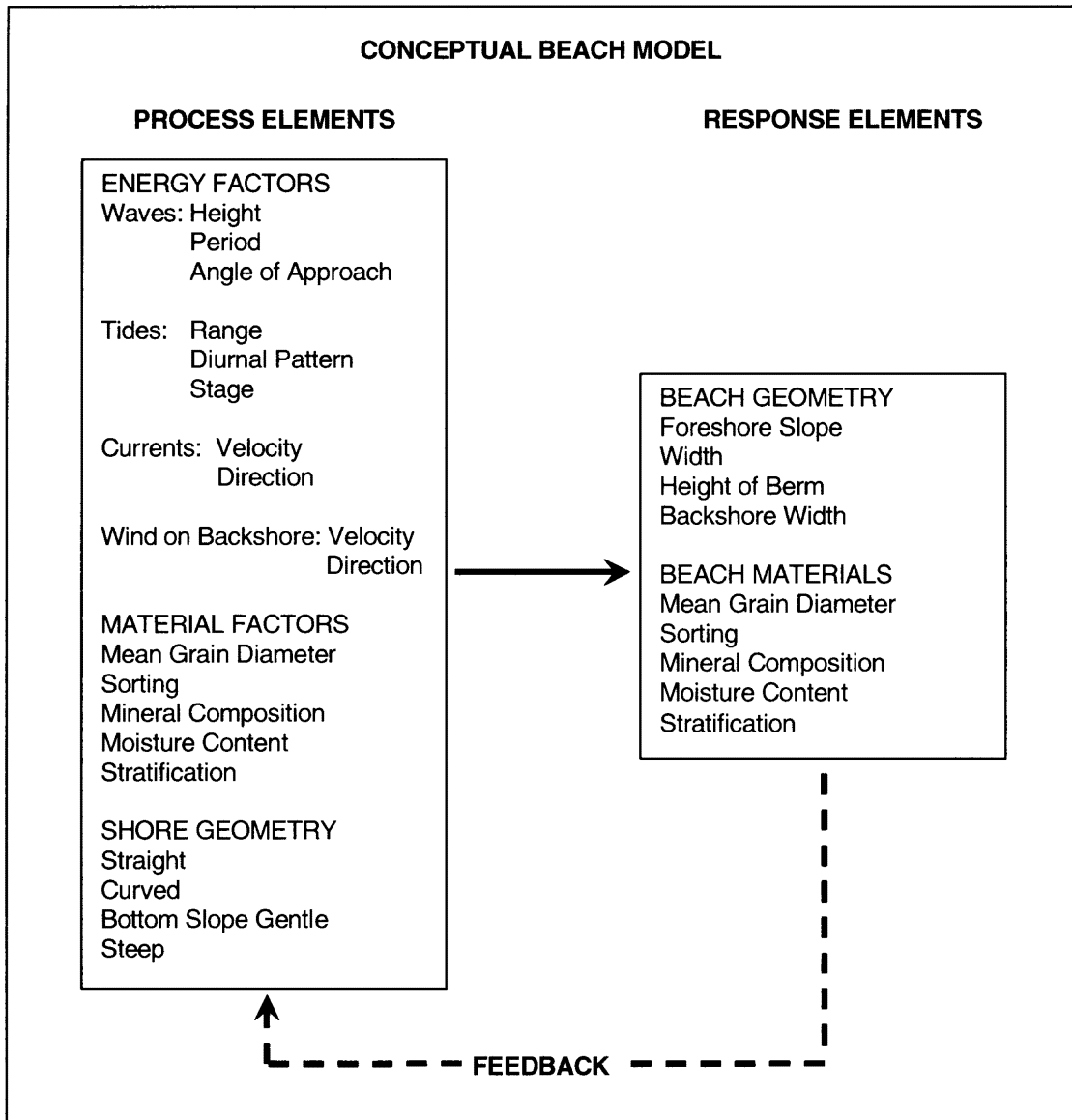


Figure 1.4: The process-response model. The complex nature of the coastal environment is acknowledged by having sediment and geometry factors represented on each side of the model. Factors on the left side (process elements) are initial properties, while factors on the right side (response elements) are the resultant properties. From Krumbein (1963).

The model shows that the process elements (energy factors, initial properties of beach material and the geometry of the shore) affect the response elements (beach geometry and beach materials) of the beach system, while the feedback loop suggests that response elements can also influence process elements. For example, on a typical sand beach, high energy storm waves result in erosion of material from the beach out to the nearshore, changing the beach morphology from a steep foreshore and flat nearshore, to a shallower beach slope with a nearshore bar. The nearshore bar (response element) then influences the incoming waves (process element) by making

them break earlier, which dissipates wave energy, causing less erosion. This negative feedback is an important part of beach response, which highlights the interactive nature of all elements within the coastal system.

By combining the concepts of the ordered control model (McLean & Kirk 1969) and the process-response model (Krumbein 1963) a solid investigative framework is produced, around which this study is based. The ordered control model provides the main structure for this investigation, in which the characteristics of the beach materials and morphology are investigated to shed light on the source areas and hydraulic factors influencing Gore Bay. The process-response model provides recognition of the interaction between all elements of the coastal system, in that no one factor is independent of any other. This thesis uses both models as a means of investigation into the Gore Bay coastal system. The models also provide the structure for the thesis presentation, as described below.

1.6 Thesis Structure

The purpose of this section is to outline the main ideas discussed in the seven chapters of this thesis. Chapter One has introduced the reader to the study, providing a conceptual context and outlining the aims and objectives of the thesis. A brief description of the location and general nature of Gore Bay was given and the investigative framework of the thesis was introduced.

Chapter Two reviews the current state of knowledge on mixed sediment beaches and expands on the ideas raised in Chapter One, thereby placing this study into the wider context of international coastal literature. The processes, sediments and morphology of three types of mixed sediment beach are described so that the distinct nature of Gore Bay can be appreciated. A classification scheme for differentiating between beach types is outlined and critiqued.

In keeping with the conceptual framework of the thesis, Chapter Three is concerned with the source area characteristics and hydraulic factors that influence the Gore Bay coastal system. The geology and geomorphology of the Gore Bay area are discussed and possible sediment sources are identified. The bathymetry, tides, currents, waves

and winds of Gore Bay are described to depict the process environment of Gore Bay. A comparison is made between local observational wave data and measured offshore regional data and a brief history of the human processes which have helped shape Gore Bay is given.

Chapter Four is concerned with the second level of the ordered control model: beach materials. The chapter reviews current methods of sedimentology, with regard to their appropriateness in mixed coastal systems and outlines the methods used in this study. Results of sedimentological investigation at Gore Bay are presented and discussed and a more qualitative method of investigating beach sediments is proposed.

The ordered control model of McLean and Kirk (1969) identifies foreshore slope as the ultimate response element on the beach. Chapter Five discusses the slope of the foreshore in Gore Bay, as well as wider patterns of beach morphology. Variations in beach morphology are described at a range of time scales, from monthly profile changes to historical variations in shoreline position and beach form.

Chapter Six brings together the findings of Chapters Three through Five, by discussing the interactions and feedback mechanisms between the processes, sediments and morphology of Gore Bay. With the results found in the previous chapters, an attempt is made to classify Gore Bay using the scheme introduced in Chapter Two. The nature of Gore Bay is compared to other mixed sediment beach types and the usefulness of coastal classifications is discussed. Implications for effective management of the Gore Bay coastal system are presented.

Chapter Seven is the concluding chapter, presenting major conclusions and findings in light of the aims and objectives of this thesis. Suggestions are made for further research, both within Gore Bay and in the wider context of mixed sediment beaches.

CHAPTER TWO

MIXED SEDIMENT BEACHES

2.1 Introduction

Beaches containing both sand and gravel are a common feature of the New Zealand landscape and as such, a local body of literature has developed on the nature of these beaches (Kirk 1967; McLean 1970; Kirk 1980; Neale 1987; Single 1992; Dawe 2000; Boorer 2002). Mixed beaches are morphologically and texturally more complex than either pure sand or pure gravel beaches, due to the way in which the different sediment components are affected by hydraulic interactions (Zenkovich 1967). Chapter One introduced the idea that there are three types of mixed beach identified in the literature: mixed sand and gravel beaches, composite gravel beaches and transitional sand and gravel beaches (as found in northern Pegasus Bay). This chapter begins by describing the characteristic features of these three beach types and then discusses the gravel beach classification system of Jennings and Shulmeister (2002). A review of the characteristics of mixed sediment beaches is required so that the distinct nature of the Gore Bay coastal system, described in the following chapters, can be fully appreciated.

2.2 Mixed Sand and Gravel Beaches

Mixed sand and gravel beaches, as described by Kirk (1980), are by far the most commonly described mixed sediment beach in the New Zealand literature. They generally consist of a wide range of particle sizes, from cobbles to fine sand, with the range of sediments found in one position on the beach as varied as any found along the entire beach (Kirk 1980). The typical morphology of a New Zealand mixed sand and gravel beach is shown in Figure 2.1. This morphology was based on numerous beach profiles from Kaikoura and South Canterbury, two of the largest sections of mixed sand and gravel coastline on the east coast of the South Island (Figure 1.1). A mixed sand and gravel beach is typically convex upward in profile, with beach width between 100-200 metres, although Dawe (1997) noted that they may be as narrow as

20 metres if severely eroded. Average elevations are four to six metres above mean sea level, but may reach as high as 14 metres (Kirk 1980). These dimensions are quite different to sand beaches, which are typically much wider and of lower elevation (Pescini 2000). Mixed sand and gravel beaches are therefore steeper than sand beaches and have average foreshore slopes of between 5 and 12 degrees.

Longshore transport is a distinctive characteristic of New Zealand mixed sand and gravel beaches and has been recognised as a major factor in their geomorphic development (Neale 1987). Kirk (1980) identified a two part sediment transport system, where movement of the coarse sediment on the foreshore is distinct from, but linked to, the movement of finer sediments in the nearshore. Seaward of the nearshore step, fine and medium sands are transported along shore by currents. In the swash zone, sediments of all sizes are transported alongshore by the asymmetry of the swash, caused by the lack of refraction after wave breaking on a mixed sand and gravel beach (Single & Hemmingsen 2000). Unlike sand beaches, there is very little onshore-offshore movement of sediment in mixed sand and gravel systems and no offshore bar.

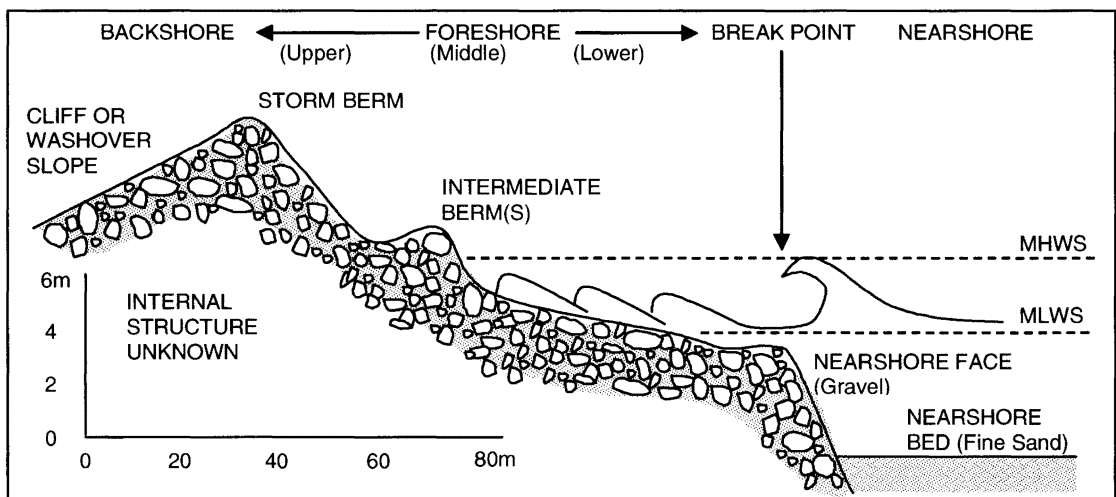


Figure 2.1: Typical mixed sand and gravel profile (adapted from Kirk 1980, p193)

Kirk (1980) identified four morphological and process zones across the beach: the backshore, foreshore, breakpoint step and nearshore (Figure 2.1). The backshore zone of a mixed sand and gravel beach is landward of the highest runup limit of storm swash. It either forms the base of an eroding cliff or is of barrier form, with a washover surface sloping from the top of the highest storm berm down to the lower

hinterland. Disc and blade shaped clasts (Folk 1965) dominate the backshore, which usually contains some of the largest sediment present on the beach.

The foreshore extends from the uppermost storm berm to the point of wave break. It is dominated by swash and backwash processes and is generally the largest and most active zone on a mixed sand and gravel beach. Single (1992) distinguished between the upper, middle and lower foreshores, each with distinct characteristics. The upper foreshore is steep and contains the largest sediment on the foreshore. The long swash of large storm waves transports a range of sediment sizes up the beach; however the backwash is not as strong due to infiltration (Packwood 1983). As a result, the largest clasts are stranded high on the beach, until a larger swash moves them higher still. The middle foreshore contains a number of berms, each associated with a wave regime of differing energy. The height of a berm is directly proportional to the height of the waves which formed it. A large number of berms on a beach indicate decreasing wave energies, as an increase in wave height will cause the destruction or modification of any berms caused by previous, lower energy wave regimes. The lower foreshore is the zone where most wave action occurs and is dominated by swash-backwash processes. Wave energy is at a peak and sediment movement is sustained even in the calmest conditions, leading Kirk (1980) to describe the swash zone as the “engine room” of mixed sand and gravel beaches. The lower foreshore also contains the break point step, a major change in slope between the shallow gradient low tide terrace and the steep nearshore face. Wave breaking is confined to this zone at all stages of the tidal cycle and the step is never exposed, even under the lowest tidal conditions.

The nearshore zone consists of the steep nearshore face and the nearshore bed. The nearshore face is a steep “wall” of coarse gravels that rest at an angle close to their angle of repose and may rise up to two metres above the seabed. The nearshore bed is gently sloping (0.5-1.0 degrees) and is composed of fine sands (Single & Hemmingsen 2000). There is a distinct separation between the sediments and morphology of the nearshore face and bed, which led Kirk (1980) to conclude that the seaward limit of a mixed sand and gravel beach is found at this boundary. The presence of the nearshore face exerts a controlling influence on the location and pattern of wave breaking and prevents onshore-offshore cycling of beach materials

(Kirk 1980). Due to the sudden rise in beach elevation at the nearshore face, there is a single line of breakers under all wave and tide conditions and the breakers are of the plunging or collapsing type (Galvin 1968).

McLean (1970) listed four common features of New Zealand mixed sand and gravel beaches:

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 Pliocene 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).

Single and Hemmingsen (2000) added to this list:

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

It will be shown in the following chapters that Gore Bay, while possessing some of the characteristics of mixed sand and gravel beaches, also displays some strong differences. The applicability of the term “mixed sand and gravel” to beaches such as Gore Bay is discussed further in Chapter Six.

2.3 Composite Beaches

Composite beaches are analogous to the *mixed beaches* of the United Kingdom (Jennings & Shulmeister 2002) and were first identified in the literature by Carter and Orford (1993). They are characterised by a strong demarcation between the gravel upper foreshore and the sandy lower beachface, with an abrupt and well defined reduction in slope across the boundary due to the change in grain size. Composite beaches are also found in southern California, where they are described as a cobble berm with a mildly sloping sandy platform seaward of the berm (Everts *et al.* 2002).

Jones (1992) states that the gravel upper foreshore has slopes greater than five degrees and that the sandy lower beach face have gradients of less than five degrees. However, in southern California, it is reported that the cobble berm face may be up to 15 degrees at the steepest section, while the sandy platform typically has slopes of less than 1.5 degrees (Everts *et al.* 2002).

A schematic representation of a composite beach is shown in Figure 2.2. At low tide, the sandy, low gradient foreshore is exposed and a dissipative surf zone exists. Breakers are of the spilling type (Galvin 1968) and a longshore bar-trough system may develop (Wright & Short 1984). At high tide, the steeper nature of the gravel ridge results in a more reflective regime and plunging waves are common. Mason *et al.* (1997) found that the amount of incident wave energy reflected from a composite gravel beach varied from 20 to 85 percent, depending on the tidal state. Beach widths may vary from 20 to 60 metres, not including the low tide surf zone. The gravel berm often contains well developed beach cusps, caused by edge waves resulting from the high reflectivity of composite beaches (Carter & Orford 1993).

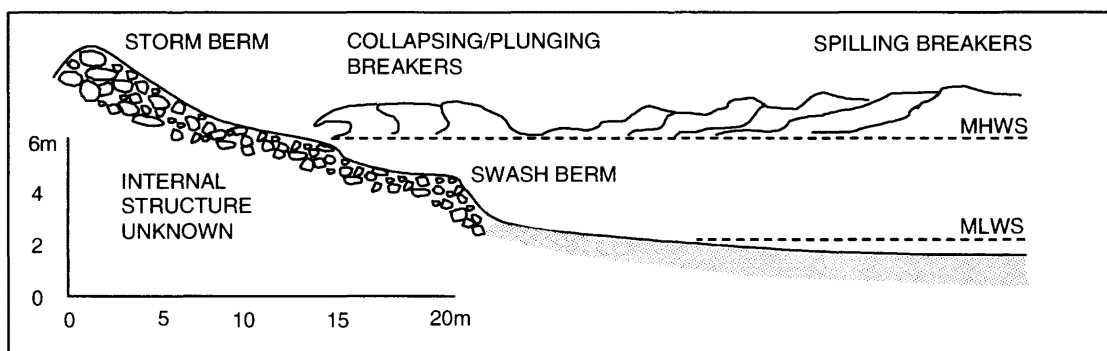


Figure 2.2: Typical composite beach profile (adapted from Jennings & Shulmeister 2002, p224)

It may be argued that these beaches are not truly “mixed” sediment beaches, as the sand and gravel components are found in distinct zones on the beach. Bird (1976) attributed the contrast to large tidal variations and the different responses of sand and gravel to storm wave activity. While storm waves tend to “throw up” coarse material onto the beach, sand is not dense enough to be deposited in the turbulent wave conditions. As the storm abates and water levels drop, sand is deposited lower down the beach.

In southern California, Everts *et al.* (2002) also found that the sand and cobble components responded differently to the process environment. The sand component tended to be transported offshore during high energy wave conditions and returned onshore under calmer, lower energy conditions, similar to the behaviour of a pure sand beach. Meanwhile, the cobble berm was found to accrete under high energy wave conditions and retreat during low energy conditions. Sorting was found to play a crucial role in the behaviour of the cobble berm, due to the reduction in permeability associated with decreased sorting which occurred when the sand terrace was in an accreted state, filling the pore spaces of the cobble berm (Everts *et al.* 2002).

The sorting-slope relationship has long been recognised as a factor in beach morphology, especially on mixed sediment beaches (Zenkovich 1967; McLean & Kirk 1969; Caldwell & Williams 1985). Waves arriving on the shore will rush up the beach until they reach the swash limit. Backwash velocities will be less than swash velocities due to percolation of seawater through the beach (Packwood 1983). Clasts transported up the beach in the swash are therefore stranded, as the backwash is not strong enough to transport them back down the beach. This results in material being pushed landward to rest at a steep angle (Quick 1991).

Poorly sorted gravels are less permeable than well sorted gravels due to finer material filling the interstitial spaces. This results in a decrease in the amount of infiltration that can occur in the swash zone. Poorly sorted beaches therefore have lower swash/backwash intensity ratios. Clasts that are pushed up the beach by the swash return down the beach under the backwash flow, resulting in a shallower beach slope (Caldwell & Williams 1985).

Parts of Gore Bay sometimes display features common to composite beaches; however, other parts of the bay show very different characteristics. The way in which the sand and gravel components respond to changes in the process environment in southern California may be applicable to Gore Bay and will be discussed further in Chapter Six.

2.4 Transitional Sand and Gravel Beaches

In a study of the beaches of northern Pegasus Bay, Hall (1995) noted that there were distinct differences to the characteristic features of mixed sand and gravel beaches. Pescini (2000) suggested that the beaches of northern Pegasus Bay have sediment compositions that enable them to sometimes behave like sand beaches, while in other instances behave like the mixed sand and gravel beaches described by Kirk (1980). Boorer (2002) suggested the term “transitional sand and gravel” to describe such beaches, a term retained in this thesis to avoid confusion with the more characteristic mixed sand and gravel beaches. The common features of these transitional sand and gravel beaches, as noted by Hall (1995) and Pescini (2000) are described below.

The transitional sand and gravel beaches of northern Pegasus Bay contain varying amounts of both sand and gravel, with the amount of gravel generally increasing to the north. Those sites with a higher proportion of gravel are steeper than sites with less gravel and a combination of spilling and plunging waves occur (Galvin 1968). Less steep slopes, with more sand, are characterised by spilling breakers. Up to three lines of breaking waves were observed, which contrasts with Kirk’s (1980) description of “a single line of plunging breakers under all wave and tidal conditions” for mixed sand and gravel beaches.

Hall (1995) found that when accreted, transitional sand and gravel beaches contain more gravel than sand, while cusps develop on the face of the foreshore berm. Conversely, an eroded beach contains a flat, non-rhythmic, sandy foreshore, backed by a gravel ridge. Hall’s (1995) morphodynamic model (Figure 2.3) identified five states, including a fully accretional, a fully erosional, and three intermediate/rhythmic states, one of which occurs on both sides of the model. Accretional states are characterised by low wave energy, erosional states by high wave energy.

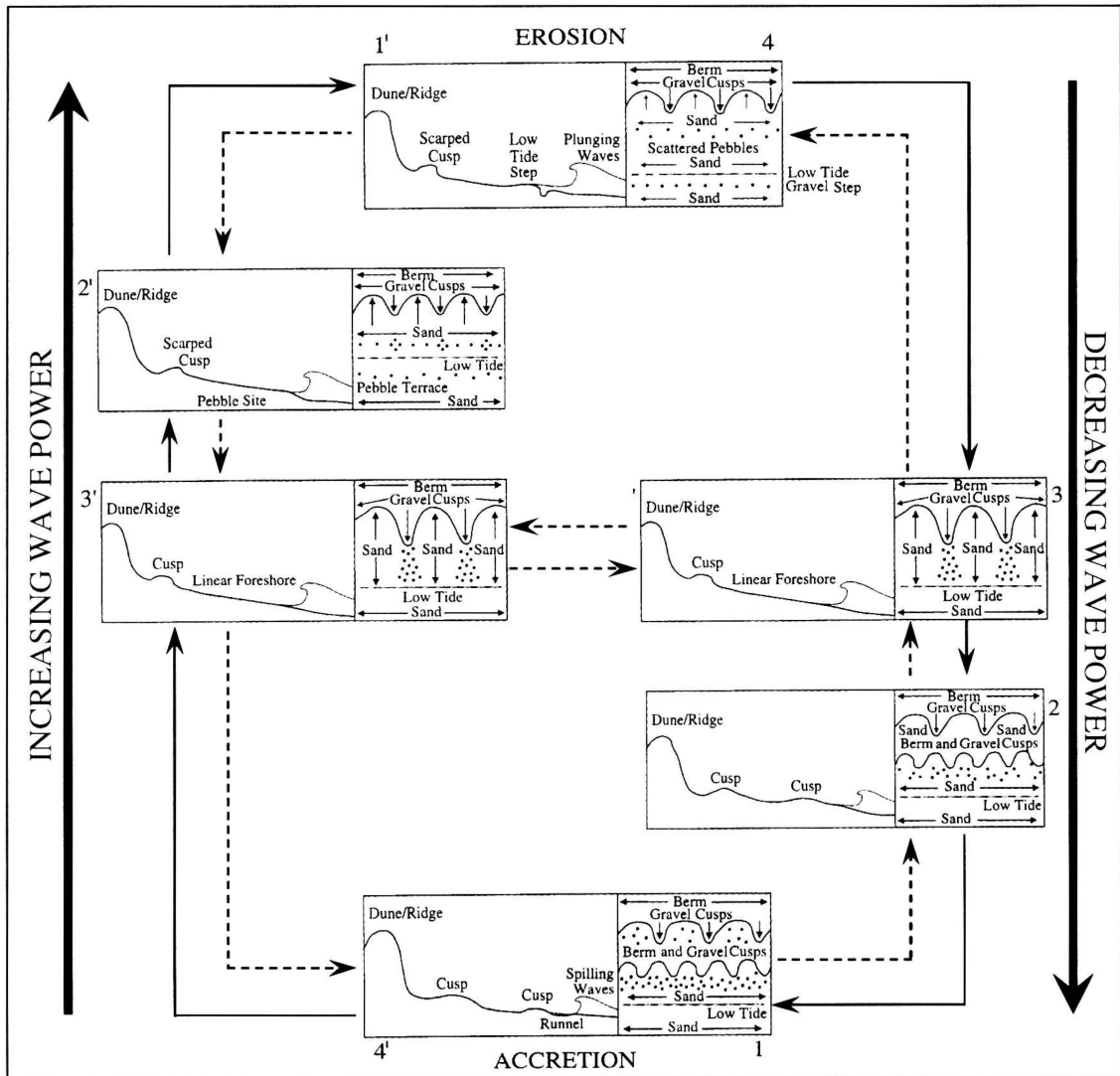


Figure 2.3: A morphodynamic model for northern Pegasus Bay. From Hall (1995).

The nearshore step, a distinct and permanent feature of mixed sand and gravel beaches, is not always present on the beaches of northern Pegasus Bay. Hall (1995) found that the nearshore step was only present when the beach was in an erosive state, and that the step was typically 30cm high. Waves do not break on this step because it is too small, and too close to the swash zone. Instead, it is the permanent presence of a nearshore sand bar (absent on mixed sand and gravel beaches) that causes plunging breakers. The absence of a distinct nearshore step allows recirculation of sediments between the near- and fore- shore, which is in direct contrast with a typical mixed sand and gravel beach.

Despite stating that the beaches of northern Pegasus Bay are a “new type of mixed sediment beach”, Hall (1995) continues to use the term “mixed sand and gravel

beach”. Due to the distinct nature of the northern Pegasus Bay beaches, Hall states that the morphodynamic model should not be applied outside the study area, and admits that there is also some variation to the model within the study area. However, Gore Bay also shows distinct differences to the characteristic mixed sand and gravel beach and several similarities to the beaches of northern Pegasus Bay. For this reason, the applicability of Hall’s (1995) morphodynamic model to Gore Bay is discussed further in Chapter Six.

2.5 Gravel Beach Classification Scheme

Jennings and Shulmeister’s (2002) field based classification scheme for beaches containing gravel sized sediment is based on 42 beaches around the South Island of New Zealand. These beaches were classified by visual observation into three end member beach types: pure gravel, mixed sand and gravel and composite beaches. The width of the beach, beachface slope, grain size, storm berm height and the number of berms on each beach were measured. These parameters were tested using linear discriminant analysis, to determine the differences between beach types. Jennings and Shulmeister (2002) found that the key variables were average grain size, Iribarren number, beach width and storm berm height.

In Jennings and Shulmeister’s (2002) classification, grain size was determined by measuring the b-axis of 50 randomly selected clasts from the storm berm and high tide samples and through laboratory sieving of the swash zone sediment sample. These techniques have also been applied in this thesis and details are given in Section 4.2. Mean grain size was determined for each of the three sample sites, as well as a mean grain size for the entire beach. Average figures proposed for each beach type by Jennings and Shulmeister (2002) are shown in Table 2.1.

Jennings and Shulmeister (2002) concluded from the data in Table 2.1 that composite beaches had the narrowest range of mean grain sizes and the highest average mean grain size. They found that mixed sand and gravel beaches had a larger range of mean grain sizes, but had the finest average mean grain size compared with other beach types. The beach containing the coarsest mean grain size (-6.13Ø) was a gravel

beach, however, on average the mean grain size for gravel beaches was less than that for composite beaches.

Table 2.1: Parameters for discriminating between various beach types, as proposed by Jennings and Shulmeister (2002). See Section 4.2 for description of the phi (ϕ) grain size scale.

| Parameter | Pure Gravel | Mixed Sand & Gravel | Composite Gravel |
|-------------------------|------------------------|-----------------------|-----------------------|
| Mean grain size range | -2.39 to -6.13 ϕ | -1.65 to -5.21 ϕ | -4.17 to -5.64 ϕ |
| Average mean grain size | -4.21 ϕ | -3.93 ϕ | -4.99 ϕ |
| Iribarren number | 1.6 to 4.0 | 0.7 to 1.95 | 0.5 to 1.8 |
| Overall beachface slope | 4.6 to 13.5 $^{\circ}$ | 2.3 to 7.4 $^{\circ}$ | 2.9 to 8.0 $^{\circ}$ |
| Wave type | collapsing | plunging | Plunging |
| Beach width | 18 to 50 metres | 30 to 80 metres | 20 to 60 metres |

From analysis of the mean grain sizes of each cross-shore sample, Jennings and Shulmeister (2002) concluded that pure gravel and composite beaches had their coarsest sediment on the storm berm, with the high tide and swash zone samples being progressively finer. This gradation was most obvious on composite beaches, where the sand component in the lower foreshore made it visually apparent. In contrast, they found that mixed sand and gravel beaches had the coarsest sediment in the swash zone, although there was little difference in grain size between the storm berm, high tide and swash zone samples.

The beachface slope was measured from the top of the highest storm berm to the low tide mark. This angle was combined with local wave climate data to calculate an Iribarren number for each beach. The Iribarren number is the product of a mathematical equation relating the beachface slope, offshore wave height and offshore wave length. It is a good morphodynamic discriminator between dissipative and reflective beaches (Bauer & Greenwood 1988).

Jennings and Shulmeister (2002) determined that pure gravel beaches had Iribarren numbers between 1.6 and 4.0, mixed sand and gravel between 0.7 and 1.95, and composite beaches between 0.5 and 1.8. These numbers indicate that pure gravel beaches are based within the steep beachface and collapsing wave domain (Bauer & Greenwood 1988), while mixed sand and gravel beaches fall within the moderately steep beachface and plunging wave domain. Composite beaches are based in the

same domain as mixed sand and gravel, however most have slightly lower Iribarren numbers, placing them slightly closer to the spilling wave domain than mixed sand and gravel beaches.

Jennings and Shulmeister (2002) found that beach width and storm berm height were also highly discriminant between beach types. However, they give little information about these two parameters. Beach width was found to vary between 18 to 50 metres on pure gravel beaches, 30 to 80 metres on mixed sand and gravel beaches and 20 to 60 metres on composite beaches. Average storm berm heights were not given for any of the beach types, nor were heights given for the storm berms of individual beaches.

This classification scheme enables “simple, field-based visual discrimination of gravel beaches into one of three main types. Through the measurement of some basic parameters this initial assessment can be confirmed” (Jennings & Shulmeister 2002, p226). However, several questions must be raised about the validity of the scheme. There is considerable overlap between the beach types in almost all of the key parameters (Table 2.1). For example, if a beach had an average mean grain size of $5.0 \text{ } \phi$, a beachface slope of 6.3° , an Iribarren number of 1.7 and a beach width of 40 metres, it could potentially be any of the three end members. In a situation such as this, it is the initial visual classification which determines the classification given to the beach. The classification becomes even more complex if the beach in question does not fit the typical description of one of the three end members. Gore Bay is one such beach that may be difficult to visually classify.

The scheme also takes no account of the variable nature of beaches. The classification was based on parameters measured at a single location on the beach, at a single time. However, the beachface slope can change on a relatively short timescale which has a direct effect on the Iribarren number of the beach. Beach slope can also vary significantly over short distances, so that the calculation of the Iribarren number is dependent on the location and timing of beach slope measurement.

The scheme also uses mean grain size as a discriminating parameter between beach types. However, on a mixed sediment beach, mean grain size may be completely irrelevant (Section 4.2.3) due to the bimodal nature of many mixed sediment beaches.

The mean grain size of a bimodal sample often refers to a grain size of which there is very little or none present in the sample (refer Figure 4.3).

The previous discussion raises questions about the applicability of Jennings and Shulmeister's (2002) classification scheme. Some answers to these questions will be provided in Chapter Six, where an attempt is made to apply the classification to the beaches of Gore Bay.

2.6 Chapter Summary

This chapter has described the common characteristics of three mixed sediment beach types, providing the reader with an appreciation for the principles of mixed sediment beaches and some knowledge with which the results presented in the following chapters can be compared. Mixed sand and gravel beaches are characterised by a steep convex upward profile, a single line of plunging breakers and by a nearshore step that is submerged at all times. Composite beaches contain a sandy lower foreshore backed by a gravel berm. The transition between sand and gravel is strongly demarcated and accentuated by an increase in beach slope and the sandy foreshore is exposed at low tide. Transitional sand and gravel beaches are extremely variable in nature, both spatially and temporally. There is strong alongshore variation in the amount of gravel present on the beach, which affects beach morphology.

A classification scheme for differentiation of pure gravel, mixed sand and gravel and composite beaches was outlined to highlight the differences between beach types. The main parameters used to discriminate between beach types were the Iribarren number, average grain size, beach width and storm berm height. Several questions were raised as to the applicability of the scheme, which will be discussed further in Chapter Six when the scheme is applied to Gore Bay.

CHAPTER THREE

INITIAL CONTROLS ON BEACH SEDIMENTS AND MORPHOLOGY

3.1 Introduction

This chapter explores the source area characteristics, hydraulic factors and other processes which affect the properties of beach materials and ultimately the morphology of the beach. This is in keeping with the conceptual framework of this thesis, introduced in Chapter One. Source area characteristics determine the characteristics of the material available for supply to the beach, while hydraulic factors result in selective erosion, transportation and deposition of the available sediments, thereby modifying the textural characteristics of the beach materials. Human activities also play a part in determining the characteristics of the beach system. Although not mentioned in either the ordered control or process-response models used as a framework for this study, human activities are an important part of the process environment. This chapter also helps meet one of the main objectives of this thesis: to identify and describe the processes operating within the Gore Bay coastal system.

3.2 Source Area Characteristics

Source area exerts a first order control over the characteristics of beach sediments by determining the nature of the materials available to form the beach (McLean & Kirk 1969). The identification of source areas is also important for determining the sensitivity of the coastal system. For example, if the only source area to a beach is a single river in times of extreme flooding, then changes in climatic conditions or human activity resulting in less flooding will mean a reduction in sediment supply to the coast. Alternatively, an increase in the frequency of flooding may result in more sediment entering the beach system.

Dawe (2000) illustrated this in his study of North Beach, Kaikoura. Dawe (2000) found that the historical supply of sediment to the south end of North Beach was from

the Kowhai River, which exited north of the Kaikoura Peninsula 5500 - 2500 years before present. Tectonic activity in the last 2500 years has resulted in a shift of the river mouth to south of Kaikoura Peninsula, so that the Kowhai River no longer supplies sediment to North Beach. As a result, the sediment at the southern end of North Beach is essentially relict and the sediment budget of the beach is in deficit.

Sediment supply to beaches may come from a variety of sources, including rivers, sea cliff erosion, longshore transport into the area, biogenic deposition, hydrogenous deposition, wind transport onto the beach and beach nourishment by humans (Komar 1998). By considering the geology and geomorphology of Gore Bay, possible source areas may be identified. The subsequent sedimentological and morphological investigations (Chapters Four and Five) will further identify which source or sources are predominant in supplying sediment to the contemporary beach.

3.2.1 Geology and geomorphology

The basement rock of Gore Bay lies within the Pahau Subterrane of the Torlesse Supergroup, of Late Jurassic to Early Cretaceous age (135 – 180ma BP). The majority of basement outcrop in the area comprises a suite of quartzofeldspathic metasediments, commonly known as ‘greywacke’. Although moderately indurated, these rocks are often highly jointed and sheared, with numerous zeolite veins further reducing their resistance to weathering and erosion.

Resting unconformably on the Torlesse basement is a younger sequence of Upper Cretaceous to Tertiary rocks (3-70ma BP). Kellahan (1998) provides a description of these cover rocks, as observed in the Cheviot Basin, based on Browne and Field’s (1985) standardised cover rock lithostratigraphy for North Canterbury. These descriptions are summarised in Table 3.1. Holocene fluvial and marine gravels and loess overlie the Tertiary sequence.

Table 3.1: Lithology of the Gore Bay area, after Kellahan(1998) and Browne and Field (1985).

| Formation | NZ Stage | Description |
|--|--|--|
| Conway Formation | Haumurian 84-65ma BP | Grey massive jarositic siltstone or silty sandstone with large subspherical concretions, which rests unconformably on the Torlesse basement rock. |
| Waipara Greensand | Tuerian 65-55ma BP | Mt Ellen Member - Alternating siliceous, indurated to poorly indurated greensand beds. Mt Ellen member was not observed in the Cheviot basin. Stormont Member - Very dark green, weakly indurated, argillaceous sandstone. |
| Ashley Mudstone and Homebush Sandstone | Tuerian – Runungan 65-34ma BP | Ashley Mudstone Member - Blue-grey to medium green-grey moderately indurated calcareous jarositic bioturbated bentonitic mudstone, and glauconitic well sorted fine sandy mudstone with common pyrite concretions. Homebush Sandstone Member - Grey friable massive to poorly stratified calcareous (trace detrital) glauconitic (trace to 15%) lithic feldspathic (<15%) sorted fine to medium quartz sand, with a ubiquitous lithic content (fine sand to pebbles of grey-black well-rounded Torlesse argillite and quartzofeldspathic arenite, comprising up to 5% of the lithology). |
| Amuri Limestone | Whaingaroan – Dunroonian 34-25ma BP | Stylobedded and open jointed creamy micritic limestone, which grades rapidly into massive micritic limestone, which is in turn overlain by sparsely glauconitic calcareous sandstone (Weka Pass Stone). |
| Waikari Formation | Otaian 22-19ma BP | Glenesk Sandstone Member - pale grey-brown weathering blue-grey fine sandstone and subordinate interbedded siltstone. |
| Mt Brown Formation | Otaian – Tongaporutuan 22-6.5ma BP | Brown soft to moderately indurated calcareous and non-calcareous massive to moderately well laminated micaceous lithic well sorted medium to very fine sandstone. |
| Greta Formation | Tongaporutuan – Nukumaruan 11-1.6ma BP | Te Ngapari Siltstone Member - (undifferentiated Greta Formation). Massive to laminated muddy siltstone and minor very fine sandstone resting conformably on the sandstones of the Mt Brown Formation. Homestead Siltstone Member – a host of transported whole concretions in massive and laminated siltstone and mudstone. Koromiko Siltstone Member – massive to laminated very fine sandy siltstone and mudstone, interbedded fine to medium sandstone, and many intraformational conglomerate horizons, which tend to be lensoidal, up to 2m thick, and comprise weakly stratified subangular to well-rounded cobbles of Greta Formation siltstone and frequently host sparse to abundant subangular to subrounded Torlesse pebbles and cobbles with a few rounded granules. |
| Kowhai Formation | Nukumuruan – Castlecliffian 2.4-0.3ma BP | Crudely to well bedded well rounded poorly sorted pebbles and cobbles of Torlesse argillite and arenite, in a matrix of silty fine to coarse angular and subangular sand. Varies in texture from almost clast supported with a sparse matrix of well sorted coarse sand to an abundant silty fine sandy medium sand matrix, and has many interbedded siltstone horizons and lenses of fine sand near the base. Basal sections are almost certainly marine, as they contain many fossil burrows in sandy siltstone horizons as well as other marine detritus such as glauconite. Discoidal clasts are common in the gravels near the base of formation. |

Structurally, Gore Bay is located in the centre of a syncline which runs perpendicular to the coast and trends northward further inland. Moving north along the coastline from the Torlesse basement rocks exposed at Point Gibson, an excellent exposure of the Tertiary sequence outcrops in the coastal cliffs and reef of Manakau Bluff (Barringer 1985). The axis of the syncline meets the coast just south of the Gore Bay village. The Tertiary sequence is reflected in the northern limb of the syncline, and Torlesse outcrops approximately one kilometre north of the Jed River. It is the reappearance of the basement rock which forms the slight headland bounding Gore Bay in the north.

The geology of the Gore Bay area was mapped nearly forty years ago, as part of the NZ Geological Survey 1:250 000 Map Series (Gregg 1964). Unfortunately, several studies which have mapped the geology of North Canterbury at a smaller scale (Guyon 1995; Kellahan 1998) have not extended to the coastline at Gore Bay. A relatively small scale (1: 25 000) geomorphic map was compiled of the Cheviot area (including Gore Bay) to assist in the identification of natural hazards (McPherson 1988). The distribution of different rock types and landform units was mapped, as well as their susceptibility to flooding, slope failure or fluvial overland erosion.

Figure 3.1 shows the geology and geomorphology of Gore Bay, adapted from McPherson (1988). The rock units identified have been given symbols that represent both the dominant (upper case letter) and subordinate (lower case letter) lithologies. Sandstones are represented by the letter S, mudstones by M, gravels by G and limestone by L. The symbol GA refers to the interbedded greywacke and argillite of the Torlesse basement. The number associated with each unit represents the strength or hardness of the unweathered unit, on a scale of one (unconsolidated) to seven (very hard). The correlation between the rock type units mapped and those described in Table 3.1 is indicated in the legend.

3.2.2 Geomorphology

In addition to the mapping of rock types, Figure 3.1 also shows the distribution of landform units such as coastal deposits, scarps, terraces, and floodplains. There is an old coastal terrace surface above Point Gibson, Port Robinson and Manakau Bluff, the edge of which is characterised by steep cliffs that are prone to mass movement. These

cliffs rise to around 75 metres above sea level, and are surrounded at their base by large angular boulders of Torlesse composition. Both Point Gibson and Manakau Bluff have rocky reefs extending to the north east.

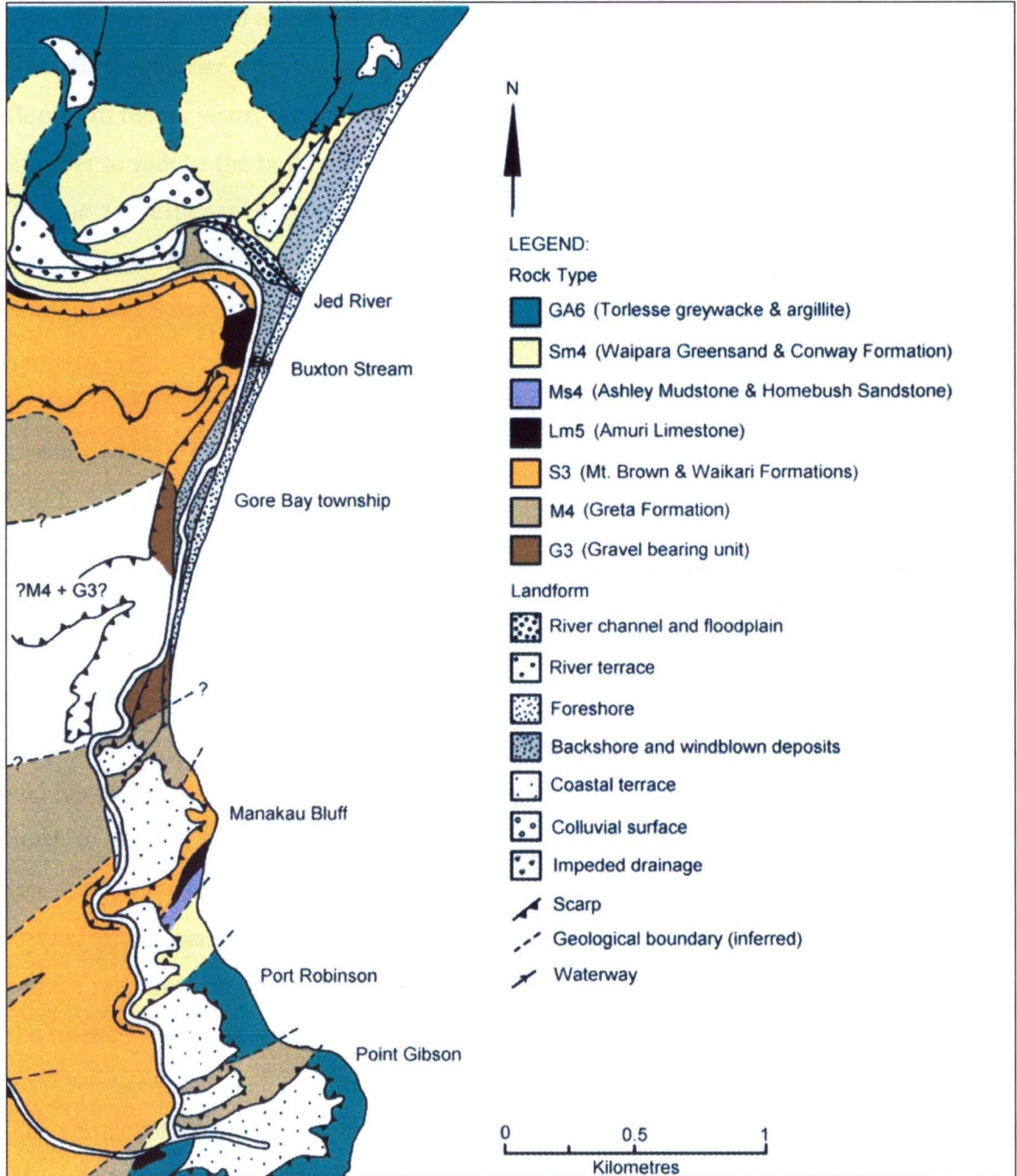


Figure 3.1: The geology and geomorphology of Gore Bay and surrounding areas. Rock type codes are described in the text and lithological descriptions are given in Table 3.1. Modified from McPherson (1988).

Gore Bay contains two permanent waterways, the Jed River and Buxton Stream, the mouths of which are located in central Gore Bay, approximately 500 metres apart. Both of these waterways have *hapua* type river mouths (Single & Hemmingsen 2000) and have no permanent opening to the sea. Instead, water ponds in a backshore lagoon behind a sand and gravel barrier beach. The water exits by means of seepage through the barrier at times of low river flow, or by barrier breaching in times of flood. In recent years, the mouth of Buxton Stream has been kept artificially lowered in order to reduce the build up of water in the lagoon before barrier breaching occurs. This is in response to several intense rainfall events which caused considerable inundation of Buxton Camping Ground. There are several terrace surfaces associated with the Jed River (Figure 3.1).

In the south of the bay, the Tweedies and Cathedral gullies contain small ephemeral streams, which flow only after periods of heavy rainfall. Any water exiting to the beach from these gullies generally ponds in the backshore, as discharge is not high enough to incise the beach.

The village of Gore Bay has been developed on an area of vegetated sand dunes between the beach and the ancient sea cliffs backing the village. While few remnants of the dunes remain visible in the south of the bay due to development of the village and historic coastal erosion, they are still present in the north of the bay. Immediately north of the Jed River, a large area of wind blown sand has been planted with pine trees, while further north vegetated dunes are found on the landward side of the small coastal plain, backed by a remnant coastal terrace. There are also small coastal terrace remnants on the southern side of the Jed River. Figure 3.2 illustrates some of the main geomorphic features in Gore Bay.

The geomorphic map shown in Figure 3.1 distinguishes between two types of coastal deposit: foreshore deposits and backshore/windblown deposits. However, the scale and accuracy of the map are such that little detail is given of the modern sedimentary landforms. The following chapters of this thesis will concentrate on describing and interpreting these areas in more detail.

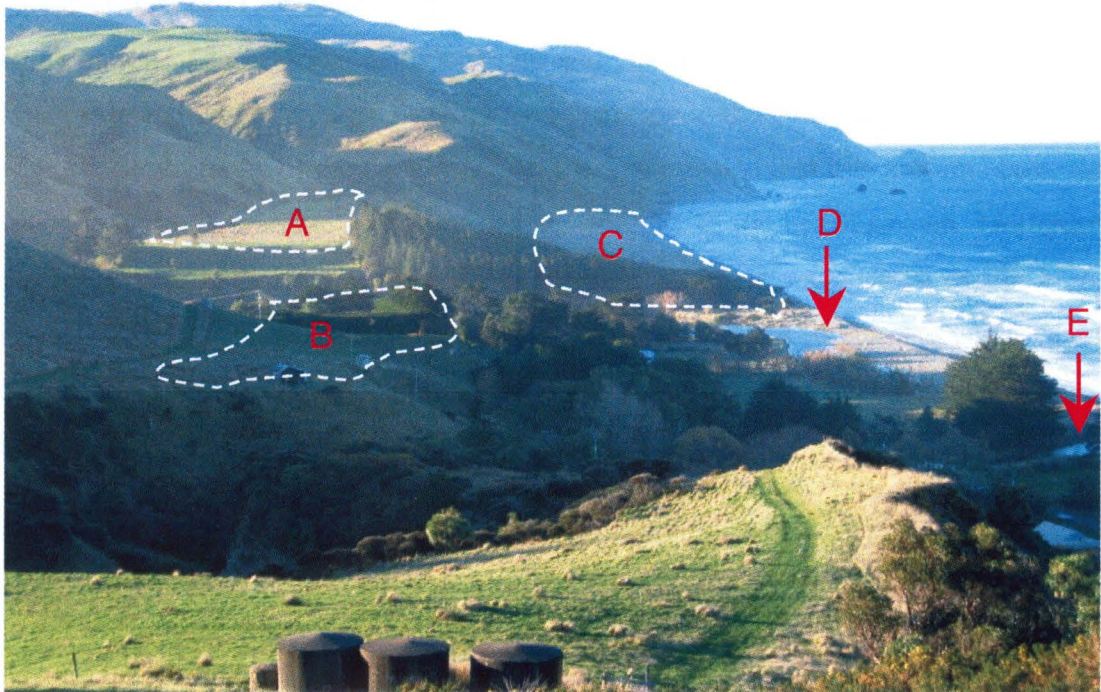


Figure 3.2: Looking north along Gore Bay with geomorphic features annotated. Dashed lines border areas of (A) & (B) raised terraces and (C) the northern coastal plain with relict sand dunes. Arrows point to the lagoons formed at the mouth of (D) the Jed River, and (E) Buxton Stream.

3.2.3 Sediment sources

Sediment may be supplied to Gore Bay from a variety of sources. The cliffs of Manakau Bluff have eroded dramatically since the late 1800s, with the latest slip in February 2002 bringing down several tons of material. While several of the units within these cliffs contain sand sized sediment, the bulk of the cliffs, and the section most prone to collapse, is composed of Greta Siltstone, which is too fine grained to remain in the beach system and quickly moves offshore. Intact blocks of siltstone may remain on the beach as cobble sized clasts for a short time, however they would quickly break down in the high energy coastal environment. Blocks of the more indurated Waipara Sandstone and Amuri Limestone would remain on the beach for longer than the siltstone, but would also wear down relatively quickly.

Above the Greta Siltstone lies a conglomeratic unit containing pebble and cobble sized clasts of predominantly Torlesse greywacke composition (Figure 3.3).

McPherson (1988) interprets these gravel bearing sediments as being the equivalent of the Kowhai Formation (G3), a unit that is younger than the Greta Formation. However, Gregg (1964) and King *et al.* (1999) interpret the gravel bearing units as a combination of the Bourne Conglomerate and Greta Siltstone members of the Greta Formation and do not identify the Kowhai Formation in the Gore Bay area. No matter what the stratigraphy of the conglomerate, the fact remains that it is present above the siltstone and is a possible source of coarse sediment to the beach system. Although the gravel bearing portion of the cliffs is not prone to direct wave attack except in the largest storms, there are small gullies in the cliffs, worn down by running water which are capable of transporting sediment to the beach, where it is available for reworking by waves.



Figure 3.3: Photograph showing Manakau Bluff which forms the southern boundary of Gore Bay. Dashed line indicates the boundary between Greta Siltstone and the overlying gravel bearing formation.

The catchment areas of Tweedies and Cathedral gullies contain significant areas of both Greta Siltstone and the gravel bearing formation. In Cathedral Gully, the conglomerate layers have been fluvially eroded into striking ‘badland’ formations, resulting in the naming of the gully (Figure 3.4). The two gullies contain ephemeral streams which pond in the backshore when in flow, rather than incising the beach.

Any material eroded from the gullies will therefore be deposited on the backshore, where it is available for reworking by waves during storm events.

The beds of both the Buxton Stream and Jed River contain a small amount of gravel sized material upstream from the coast. Although the beds of these rivers are largely immobile, gravel is likely to be transported as bed load during high flow events. During high seas and extreme flood events, this sediment can move from the lagoon to the beach system.

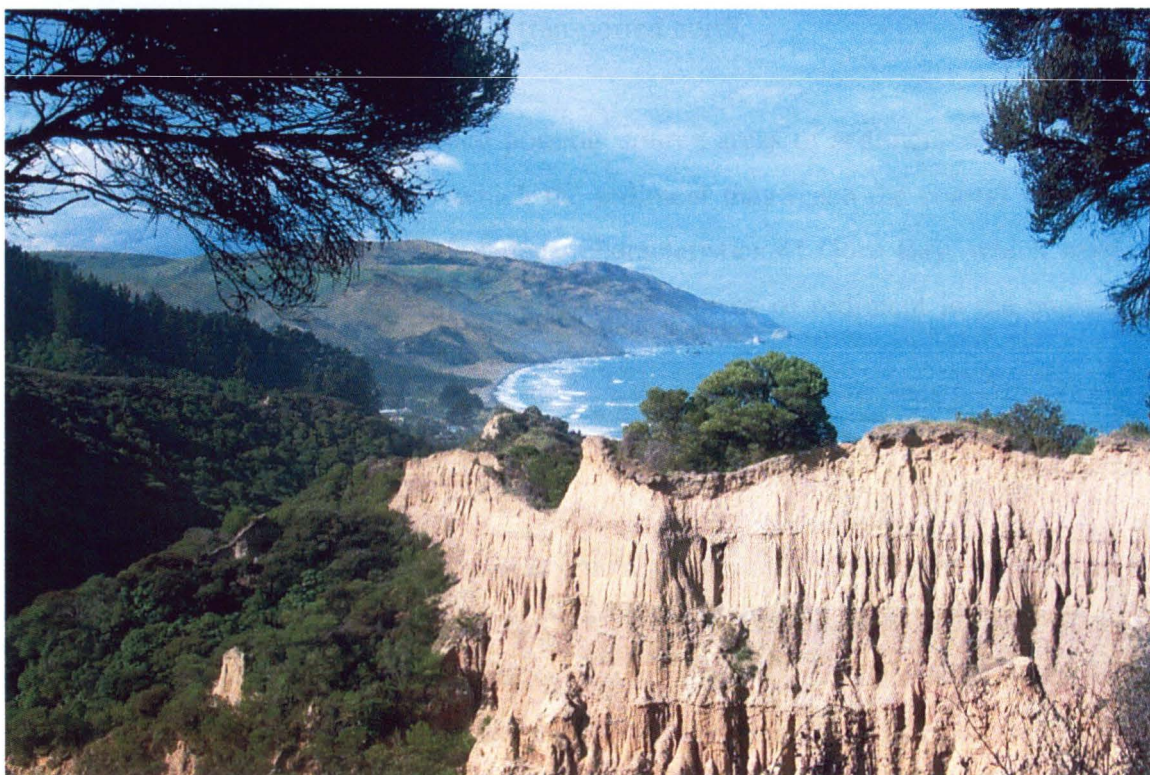


Figure 3.4: Photograph of “The Cathedrals” with Gore Bay in the background. Fluvial dissection has caused this magnificent ‘badland’ landscape within the gravel bearing formations in Cathedral Gully.

The coastal plain to the north of the Jed River consists of a mixture of sands and gravels and is overlain by sand dunes in places. The plain lies approximately two to four metres above chart datum (one to three metres above mean sea level). Erosion of the plain would provide sediment to the beach system, however if the plain is aggrading, then it is a sediment sink rather than a source.

Another possible supplier of sediment to Gore Bay could be through longshore transport. The Waiau and Hurunui Rivers supply large amounts of gravel, sand and

silt to the coast and the mouths of these rivers are less than ten kilometres north and south of Gore Bay respectively. However, the reef systems extending from Point Gibson and Manakau Bluff to the south of Gore Bay are likely to prevent any beach forming sediment moving north from the Hurunui River. There are no large reef systems or headlands between the Waiau River and Gore Bay which would block sediment transport, however, the coastline south of the Waiau is predominantly rocky, whereas the coastline north of the Waiau consists of mixed sand and gravel beaches (Yetton & Garland 1988). This indicates that the majority of sediment reaching the coast from the Waiau River is probably transported north.

The previous discussion has outlined possible source areas of sediment within Gore Bay and possible mechanisms by which the sediment may reach the coastal system. Chapter Four investigates the sedimentary characteristics of Gore Bay, which may allow confirmation or rejection of these areas as sources of sediment to the coastal system.

3.3 Hydraulic Factors

Knowledge of the process environment is crucial to the understanding of any coastal system. While source area characteristics are thought to have a first order control on the sedimentary characteristics and morphology of a beach, hydraulic factors such as tides, currents, winds and waves control the day to day characteristics of the beach as it attempts to reach equilibrium with the ever-changing conditions. The following sections will outline the nature of the hydraulic processes within Gore Bay. This knowledge can then be applied to the analysis of sedimentary and morphological features in Chapters Four and Five.

3.3.1 Tides, currents and bathymetry

Tides

Tides are the periodic rise and fall of the ocean surface due to the gravitational attraction of the moon and sun. Because the movements of the earth, moon and sun are not constant, tidal cycles are not constant in time or magnitude. Tides are important in the coastal environment as the tidal range continually shifts the land/water interface both horizontally and vertically. These changes determine the

level at which other coastal processes operate, by changing the water depth and shifting the swash, surf and wave shoaling zones (Short 1999).

The tidal cycle in Gore Bay is semi-diurnal and micro-tidal, with a mean spring tidal range of around 1.5 metres. However, under extreme tides, this range may extend to more 2.5 metres. Mean sea level is approximately 1.1 metres above the 1937 Lyttelton Datum (Land Information New Zealand 2003).

Currents

The prevailing offshore current is the Southland Current, a relatively cold body of water moving up from the south west along the coast. Typical flows are about 1.5 knots ($0.8\text{m}\cdot\text{s}^{-1}$) in summer and up to 1 knot ($0.5\text{m}\cdot\text{s}^{-1}$) in winter (Yetton & Garland 1988). Strong northerly winds can induce counteractive surface currents to the south, which reduce the ability of the Southland Current to transport sediment.

Gibb (1979) shows a northward net longshore drift for most of the North Canterbury shoreline. Rates of net movement appear lowest in the south, where the southern net drift generated by Pegasus Bay has most influence. Gibb (1979) estimates sediment volumes in the order of 100 000 - 250 000 cubic metres per year, which is low in comparison to elsewhere on the east coast of the South Island, (e.g. 2 – 4.5 million cubic metres off Banks Peninsula). This is in keeping with Duns (1995) who found that net longshore transport in northern Pegasus Bay is to the north, in the order of 200 000 cubic metres per year, while net longshore transport in central and southern Pegasus Bay is to the south.

Yetton and Garland (1988) report that longshore drift patterns in the Cheviot area are considered to be essentially local, as much generated by headland wave pile up as prevailing winds. Observations tend to support this statement, with local surfers reporting that during periods of strong north easterly swell, there is a strong current to the south in Gore Bay (Sorenson 2003, pers. com.).

Yetton and Garland (1988) note that a lack of research into longshore drift patterns in the area limits interpretation. They suggest that a northward net drift is supported by river bar orientation, with the Hurunui and Conway rivers both having northward

trending river bars. However, the bar pattern at the Waiau River is more neutral, while the bar at the mouth of the Jed River is to the south.

Bathymetry

Available bathymetric data for the Gore Bay area is restricted to the 1:200 000 coastal chart series (Herzer & Carter 1983). While this is too large scale to allow detailed interpretation of the bathymetry within Gore Bay, an understanding of the nature of the coastal shelf can be gained. Bathymetrical features determine the way in which waves approaching the coast are refracted, therefore affecting the distribution of energy along the coast.

The continental shelf of North Canterbury is steeply sloping and typical of a coast of tectonic emergence (Inman & Nordstrom 1971). The shelf edge is approximately 30 kilometres off the coast of Gore Bay at a depth of around 130 metres. North of Gore Bay, around ten kilometres offshore, the sea bed drops steeply into the Conway Trench, an arm of the much larger Hikurangi Trench. South of Gore Bay, the width of the continental shelf increases to approximately 60 kilometres offshore in Pegasus Bay.

3.3.2 Wind

Wind is an important agent in the coastal environment, not only in the building of windblown landforms such as dunes, but also in the creation and modification of waves and currents (Masselink & Pattiaratchi 1998; Xu & Wright 1998). It will be shown in Section 3.3.3 that locally generated waves play an important role at Gore Bay; therefore a description of the wind environment is necessary.

The wind climate in Gore Bay reflects the large scale wind regime of New Zealand. New Zealand's wind regime is dominated by easterly moving anticyclones and frontal systems, which produce three major wind fields in the Canterbury Region. These are the north westerly föhn winds, southerly frontal winds and easterly/north easterly winds. In addition, local thermally generated sea breezes, modified by the orientation of the coastline also add to the frequency of north easterly winds.

Due to the lack of a climate station in Gore Bay, wind data for Cheviot (Station 4566) and Kaikoura (Station G23464) were obtained from the National Institute of Water and Atmospheric Research Climate Database. A summary of this information is shown in Table 3.2. It can be seen that Kaikoura and Cheviot show distinctly different wind climates. Noticeably, Cheviot is subject to a significantly higher frequency of north westerly winds than Kaikoura. Although the data collection period for each station is different, both plots are considered to approximate general conditions. The difference is due to the fact that the Seaward Kaikoura Ranges effectively shelter the Kaikoura area from all but the most severe north westerly winds.

So how do the wind patterns shown by these two stations relate to the wind environment at Gore Bay? Kaikoura is located approximately sixty kilometres north east of Gore Bay, whereas Cheviot is only eight kilometres north west. However, Cheviot is sheltered from the coast by a series of coastal hills, some of which are over 300 metres high. Therefore it is expected that any locally generated sea breezes would not be recorded by the Cheviot station.

Table 3.2: Wind data from the Cheviot and Kaikoura climate stations showing frequency of winds from each direction. Note: North, East, South and West directions cover 40 degree sectors (e.g. East: 070° to 110°), while Northeast, Southeast, Southwest and Northwest directions cover 50 degrees (e.g. Southwest: 200° to 250°).

| | N | NE | E | SE | S | SW | W | NW |
|----------|----|----|---|----|----|----|----|----|
| Kaikoura | 14 | 20 | 6 | 2 | 14 | 18 | 17 | 4 |
| Cheviot | 7 | 14 | 6 | 5 | 5 | 10 | 9 | 26 |

Figure 3.5 shows wind roses of the Kaikoura and Cheviot data, as well as for observational data recorded by a Gore Bay resident between January 2002 and September 2003. While the observational data is not as accurately recorded as the climate station data (see Section 3.3.3 for details), it gives an indication of the general wind conditions at Gore Bay and shows that there are differences to both the Cheviot and Kaikoura data. Winds at Gore Bay most frequently come from a north westerly direction, while south westerly winds are also common. Onshore winds, (north easterly and easterly winds combined) occur almost as often as north westerly winds.

It is concluded that wind data from the climate station at Cheviot (Station 4566) is the best approximation for conditions at Gore Bay, although there are minor differences.

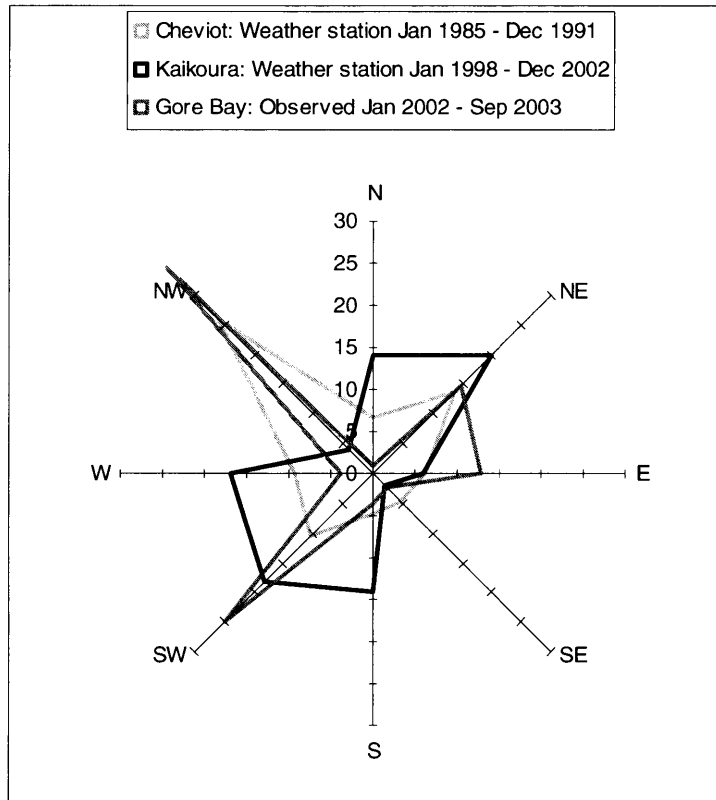


Figure 3.5: Wind roses for Gore Bay, Kaikoura and Cheviot. Partitioning of direction was achieved using the same categories as Table 3.2.

3.3.3 Regional wave data

Waves are one of the most important processes within the coastal environment as they are the major supplier of energy to the coast. Knowledge of wave conditions is therefore essential for any study of the coastal environment. The east coast of New Zealand has been classified as a high energy “east coast swell environment” (Davies 1964). The unlimited fetch of the South Pacific means that large southerly swells are a frequent occurrence, with locally generated waves often superimposed on the swell. In general, southerly seas are frequently higher and of longer period than those coming from the north east. Kirk (1975) suggests that southerly swells typically have periods between ten and fifteen seconds, while locally generated waves (frequently from the east or north east due to the predominant winds) have shorter periods of around six to eight seconds.

Environment Canterbury (the regional council) operates a directional waverider buoy, located 17 kilometres offshore of Banks Peninsula, which is approximately 100 kilometres south of Gore Bay (Figure 3.6). This records deep water wave characteristics. Deep water wave characteristics are modified as they travel across the continental shelf, so that observed wave conditions at a particular point on the coast may be different to the deep water wave conditions (Komar 1998). At present, it is unknown exactly how deep water wave conditions recorded by the wave buoy relate to wave conditions in North Canterbury. The following discussion will compare deepwater wave characteristics recorded by the wave buoy with observational data from Gore Bay so that the relationship between the two can be determined.

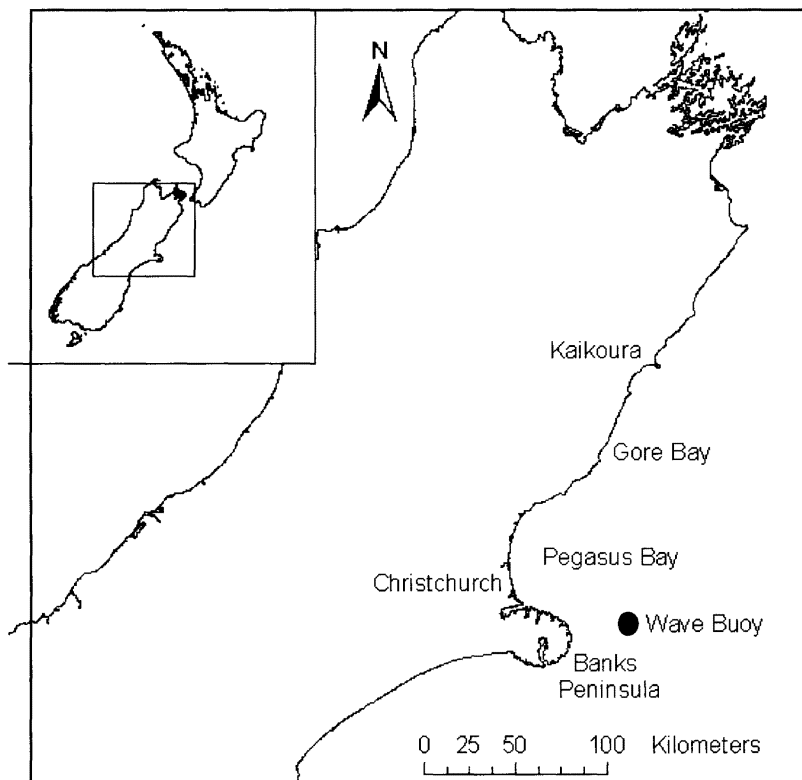


Figure 3.6: Map showing location of wave buoy (black spot) in relation to Gore Bay.

Methods

The Canterbury wave buoy is moored in approximately 76 metres of water, 17 kilometres east of Le Bons Bay, Banks Peninsula at Latitude 43° 45' South, Longitude 173° 20' East (Environment Canterbury 2003). The wave buoy collects data on wave height, direction and period. Two measurements of wave height are recorded, maximum wave height (H_{max}) and significant wave height (H_{sig}). Maximum wave height refers to the height of the largest wave to pass the wave buoy during a standard measure of time, while significant wave height refers to the average height of

the largest third of all waves within a standard measure of time. Significant wave height is considered to roughly correspond with visual estimates of wave height (Komar 1998). The data utilised in this study is a combination of hourly and three hourly data between January 2002 and September 2003. Due to equipment maintenance and technical difficulties, coverage is not complete during this period. Data was kindly supplied by Environment Canterbury.

Observational data was kindly donated by Mr. John Sorenson, a Gore Bay resident of fourteen years, with over forty years surfing experience. Mr. Sorenson has been recording wind and wave conditions at Gore Bay for personal interest for more than four years. For comparison with deepwater wave data from the wave buoy, only data for 2002 and 2003 were used in this study. Although not using conventional observation methods (e.g. Schneider 1981), the observations provide a useful data set with which to compare deep water wave data, the limitations of which are discussed below.

Observations were of a descriptive nature, whereby wave heights and directions were noted amongst other observations. A typical entry may have read: “Light northwest breeze early on, turned easterly mid morning. Swell picked up overnight, 3-4 feet from the south.” From each day's entry, wave height, wave direction, wind direction and wind intensity were extracted and compiled into a spreadsheet. In addition to these parameters, any qualitative information on the nature of the surf was also extracted. For example, phrases such as “a bit lined up”, “sloppy”, “disorganised”, “peaky”, “hollow” and “inconsistent” were helpful in understanding the nature of the wave environment.

Wave height was recorded in “feet”, however it must be noted that a surfer’s “foot” does not necessarily correspond to an imperial foot (12 inches). Because the exact relationship between observed “feet” and metres is unknown, the term “feet” has been retained to avoid spurious accuracies which may be assumed if observed wave heights were stated in metres. Although the observed wave heights cannot be directly compared with the wave buoy data, the observed heights can be considered a reliable estimate of relative wave height, as they were recorded by a single observer with wide experience of both Gore Bay and surfing in general.

Observed wave height was generally recorded as a range of heights, for example 2-3 feet. When graphing wave height, the mid point of the height range observed was used. For example, if observed wave height was 2-3 feet, it would be graphed as 2.5 feet, 3-4 feet as 3.5 feet and so on. It was noted by Mr. Sorenson that wave height is hard to estimate when larger than six feet, therefore any waves larger than this were recorded in observation as six feet plus. For graphing purposes, these large waves were given a height of 6.5 feet, when actual wave height may have been higher than this.

Wave and wind direction were generally indicated by compass points, for example north or north east. Wind speed was indicated through the use of qualitative terms such as “light”, “moderate” and “strong”. Where more than one parameter was recorded in a single day, for example “3-4 foot swell dropping to 1-2 foot after lunch”, the first recording was used, as the majority of observations were taken in the early morning.

Unfortunately, not all parameters were noted for each day. Wave height was recorded on 90% of days in 2002, and 63% of days between January and September 2003, an average of 78% coverage over the entire study period. Wave direction was recorded on 75% of days in 2002 and 54% of days in 2003, an average of 66% coverage for the study period. Despite this, the data gained from the observations is useful, if not complete.

Results

Analysis of the wave buoy data (Figure 3.7) shows that the majority of significant wave heights were between one and three metres. Less than 5% of significant wave heights were less than one metre, while less than 10% were higher than three metres. Analysis of the observational data (Figure 3.8) shows that the most frequently occurring waves were between one and three feet high, while waves more than six feet high occurred on less than two percent of the days observed.

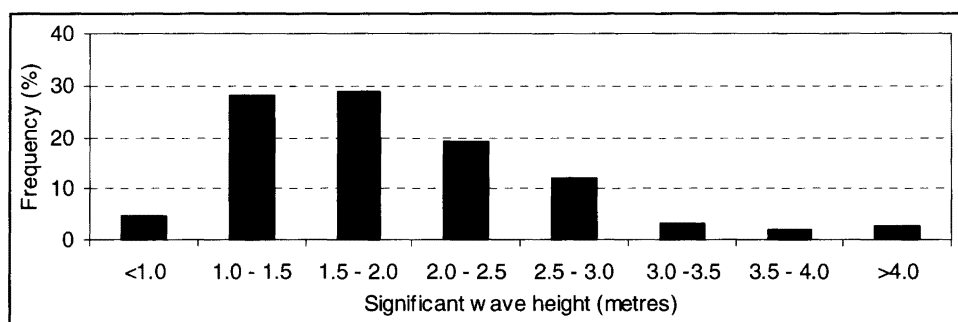


Figure 3.7: Frequency of wave height classes, as measured by the wave buoy.

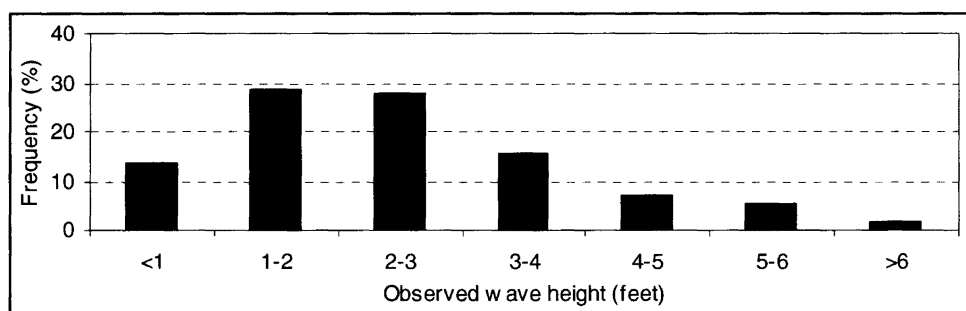


Figure 3.8: Frequency of wave height classes, as observed at Gore Bay.

The direction from which waves arrive at a coast can determine the distribution of energy along the coast, through wave refraction and sheltering effects. Sheltering and refraction are important factors in determining the distribution of wave energy at Gore Bay. The full force of southerly waves are felt north of the Jed River, while south of the Jed, wave energy arriving from southerly waves decreases towards the south of the bay, due to refraction around Point Gibson. This is illustrated in Figure 3.9. Waves arriving from the north east are felt more strongly in the south than in the north of the bay. At all times there is a wide surf zone in Gore Bay, usually extending approximately 2-300 metres. Under low energy conditions the width of the surf zone may decrease to less than 100 metres.

Wave direction data from the wave buoy shows that southerly waves are the most common, occurring around 45% of the time (Figure 3.10). South easterly, easterly and north easterly waves are the next most common, with each occurring approximately 15% of the time. Observational data from Gore Bay shows a similar distribution as the wave buoy, with some slight differences. Southerly waves are less frequent in Gore Bay than offshore of Banks Peninsula; however they are still the dominant wave direction (32%). Easterly waves are almost twice as frequent at Gore

Bay than at the wave buoy, with north easterly and south easterly waves also slightly more frequent. Nearly ten percent of waves recorded by the wave buoy were from a south westerly direction, while no south westerly waves were observed in Gore Bay. This is due to refraction of south westerly waves around Point Gibson, making them appear southerly to an observer in Gore Bay.



Figure 3.9: Large southerly swell at Gore Bay, 8th July 2003. The full force of the waves is felt in the north of the bay, while wave energy decreases to the south due to refraction of the wave crests (dashed lines) and the sheltering effect of Point Gibson and Manakau Bluff.

Figure 3.11a shows the relationship between observed wave heights at Gore Bay and significant wave height recorded by the wave buoy. While there is significant scatter, it can be seen that there is a general trend of increasing wave heights at Gore Bay with increasing wave heights at the wave buoy. Figure 3.11b shows the relationship between wave directions observed at Gore Bay and recorded by the wave buoy. Once again, there is significant scatter of the data points. However, it can be seen that there are several clusters of data points. There is a concentration of data points indicating that east to north easterly waves at the wave buoy (45-90°) often correspond to waves

from a similar direction being observed in Gore Bay. Another cluster indicates that south west to south easterly waves recorded by the wave buoy (135-225°) are often observed as south to south easterly waves at Gore Bay (135-180°). However, there is also a large cluster that indicates that often, south to south westerly waves are recorded at the wave buoy (180-225°), when east to north easterly waves are observed at Gore Bay (45-90°).

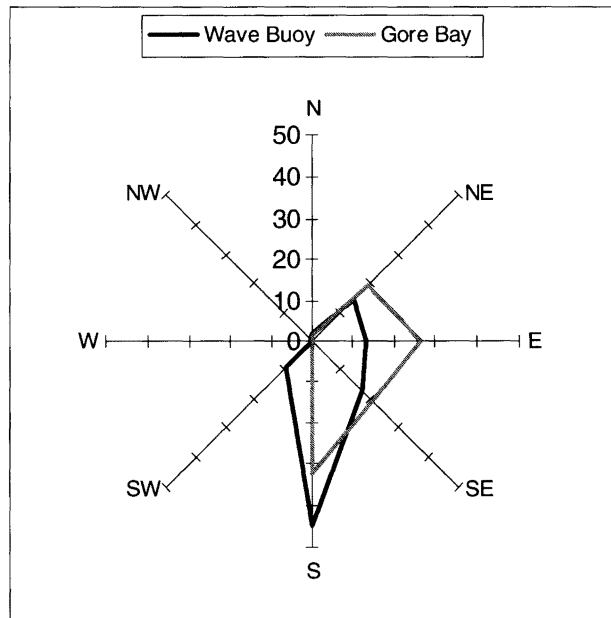


Figure 3.10: Wave rose for wave buoy data and Gore Bay observation data. Both plots are for the period January 2002 to September 2003.

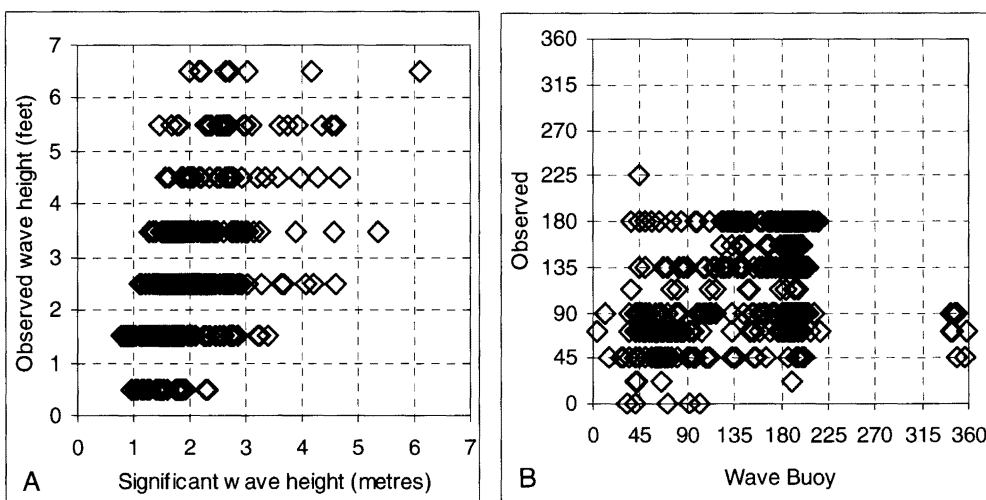


Figure 3.11: The relationship between deepwater wave characteristics (recorded by the wave buoy) and observed wave characteristics at Gore Bay. A) Wave height and B) wave direction.

The discrepancies between wave heights and directions recorded by the wave buoy and observed in Gore Bay may be due to a number of factors:

1. The wave buoy is recorded in deep water, more than 17 kilometres from land. Therefore any waves measured by the buoy have not experienced significant shoaling or refraction. On the other hand, waves observed at Gore Bay have undergone significant shoaling and refraction as the wave has travelled across the continental shelf. Wave characteristics would therefore be expected to be different at Gore Bay. It is the purpose of this comparison to attempt to determine a relationship between deep water wave conditions and those waves observed at Gore Bay. However, the following two factors mean that determining such a relationship is not as straightforward as might be expected.
2. The qualitative nature of the observations made at Gore Bay. Wave height is difficult to observe accurately, i.e. what might be called a 1-2 foot wave on one day, may be called a 2-3 foot wave the next. However, it has been mentioned previously that the observer is an experienced surfer who has been recording wave conditions at Gore Bay for more than four years. It is assumed that the relative heights of observations are approximately correct.
3. The waves being observed at Gore Bay are not the same waves being recorded by the wave buoy. The wave buoy is located approximately 100 kilometres south of Gore Bay. Local generation of waves by locally generated winds (e.g. sea breezes) at Gore Bay may mean that waves arrive at Gore Bay which do not travel past the wave buoy.

In order to investigate this last point, an examination was made of the direction from which waves of different heights came. Figure 3.12 shows the frequency of wave direction by height class recorded by the wave buoy. It can be seen that southerly waves dominate all wave height classes. Figure 3.13 shows the frequency of wave direction by height class observed at Gore Bay. Southerly waves are much less dominant at Gore Bay, especially at lower wave heights. This indicates that a significant portion of smaller waves observed at Gore Bay are locally generated easterlies or north easterlies and are not recorded by the wave buoy.

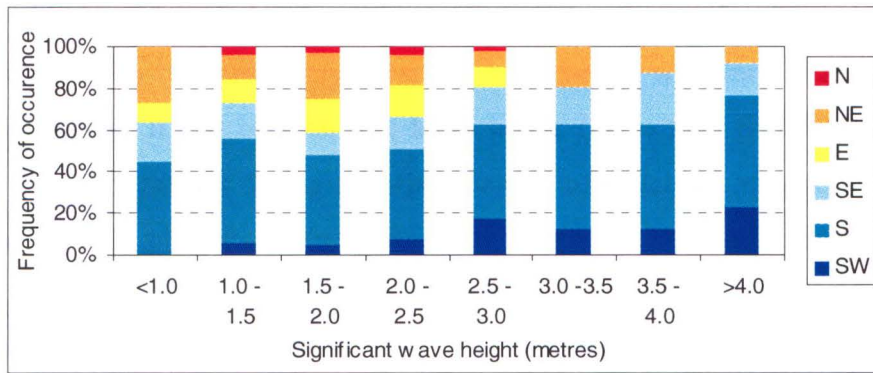


Figure 3.12: Frequency of wave direction by height class, wave buoy.

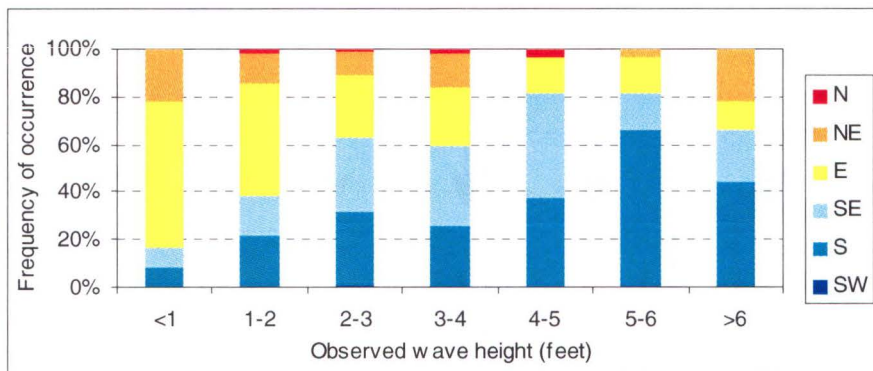


Figure 3.13: Frequency of wave direction by height class, Gore Bay.

From the comparison of deep water wave conditions recorded by the Environment Canterbury directional waverider buoy off Banks Peninsula with observed wave conditions at Gore Bay, it can be concluded that although there is general agreement between the two datasets there is no clear relationship. Future studies requiring quantitative information on wave conditions in Gore Bay or greater North Canterbury are therefore recommended to collect site specific wave data rather than relying on the wave buoy data.

3.3.4 The short term wave climate

While the observational data collected by Mr Sorenson at Gore Bay has been useful for comparison with the deepwater wave buoy data, it can also be used to investigate how the wave climate has varied over the study period of this thesis. The following section summarises the observational wave data so that it can be used for analysis of variations in sedimentary and morphological characteristics in the following chapters of this thesis.

Figure 3.14 shows observational wave height plotted over time for the period January to September 2003. Unfortunately there is a large period with very little data during March and April. It can be seen that large waves (more than five feet high) were observed on six occasions during the study period, of which all but one were in July and August. This suggests a strong seasonal pattern to wave heights in Gore Bay, however, similar analysis of observed wave heights for 2002 show no such pattern, with large waves occurring in all months. The arrows in Figure 3.14 indicate days on which beach profiles were surveyed at Gore Bay. In order to analyse the variations in beach morphology shown by profile analysis in Chapter Five, a summary of wave conditions between survey periods is given below.

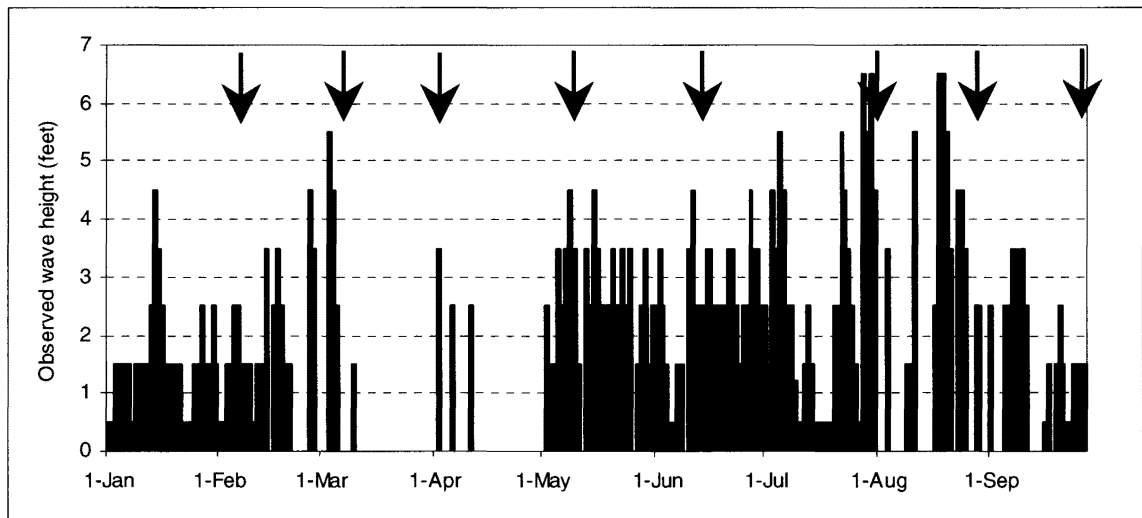


Figure 3.14: Observed wave height at Gore Bay between January and September 2003 (in “feet”, see text for details). Arrows indicate days on which beach profiles were surveyed, discussed in Chapter Five.

2nd February 2003

Observational wave height was recorded every day in the month preceding the February 2nd surveys. The majority of the month was fairly calm with one to two feet waves common. A moderately large wave event (4-5 feet) from the south occurred about two weeks prior to survey, however wave heights in the week preceding survey did not exceed three feet and were predominantly from the north east.

5th March 2003

Observational wave height was recorded on 22 of the 31 days between the February and March surveys. Wave heights generally increased over this period, with 5-6 foot waves from the north east occurring two days before the survey.

5th April 2003

Unfortunately no wave heights were observed between the March and April surveys and the deepwater wave buoy was non operational for the majority of this period also. On the day of survey there were 3-4 feet waves from a southerly direction.

10th May 2003

There is very little wave height data for the majority of the period between the April and May surveys, however there is solid coverage for the week preceding data collection. Wave heights during this week were up to 4-5 feet from a south or south easterly direction.

13th June 2003

Observational wave height was recorded on 31 of the 34 days between the May and June surveys. Wave height for this period averaged 2-3 feet, with some days recording 3-4 foot waves. The large majority of these were from a southerly or south easterly direction. Two days prior to data collection, 4-5 feet waves from the south were observed at Gore Bay.

7th July 2003

Beach profiles were not collected on this date; however sediment samples for analysis in Chapter Four of this thesis were collected on July 7th. It is therefore important to summarise the wave conditions preceding sediment sample collection. Wave height was relatively high, with a large (5-6 feet) waves from the south occurring just prior to collection.

31 July 2003

Profile collection at the end of July was preceded by four days of large waves (more than six feet) from a north easterly direction. Five to six feet waves from the south were observed in Gore Bay around a week before.

28th August 2003

The dominating wave event between the July and August profiles occurred 7-10 days before survey and consisted of easterly waves more than six feet high. Wave heights gradually decreased after this, and were 2-3 feet on the day of data collection.

27th September 2003

Observed wave heights at Gore Bay were relatively low between the August and September profiles, with maximum observed height of 3-4 feet from the south east approximately two weeks before survey. The week prior to data collection consisted of small north easterly waves, rarely exceeding two feet.

3.3.5 The long term wave climate

Section 3.3.4 has described the short term wave climate for comparison with sediment and morphology investigations later in this thesis. However, the longer term wave climate is also of interest to this study. Historically, Gore Bay has seen sporadic episodes of erosion, usually associated with large storms (Yetton & Garland 1988). However, in more recent times there have been few reports of erosion at Gore Bay (Section 3.4.2). It is of interest to see whether this is due to a lack of large storm events or to a shift in the behaviour of the beach system itself. This section will investigate the frequency of large storms to affect the Canterbury region over the last forty years.

Table 3.3 summarises the storms which have been documented as causing either flooding or erosion in Canterbury since 1962. Prior to 1962 storm records are scarce, but there are documented storms in 1952, 1949, 1929, 1903, 1901 and 1891. It can be seen in Table 3.3 that the majority of storms have occurred between April and August, supporting the idea of a seasonal variation in wave heights along the Canterbury coast. Although the direction of wave propagation is not known for some of the more historical storms, it can be seen that most of the damage causing storms in Canterbury have come from a southerly or south easterly direction.

Table 3.3: The frequency of damage causing storms in Canterbury documented since 1960.

Direction of wave propagation indicated if known. (Data provided by Environment Canterbury).

| Year | J | F | M | A | M | J | J | A | S | O | N | D |
|------|---|---|----|----|-----|---|-----|----|---|---|---|---|
| 1962 | | | | 1 | | | | | | | | |
| 1963 | | | | | | | | | | | | |
| 1964 | | | | | | | 1 | | | | | |
| 1965 | | | | | 1 | | | | | | | |
| 1966 | | | | | | | | | | | | |
| 1967 | | | | | | | | | | | | |
| 1968 | | | | 1 | | | | | | | | |
| 1969 | | | | 1 | | | | | | | | |
| 1970 | | | | | | | 1 | | | | | |
| 1971 | | | | | | | | | | | | |
| 1972 | | | | | | | | | | | | |
| 1973 | | | | | | | | 1 | | | | |
| 1974 | | | | | | 1 | | 1 | | | | |
| 1975 | | | | | | | | | | | | |
| 1976 | | | | | | | | | | | | |
| 1977 | | | | 1 | | | SE | | | | | |
| 1978 | | | | | | 2 | | | | | | |
| 1979 | | | | | | | | | | | | |
| 1980 | | | | | | | | | | | | |
| 1981 | | | | | | | | | | | | |
| 1982 | | | | | | 1 | | | | | | |
| 1983 | | | | | | | | | | | | |
| 1984 | | | | | | | | | | | | |
| 1985 | | | | S | ESE | | E | | | | | |
| 1986 | | | SE | | | | | | | | | |
| 1987 | | | | | | | | | | | | |
| 1988 | | | | | | | | | | | | |
| 1989 | | | | | | | | | | | | |
| 1990 | | | | | | | | | | | | |
| 1991 | | | | | | | | | | | | |
| 1992 | | | | | S | S | | SE | | | | |
| 1993 | | | | | | | | | | | | |
| 1994 | | | | | | | | | | | | |
| 1995 | | | | | | | | | | | | |
| 1996 | | | | | | | | | | | | |
| 1997 | | | | | | | | | | | | |
| 1998 | | | | | | | | | | | | |
| 1999 | | | | | | | SE | | | | | |
| 2000 | | | | | | S | | | | | | |
| 2001 | | | | | | | ENE | | | | | |
| 2002 | | S | | SE | | | | | | | | |
| 2003 | | | | | | | | | | | | |

Often, several large storms will occur in rapid succession. This has occurred in 2002, 1992, 1985, 1978, 1977 and 1974. At other times, several years will pass between damage causing storms, for example 1987-1991 and 1993 to 1999. The significance of the frequency of coastal storms at Gore Bay will be discussed further in Section 3.4.2 and Chapter Five.

3.4 Human Processes

One important process in the coastal environment, which is often neglected or understated within coastal models, is human activity. Humans have the capability to cause more change in the coastal environment than the biggest waves or the strongest winds. While the frameworks upon which this thesis is based do not acknowledge human activity as a process variable, this study recognises that humans have played a significant role in the development of the Gore Bay coastal system.

3.4.1 Human settlement

Maori presence along the Gore Bay coast was thought to be short term, with the mouths of the Buxton and Jed Rivers forming the basis of camp sites. Evidence of fire pits and artifacts can still be found in the dune field north of the Jed River, while two groves of karaka trees imply occupation for at least several weeks at a time (Wilson 1993). There is no evidence of permanent Maori occupation at Gore Bay or elsewhere in the Cheviot area.

Europeans first settled in Gore Bay in the late 1840s when John Caverhill founded the Cheviot Hills Station (Wilson 1993). Gore Bay was initially used to send and receive supplies from the surrounding properties, as there were no roads connecting the Cheviot area north or south. In the 1860s, surveyors laid out a township; however the bay did not acquire any permanent residents. A road was constructed on the seaward side of the sections and in 1867 a cottage was built for the wife of the Cheviot Hills Station manager, which is still present in Gore Bay today.

Delays in loading and unloading goods due to bad weather resulted in a slipway being constructed in Port Robinson, which is more sheltered than Gore Bay due to reefs either side. The slipway was used successfully for the first time in October 1879. A

road was constructed from Gore Bay, around Manakau Bluff to Port Robinson in 1894 (Figure 3.15). The Port Robinson road was frequently closed due to land slips, with the 1901 Cheviot earthquake causing massive slope failure and closure of the road for six months. In 1907, Cheviot County was linked to the rest of Canterbury by rail. Soon afterwards, the slipway at Port Robinson ceased activity. The Port Robinson road was permanently closed in 1908/1909 after a series of massive land slips (Department of Lands and Survey 1986).

By 1920, the recreational appeal of Gore Bay had been recognised and sixteen acres of Gore Bay had been subdivided. In 1952 there were 30 houses and baches in Gore Bay and by 1976 there were 50 houses, half of which were permanently occupied (de Groot 1979). Today, more than 80 houses are present in Gore Bay, with 16 permanent residents.

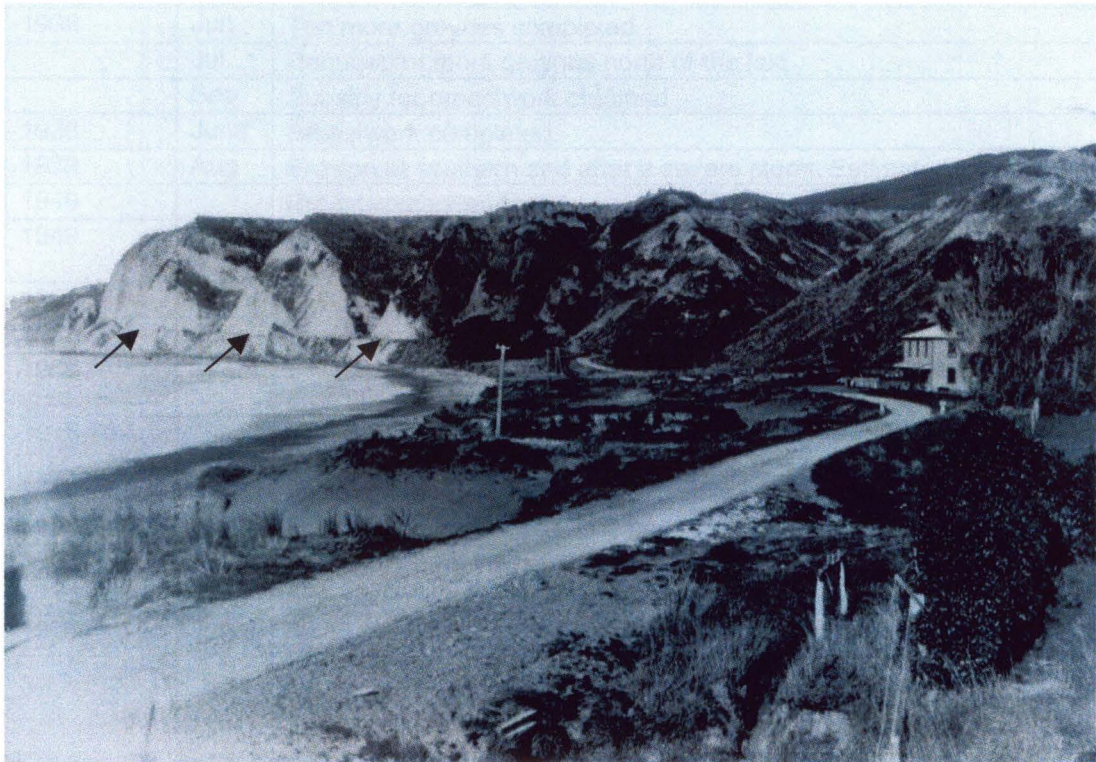


Figure 3.15: Gore Bay in 1901. Note the Port Robinson Road which joined Gore Bay with Port Robinson, around Manakau Bluff (arrows). The road in the foreground was diverted inland in the 1950s due to erosion problems. Reproduced and adapted from Slark (1984).

3.4.2 Response to erosion

Erosion has been documented at Gore Bay since the late 1800s and human response to erosion occurred soon after (de Groot 1979; Department of Lands and Survey 1986).

Table 3.4 summarises the main erosion events and responses. It can be seen that erosion has occurred in three main episodes: 1934-1939, 1951-1952 and 1975-1978. These correspond to periods of higher than usual wave conditions, usually through a combination of storm and spring tides (Yetton & Garland 1988).

Table 3.4: Summary of human response to coastal erosion at Gore Bay. Modified from de Groot (1979) with additional material from Slark (1984), Wilson (1993) and Department of Lands and Survey (1986).

| | | |
|------------|------|---|
| Late 1800s | | Areas of foredune were landscaped and levelled to improve ocean views and to increase the land area suitable for construction. Vegetation was also removed. |
| 1902 | | First groynes constructed |
| 1934 | Feb | Cheviot County Council discusses erosion with the Public Works Department after a section of road was washed away. Residents see a need to protect the foreshore north of the last groyne. |
| 1935 | Feb | Existing groynes are repaired and three new groynes constructed further north. |
| | Dec | Plan for further groynes and breastwork |
| 1936 | Jun | Ten more groynes completed |
| | Jul | Request for more groynes north of the last |
| | Sep | Subsidy for breastwork obtained |
| 1938 | June | Breastwork completed |
| 1939 | Aug | Erosion at southern end after a severe storm. Estimated 25' removed. |
| 1940 | | Breastwork extended |
| 1949 | | Residents used engineer's report to back claim for keeping the seafront road |
| 1951 | Jun | £150 from Cheviot County Council for protection works |
| 1952 | | Breastwork partially wrecked |
| 1953 | | Breastwork extended 330'. Agitation for sea front road dropped, road diverted inland along Moody and Farmer Streets. |
| 1975-76 | | High summer tides. Gore Bay Environmental Protection Committee formed, aimed at replacing old seawall and combat erosion caused by very high tides. |
| 1976 | Aug | Protection works repair fund began |
| 1977 | May | Council dumped material (earth fill, tree trunks, and concrete ballast) along banks, especially in places where the road was threatened. |
| 1978 | June | 3800' seawall completed, extending from Cathedral Road to Farmer Street. Wall consisted of 7' treated pine posts placed 2 inches apart and protruding approximately 1.5 feet above the surface. Between Farmer Street and Buxton Creek, macrocarpa logs were anchored down with chains and covered with earth to form a bank protecting what is now the Buxton Reserve. |
| | Jul | Wall damaged by storm event. Approximately 300 posts were replaced, strengthened with wire and backfilled with gravel. Continuing individual action, e.g. heavy debris laid to protect sand banks. |
| 1978-84 | | Erosion minimal with only moderate storms and tides. |
| 1984-2003 | | There have been several large slips off Manakau Bluff, the most recent in February 2002, but little erosion of the beach, or bank retreat. |
| | | No known protective works have occurred during this period, except that the mouth of the Buxton is regularly bulldozed to prevent lagoon build up during heavy rainfall events causing flooding. |

Responses to erosion in Gore Bay have included the construction of groynes, breastwork and seawalls, re-routing of the sea front road, the dumping of material along “at-risk” sections of the bank and preventative measures such as the regular bulldozing of the Buxton Stream mouth. The effects of these activities on the sediments and morphology of the beach are difficult to quantify and may be fairly insignificant compared to the effects of the hydraulic factors discussed previously. However, it is important to keep them in mind when interpreting results from the sedimentary and morphological investigations in the following chapters.

3.5 Chapter Summary

In keeping with the conceptual framework introduced in Chapter One, this chapter has discussed the initial controls on beach sediments and morphology. Source area characteristics have a first order control on the sedimentary characteristics of a beach and are therefore an important part of any coastal investigation. By considering the geology and geomorphology of Gore Bay, possible source areas to the beach were identified. These include the gravel bearing sediments overlying the Greta Siltstone on Manakau Bluff, the Jed River, Buxton Stream and reworking of the northern coastal plain.

Hydraulic factors have a second order control on beach sediments, resulting in constant readjustment of the beach to the changing conditions. The majority of winds in Gore Bay flow from three directions, the north west, the south west and the east/north east. This pattern reflects the wind regime of the South Island of New Zealand. Observations of wind conditions at Gore Bay correspond fairly well to winds recorded at the Cheviot climate station, despite the hills which separate Cheviot from the coast and block locally generated sea breezes.

Gore Bay has a high energy wave environment, whereby the majority of waves arrive from either a southerly or north easterly direction. The wave environment of Gore Bay was described through the analysis of observational data. Data recorded by a directional waverider buoy moored offshore of Banks Peninsula was compared to observational data to investigate how deep water wave conditions relate to observed conditions at Gore Bay. It was found that while the same general trends can be seen

in both data sets, Gore Bay receives many locally generated waves from an easterly or north easterly direction, which are not recorded by the wave buoy. There is a slight seasonal pattern to wave heights, with large waves occurring more frequently in winter months than summer, however large waves can occur at any time of the year.

Humans have played a significant role in the Gore Bay coastal environment, mainly in response to several episodes of erosion in the past hundred years. Various response measures have been undertaken, including the construction of groynes, seawalls, breastwork, the dumping of materials along threatened sections of foredune and the artificial lowering of the barrier at the mouth of Buxton Stream.

CHAPTER FOUR

BEACH SEDIMENTS

4.1 Introduction

An understanding of the nature of beach sediments is considered an essential prerequisite to effective and efficient coastal management, planning and development (Kirk *et al.* 1987). The characteristics of beach sediments influence the way in which they are transported and therefore how the beach responds to changes in the process environment (Krumbein 1963; McLean & Kirk 1969; Orford 1975; Bluck 1999). Variations in sedimentary characteristics can be used to infer the direction of sediment transport and ultimately determine source and sink areas of the system (Sunimara & Horikawa 1972; McLaren 1981; Le Roux 1994). The aim of this chapter is to identify and describe the sediments of the Gore Bay coastal system and interpret the patterns found.

Section 4.2 begins by describing the fundamental properties of individual sediment particles and reviews various techniques for measuring, describing and analysing these properties. The application of such analysis to mixed sediment beaches is discussed and the procedures used for the collection, preparation and treatment of the sedimentary data of this study are outlined. Section 4.3 presents the results of the sedimentary investigation of Gore Bay and discusses the significance of these findings. Section 4.4 introduces a more qualitative method of describing beach sediments for use with interpreting temporal changes in processes and beach morphology. The chapter concludes with a summary of the main findings.

4.2 Sedimentary Research Techniques

Analysis of coastal sediments is based around ideas and methodologies from the field of sedimentology. Sedimentologists analyse the texture of sedimentary deposits to provide information on the characteristics of the sediment and the processes involved at the time of accumulation (Lewis & McConchie 1994b). For ancient deposits,

textural analysis is used to infer the transport history and depositional environment relating to the formation of that deposit. The same principles can also be used to describe the settings of contemporary accumulations such as coastal and fluvial environments. Textural properties of individual grains, such as size, shape, roundness, density and surface textures, interrelate to influence the bulk density, porosity and permeability of the deposit as a whole (Boggs 1995). This in turn influences the way in which beach morphology responds to changes in processes (Krumbein 1963; McLean & Kirk 1969).

The use of a single technique to interpret sediments on a mixed sediment beach can result in uncertainty, as all methods have limitations and make various assumptions which may or may not be valid. Some commonly used methods are described in the following sections, where their limitations and uncertainties will be discussed. Dawe (1997) suggested that a combination of techniques be employed to identify trends that would otherwise be tenuously concluded on the basis of one technique. Therefore, a *multiple sediment analysis* approach has been used in this thesis, using the methods explained in the following sections.

4.2.1 Statistical grain size analysis

It has long been recognized that the size of individual sediment grains is one of the most important attributes in determining the bulk properties of sediment accumulations (Pettijohn 1957; Lewis & McConchie 1994a; Boggs 1995). This importance is highlighted in the study of coastal environments by the fact that many descriptions of beaches include mention of the estimated sediment size, for example a “sandy” or “mixed sand and gravel” beach.

Grain size is commonly measured on the Udden-Wentworth grade scale, a geometrical millimetre grade scale based on the \log^2 scale, shown in Appendix A (Udden 1898; Wentworth 1922). In this scale, the boundaries between grain sizes are arbitrarily fixed so that each grain size category is twice the preceding size. For example, very coarse sand (1mm) is twice the size of coarse sand (0.5mm), which in turn is twice the size of medium sand (0.25mm). Krumbein (1934) modified the scale slightly, by classifying the boundaries between the Udden-Wentworth classes using the following formula:

$$\Phi = -\log_2 d$$

where: Φ = Phi size

d = sediment particle diameter in millimeters.

Negative phi values are therefore associated with coarse grain sizes, and positive values for finer grain sizes. Because sand and finer sediments were the most widely studied at the time, the introduction of the phi scale largely avoided the difficulties of constantly working with negative values and fractions.

Although the Udden-Wentworth grain size scale is relatively straight forward, the definition of grain size, and therefore the techniques used to measure it, is not.

Pettijohn (1957) suggested six different ways of expressing grain size:

1. volume
2. weight
3. surface area
4. cross-sectional area
5. settling velocity
6. intercepts through particles or projections

If all particles were spherical, then a measure of grain diameter through any plane of the sphere would be a sufficient measure of size (Pettijohn 1957). However, spherical grains are extremely rare in nature, especially in the coastal environment. Figure 4.1 shows a non-spherical grain, defined by three mutually perpendicular axes, corresponding to the length, width and thickness of the grain. All three axes are easily measured with vernier callipers for pebble sized and coarser grades, however measurement of axes on smaller grains is difficult. The problem is compounded by the fact that samples of finer sediments contain an immeasurable number of particles.

All methods of grain size measurement have associated errors and uncertainties, so it is preferable to use a technique that can be applied to the entire range of grain sizes present in the study area, so any errors are standardised. One of the most popular

techniques of grain size measurement, which has been utilised in this research, is sieving.

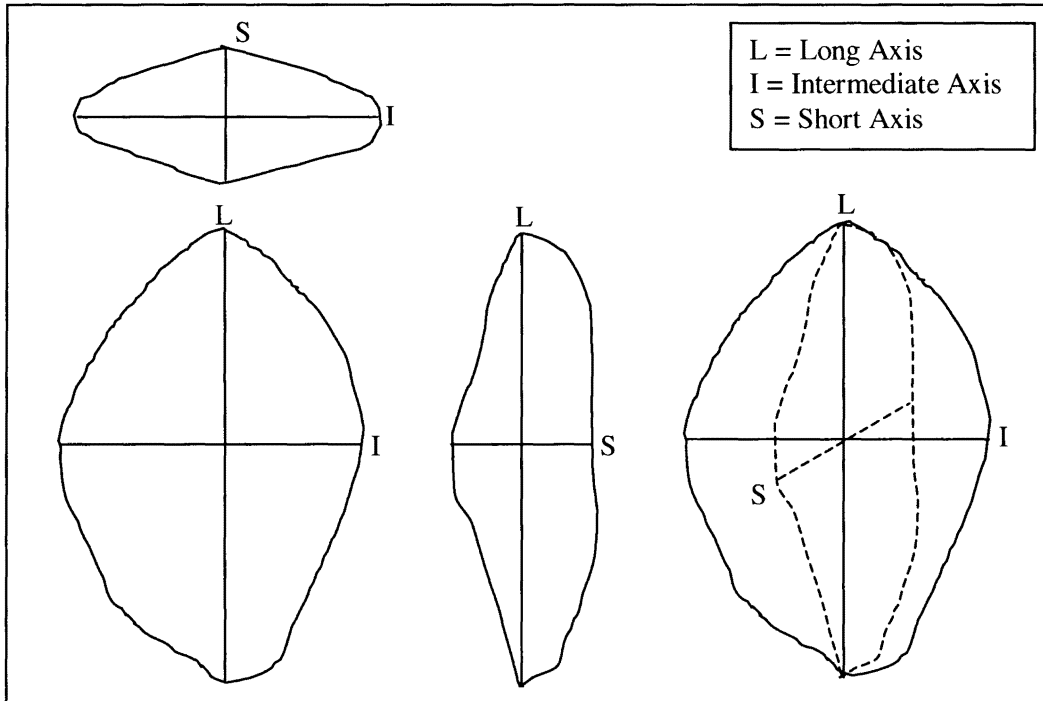


Figure 4.1: Diagrams showing the three mutually perpendicular axis of a non-spherical grain, as specified by Krumbein (1941).

The sieving procedure involves arranging a series of sieves in an ordered stack, the aperture of the screens decreasing by $\frac{1}{2}$ or $\frac{1}{4}$ \emptyset intervals from top to bottom of the stack. The sediment sample is dried and weighed, then placed in the top of the sieve stack, which is shaken mechanically for a standard period, usually 15 minutes. This allows each grain to pass through those sieves which have larger apertures than the grain and collect on the sieve which has apertures smaller than the grain. To obtain a size distribution of the sample, the sediment remaining on each sieve after the shaking period is then weighed and converted to a percentage of the total sample weight. Sieving therefore provides a measure of the width of the minimum diameter through which a particle will pass. Pettijohn (1957) refers to this as the “sieve diameter”, which is equal to the diameter of the intermediate axis (refer Figure 4.1). Although only measuring one dimension of the particle, sieving can be used to measure all sediment between coarse gravel and very fine sand, which provides a degree of standardisation to the measurement of grain size. Sieving is particularly suited to mixed sediment beaches, which contain a wide range of sediment sizes and are usually devoid of fine silt-clay sized sediments.

A “gravelometer” is used for sediment too coarse to pass through the sieves (coarser than -4ϕ). This works on the same principles as sieving, by measuring the sieve diameter or intermediate axis of the grains. A gravelometer is a template containing apertures for intermediate axes from -4ϕ to -12ϕ in diameter. Each coarse particle is passed through each of the holes in the gravelometer, until an aperture is tried that the particle will not pass through, no matter which way it is tried. The weight of particles not passing through each aperture is then recorded in the same way as the sieve data.

There are a number of commonly used techniques for measuring sediment less than $+4\phi$ (the smallest size suitable for sieve analysis), including hydrometer and pipette analysis. As there is little material finer than $+4\phi$ at Gore Bay, these techniques were not necessary, however Lewis and McConchie (1994b) and Folk (1965) give a good review.

One of the main criticisms of sieving is that it does not take into account the shape or sphericity of the grains. Kennedy *et al.* (1985) suggested that irregular shaped particles take longer to pass through a sieve than more equant and smooth particles. It was therefore concluded that the results of sediment sieving are both size and shape dependent and should only be used to describe the general distribution of particle size. However, as long as the limitations of the method are recognised, sieving is probably the most useful method for determining the grain size of a suite of sediment samples, and is the method used in this study.

Once the raw data has been collected, there are a number of ways in which it can be manipulated and utilized to aid interpretation. This usually involves calculating summary statistical parameters including the mean, median, mode, standard deviation (or sorting), skewness and kurtosis. Mean grain size refers to the average grain phi (ϕ) size of a sample. The median is the phi size at the fifty percent by weight percentile, i.e. half the particles are finer than the median and half are coarser. The mode refers to the most commonly occurring grain size in the sample. However, there may be more than one mode in a sample. Bimodal and polymodal sediment samples are common on mixed beaches and will be discussed further in Sections 4.2.2 and 4.2.3. The standard deviation is the variance in the sample from the mean and is a measure of the sorting. Samples containing a wide range of sediment sizes will have

a large standard deviation and be poorly sorted. Samples with a narrow range of sediment sizes will be well sorted and have a small standard deviation.

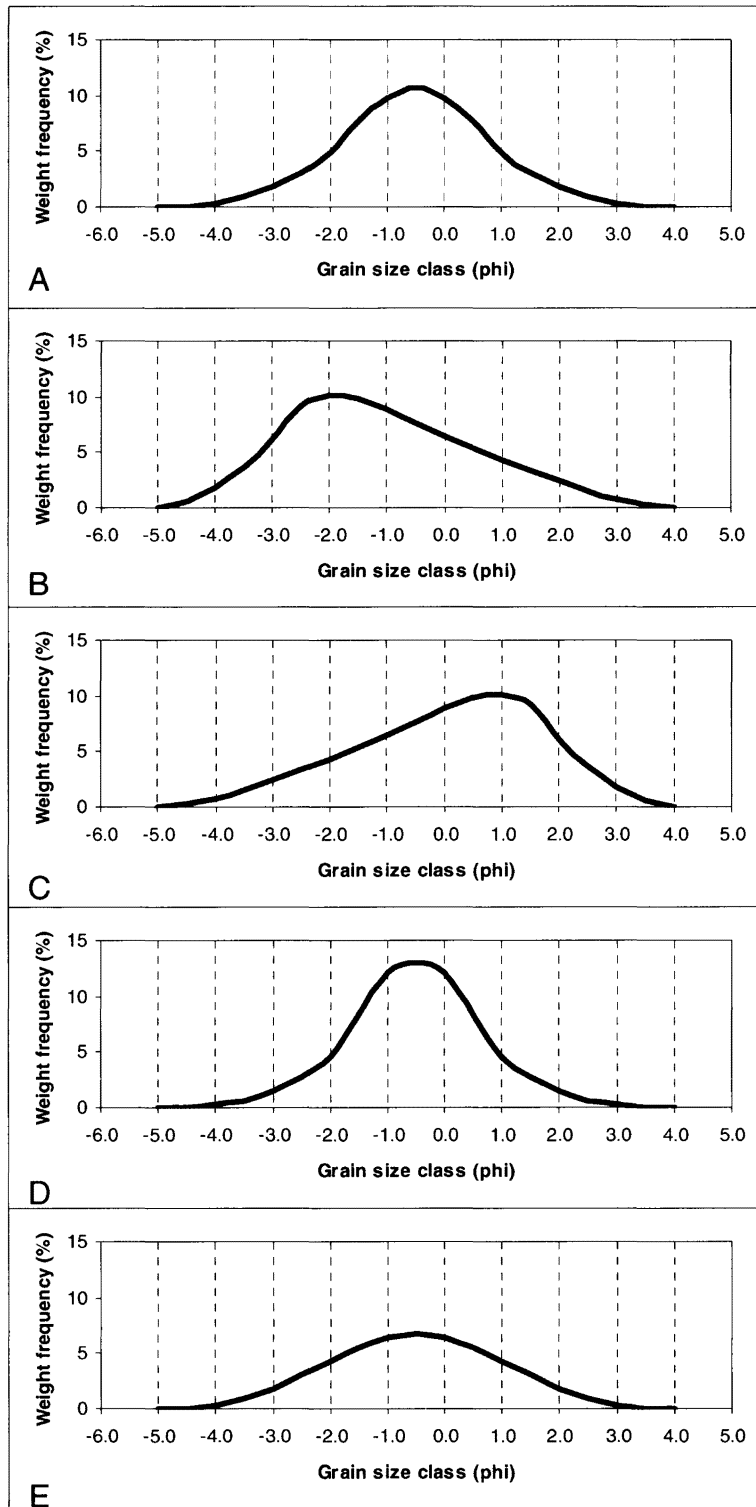


Figure 4.2: Distribution curves for (A) a “normal” sample, (B) a positively skewed sample, (C) a negatively skewed sample, (D) a leptokurtic sample, and (E) a platykurtic sample. See text for further explanation.

Skewness and kurtosis are parameters that describe the statistical distribution of the data relative to a normal (Gaussian) distribution curve (Figure 4.2a). Skewness is a measure of the degree of symmetry in the distribution curve of the sample. A positively skewed sample (Figure 4.2b) contains an excess of fine material when compared with a normally distributed curve. A negatively skewed sample contains an excess of coarse material (Figure 4.2c). Kurtosis refers to the peakedness of the distribution curve and is a measure of the ratio between the sorting of the tails and central portion of the sample. If the central portion is better sorted than the tails, then the curve is excessively peaked, or leptokurtic (Figure 4.2d). If the tails are better sorted than the central portion of the curve, the curve is deficiently peaked, or platykurtic (Figure 4.2e). Strongly platykurtic curves are often bimodal, with a two-peaked frequency curve.

The statistical parameters outlined above can be calculated either by graphical methods (e.g. Folk & Ward 1957) or by the method of moments (e.g. Van Orstrand 1925; Wentworth 1929). The advantages and disadvantages of both have been widely discussed and until recently it has generally been agreed that either method is appropriate, as long as the method used is reported and the weaknesses are recognised and acknowledged (Inman 1952; Middleton 1962; Folk 1966; Lewis & McConchie 1994a). Folk (1966) stated:

Presumably the same geologic conclusions would be reached no matter which method is used, because sample-to-sample variation in most geologic suites is so large as to outweigh precise hair-splitting over details of statistical orthodoxy.

However, Balsillie (2002) argues that graphic measures are not a good approximation to moment measures and that their use should be discontinued now that computers can quickly and efficiently calculate the method of moment parameters. This argument is based on a comparative study of 211 sediment samples (Balsillie *et al.* 2002). Although both methods provided approximate agreement for calculation of the mean, it was found that the graphic method underestimated the moment mean by 0.6Ø. The correlation between the two methods progressively decreased as the order of the moment increased, so that the correlation between methods for standard

deviation was $r^2 = 0.8054$, for skewness was $r^2 = 0.2841$ and for kurtosis was $r^2 = 0.0990$.

Although the method of moments technique is thought to be more mathematically accurate than the graphical method, Folk (1966) identified several disadvantages:

1. Because the method of moments technique utilises the entire data set, not just a few selected percentiles, difficulties arise when the distribution curve is open ended (i.e. containing an unanalysed pan fraction). Assumptions then have to be made about the unanalysed fractions before the parameters can be calculated. With the graphical approach, such assumptions are required only when the pan fraction exceeds five percent weight.
2. Secondly, irregularities in the data due to faults in the sieving equipment can cause distortions in the calculations, especially of the higher order moments of skewness and kurtosis. For this reason, it is wise to plot a cumulative distribution graph no matter which method is being used; as such irregularities are easily identified by a kick in the graph at the same phi value for all samples.
3. The method of moments also assumes that the grains within a given class interval have a centre of gravity at the halfway mark of that class. However, Folk (1966) found that the true midpoint may deviate from this assumption by as much as 0.3ϕ .

The underlying assumption of these statistical parameters, whichever method is used to determine them, is that sediment populations should display normal Gaussian distributions (Figure 4.2a). However, few if any sediment deposits are normally distributed. Balsillie (2002, p.iv) states:

Nor would we wish them to be [perfectly Gaussian], since the deviation from the Gaussian can be interpreted to explain their transdepositional history.

Some deposits show such variation from a normal distribution that the statistical parameters of mean, standard deviation, skewness and kurtosis do not describe the distribution efficiently, as illustrated in Figure 4.3 (Curry 1960; Dias & Neal 1990). In the example shown, both samples have the same mean grain size. However, it can

be seen that there is actually no sediment of the mean grain size present in the bimodal sample. Bimodal sediments are extremely common on mixed sediment beaches; therefore statistical grain size parameters alone are not enough to accurately describe the sedimentary characteristics of the beach (Folk 1966). It has been suggested that description of polymodal sediments by these statistical parameters is of little value for doing more than identifying the gross characteristics of the texture (Curry 1960; Ashley 1978).

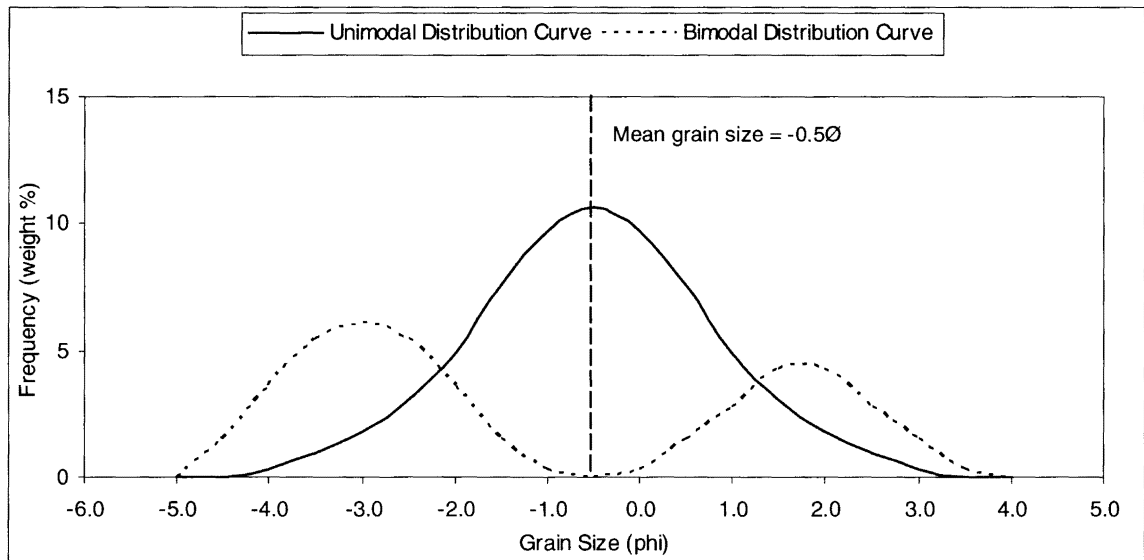


Figure 4.3: Grain size distribution of a bimodal sediment sample (solid line) compared with a normally distributed sample (dashed line). Both samples have the same mean grain size.

In a bimodal sediment sample such as that shown in Figure 4.3, the measures of mean grain size, skewness and kurtosis tell little about the characteristics of the sample due to the wide variation from the Gaussian. Sorting, measured by the standard deviation of the sample about the mean, can be useful when describing bimodal sediments as it gives the phi size range that the majority (67%) of the grains falls between. This can give an indication of how far apart the modes are, i.e. a bimodal sample with modes at -2ϕ and 1ϕ will be better sorted than a bimodal sample with modes at -4ϕ and 3ϕ .

Due to the difficulties of describing bimodal samples with the traditional summary statistics, this study will not use mean grain size, sorting, skewness or kurtosis to interpret the sediments of Gore Bay. Instead, other more suitable methods of sedimentary analysis will be used, as described in the following sections. However, mean grain size and other summary statistics are widely used in the literature and have been used to describe other New Zealand mixed sediment beaches (Kirk 1967;

McLean & Kirk 1969; McLean 1970; Hall 1995; Dawe 2000; Pescini 2000; Jennings & Shulmeister 2002). For these reasons they are provided in Section 4.3.1 as a means of comparison and to describe general trends.

4.2.2 Proportion of sand

Due to the difficulties of describing polymodal sediments using summary grain size statistics, sediment samples are often described by the relative proportions of gravel, sand and mud which make up the sample. These proportions are commonly plotted on a ternary plot (triangular graph), the apexes of which represent 100% gravel, 100% sand and 100% mud respectively, as shown in Figure 4.4. It can be seen from the diagram that the boundaries between gravel classes fall at 80%, 30%, 5% and 0.01% (a trace). The slightest presence of gravel in a sediment sample is considered meaningful, as it reflects the hydraulic environment at the time of deposition (Folk *et al.* 1970). Similarly, by relating such ideas to the conceptual model, a trace of gravel also leads to recognition of source areas.

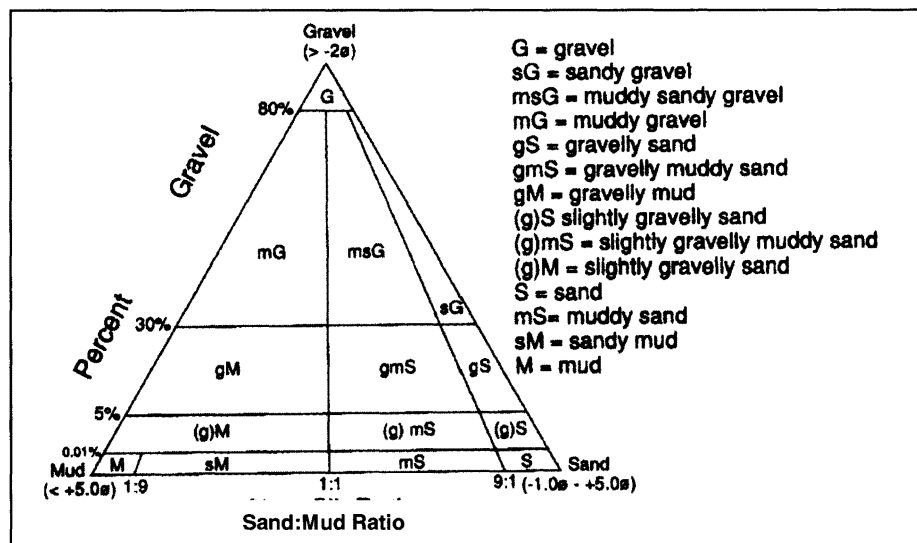


Figure 4.4: Ternary plot for gravel bearing sediments (Folk *et al.* 1970).

Mixed sediment beaches of New Zealand, especially those on the eastern coast, are generally of too high energy for sediment smaller than very fine sand to remain on the beach. Therefore, the ternary diagram described above can be simplified to a simple ratio between the proportion of sand and gravel on the beach. The boundaries suggested by Folk *et al.* (1970) can still be applied to ascertain the classes of gravel (G = <20% sand), sandy gravel (sG = 20-70% sand), gravelly sand (gS = 70-95% sand), slightly gravelly sand ((g)S = 95-99.99% sand) and sand (S = >99.99% sand).

Pescini (2000) used this method when describing the transition between the sand and mixed sand and gravel [sic] beaches of northern Pegasus Bay.

The proportion of sand in a sample can be determined a number of ways (Lewis & McConchie 1994b). The weight of sand sized sediment in a sample can be expressed as a percentage of the total sample weight or a visual estimation can be made of the percentage of sand covering the surface of the deposit. Alternatively, a 10x10 grid can be laid on the surface of the deposit, and the number of nodes which overlie sand, rather than gravel, counted. The results of these methods are likely to yield different results, so care should be taken to express which method is used.

While describing the proportions of different grain sizes present in a sample is a useful way of quickly illustrating the large scale constituents of a sediment sample, it offers little quantitative information on the sizes of individual sediment components within a bi- or poly- modal sample. For example, a bi-modal sample may have modes at -3ϕ (pebble) and -7ϕ (cobble), but would only be represented as one point on the ternary plot, in the gravel category (Figure 4.4). A more quantitative method of determining individual sediment components within a sample is through modal analysis, as described below.

4.2.3 Modal analysis

Modal analysis is based on the idea that in many cases, deviations from normality arise because sediments are often mixtures of two or more components (Curry 1960). Each of the separate components may in itself be normally distributed, but the overall sediment population is not normal.

Modal analysis involves the identification of the modes representing the component populations from the frequency distribution curves of bi- or poly- modal samples (Curry 1960). The geographic distributions of the individual components can then be traced, to provide a greater understanding of the deposit. There has been considerable debate over the construction of frequency distribution curves in relation to the large influence the choice of x-axis scale has on the shape of the curve and therefore its interpretation (Lewis & McConchie 1994a). Krumbein (1934) outlined a method of deriving what he called a unique frequency curve from the cumulative

curve via a method of graphical differentiation using a tangentometer. The unique frequency curve was described as being the integral of its corresponding cumulative curve.

Due to the difficulty in acquiring a tangentometer, Brotherhood and Griffiths (1947) outlined an involved mathematical method of determining the unique frequency curve, whereby the first, second and third differences of the cumulative curve were compared to obtain an approximate derivative. Curray (1960) felt that Brotherhood and Griffiths' (1947) method was too time consuming and so used a less precise method based only on the first differences.

With the advent of computers, Brotherhood and Griffiths' (1947) method is now less time consuming and therefore was used to create unique frequency curves for a selection of sediment samples in this study. Comparison of the unique frequency curves with the frequency distribution curves (created directly from the raw sieve data) showed little variation between the two curves, especially for the purpose of identifying modal peaks (Figure 4.5). It is therefore concluded that for modal analysis, the frequency distribution curve derived directly from raw sieve data is sufficient for identifying modal peaks.

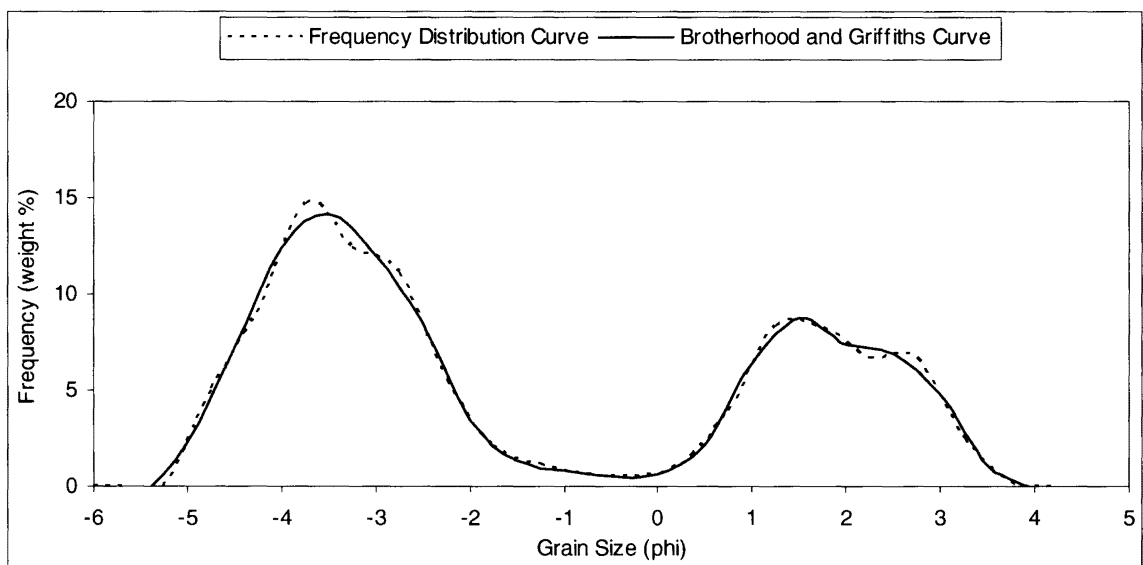


Figure 4.5: Comparison of mathematically derived unique frequency curve (Brotherhood & Griffiths 1947) with the frequency distribution curve derived directly from raw sieve data. The same modal peaks are detected from either curve; therefore the complex mathematical derivation is unnecessary for modal analysis.

From the frequency distribution curve, modes may be identified using a computer program (Van Andel 1973; Dias & Neal 1990). However, Curray (1960) suggested that modes may be approximated ‘by eye’, a method utilised by several studies with considerable success (Dawe 2000; Pescini 2000; Boorer 2002). The solid line in Figure 4.6 is a frequency distribution curve from a study of sediments in the Panama Basin (Van Andel 1973). Van Andel (1973) used a Dupont 310 Curve Resolver to identify six modes from the curve shown. These are identified in Figure 4.6 by the dashed lines annotated with letters. It can be seen that there is a primary mode at 8ϕ (F) and several smaller modes (a, A, C, D and f). It is acknowledged that the modes identified by lower case letters may be due to edge effects or may represent small deviations of the adjacent modes from a true normal distribution. The mode labelled C was identified in order to fill the “shoulder” on the adjacent D mode, however it is acknowledged that mode C may also represent a deviation from a true normal distribution of mode D (Van Andel 1973). When these smaller, spurious modes are removed, one is left with three modes, A, D and F. This is in keeping with the results of visual identification of modes using the method described by Curray (1960).

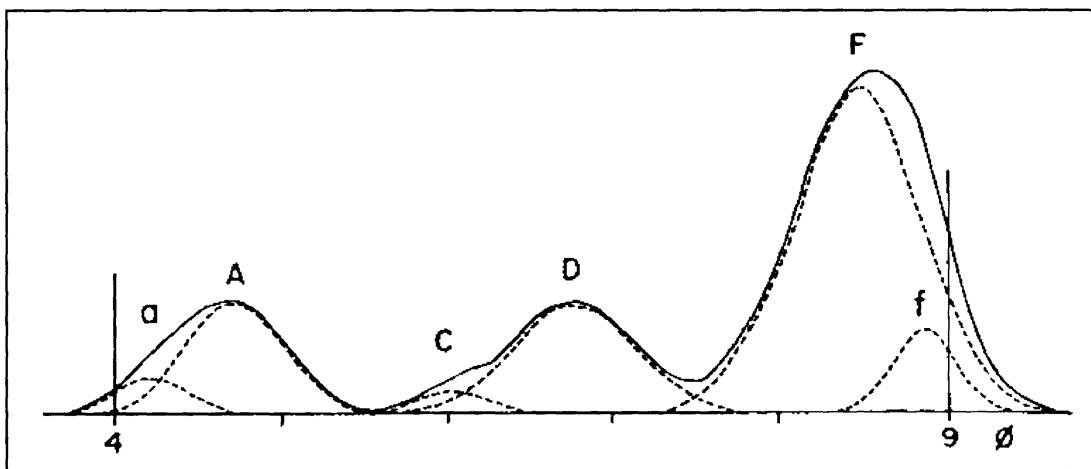


Figure 4.6: Example of mode identification from Van Andel (1973). Solid line is the frequency distribution curve for a sample of $+4\phi$ to $+9\phi$ sized sediments, dashed lines (a through f) are distribution curves for the modes identified. See text for further explanation.

Modal analysis will be used in this thesis to identify discrete sediment populations present in Gore Bay using the visual method of Curray (1960). Used in conjunction with the conceptual framework introduced in Chapter One and the findings of Chapter Three, it is hoped modal analysis will allow the determination of sediment source areas and transport direction in Gore Bay.

4.2.4 Grain morphology analysis

The morphology or form of the individual grains making up a sedimentary unit is also an important textural characteristic. Grain morphology often reveals more about the depositional history of the sediment than grain size and is therefore of equal or more importance than size analysis. Benn and Ballantyne (1993) described particle morphology as a sum of three scale-related properties: shape; roundness; and texture. The latter of these refers to the surface roughness of the individual particles and was not considered in this thesis.

Particle shape

Particle shape (also called sphericity) is commonly described by measuring the long (L), intermediate (I), and short (S) particle axes, which are mutually perpendicular (Figure 4.1). The ratio of the three axes determines the shape of the particle. There are several methods of classifying particle shape data. Benn and Ballantyne (1993) reviewed these methods, concluding that the ternary diagram of Sneed and Folk (1958) provides an appropriate standard method of representing data, without the bias or distortion introduced in some methods.

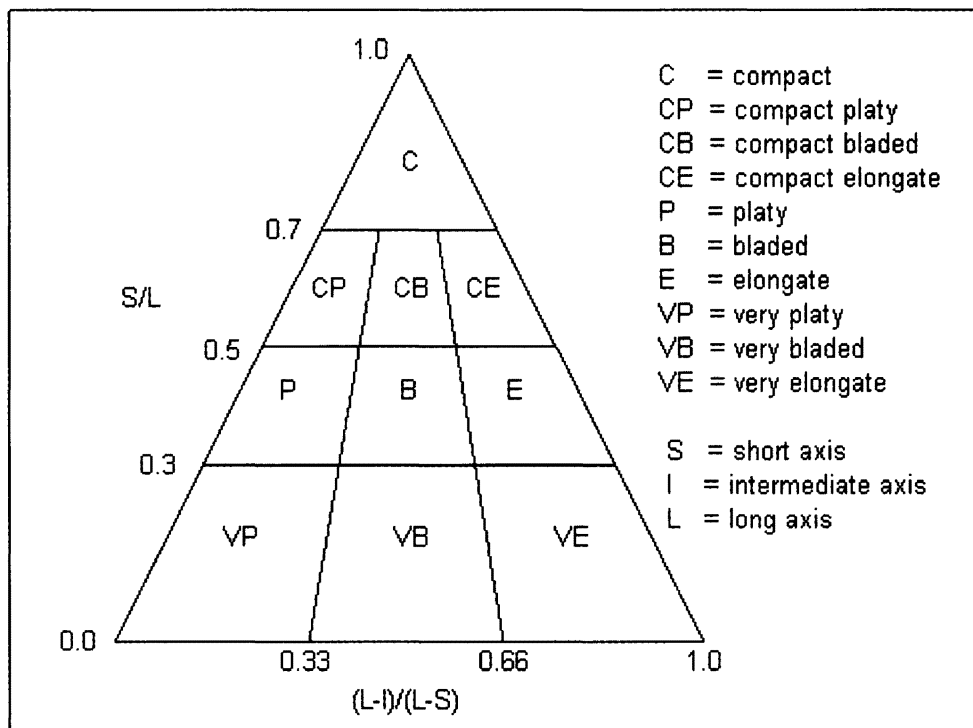


Figure 4.7: Sphericity-form diagram for representing particle shape (after Sneed & Folk 1958).

See text for further explanation of the classes shown.

Particle shape is strongly influenced by the properties a particle inherits from its parent material, such as its internal isotropic characteristics. It is generally believed that little modification to particle shape occurs after derivation from the source (Lewis & McConchie 1994b). However, certain shapes may be concentrated in certain environments, due either to selective sorting or to actual modification of the grain shape by active environmental processes. Beaches generally contain an abundance of platy pebbles, while elongate and bladed shapes are often found in river sediments (Folk & Ward 1957; Dobkins & Folk 1970; Reineck & Singh 1973). This relates back to the conceptual framework of the thesis whereby source area has a first order control over beach materials and hydraulic factors a second order control.

Roundness

Roundness refers to the nature of the edges and corners of a grain, which indicates the degree of abrasion the particle has undergone or its transport history (Lewis & McConchie 1994b). The roundness of gravels is independent of shape and is often dependent on sediment size (Reineck & Singh 1973). Waddell (1933) developed an equation to quantify the degree of particle roundness:

$$\text{Roundness} = \sum \frac{(r/R)}{N}$$

where: r is the radius of the curvature of the grain corners

R is the radius of the largest inscribed sphere

N is the number of corners

A roundness value close to one indicates a very well rounded grain, while a value close to zero indicates a very angular grain. However, difficulty in measuring these parameters for a three dimensional particle means that particle roundness is usually measured qualitatively by visual comparison with silhouette charts (Krumbein 1941). The silhouette chart used in this study is presented in Appendix B.

Roundness is the least indicative texture of depositional environment, as it requires a long history of abrasion to round detrital grains substantially and care must be taken not to confuse the roundness of the particle with its age or the distance it has travelled

from its original source (Lewis & McConchie 1994b). Roundness varies not only with the distance travelled, but also with size, lithology and shape (Bluck 1969).

In coastal environments, the most important characteristics to look for are:

1. trends of changing roundness along shore, which may indicate the direction of transport,
2. marked differences within the local population, such as differences in roundness between grains of the same size and composition, which may indicate unusual histories or multiple sources for the sediment.

4.2.5 Rollability analysis

While textural analysis is a useful tool for describing coastal sediments, it has been noted that the methods are still inadequate in regards to placing the sediment into its proper genetic environment (Winkelmolen 1982). In response to this perceived inadequacy, Winkelmolen (1982) developed a method of analysis based on the functional shape of sediment grains and their ability to roll. Rollability analysis takes into account the independent variables of mass, density and shape; which were suggested to be the fundamental properties controlling the transport and deposition of a particle.

Winkelmolen (1982) found that more equant grains have a higher propensity to roll, while less equant grains had relatively lower rollability. Grains with higher rollability therefore had lower surface to weight ratio and were found to be less transportable due to their reduced susceptibility to drag forces from the transporting medium. Lower surface to weight ratios also result in more friction with the bed, further reducing their transportability. Grains of higher rollability should therefore be found closer to their source than grains with lower rollability.

Rollability is measured in a slightly inclined (2.5°) cylinder which revolves at about 16rpm (Figure 4.8). A small sample of sand (1-2 grams) is placed at the upper end of the inside of the cylinder. As the cylinder revolves, the grains are pulled up the side of the cylinder until they begin to roll. Due to the slight inclination, as the grains roll back down they move on a slight diagonal towards the lower end of the cylinder. The shape of the grain will determine the path it travels and the time it takes to emerge at

the lower end. Grains with a low rollability (more transportable) will travel further up the side of the cylinder before they start rolling, so will occupy a zone higher up the slope than grains of higher rollability (less transportable), which will remain close to the bottom of the cylinder. The more rollable grains will also move more quickly towards the lower end of the cylinder. As the grains emerge at the lower end of the cylinder they are guided by a funnel onto an electronic scale. The time it takes for 50% of the sample by weight to emerge from the cylinder is its rollability.

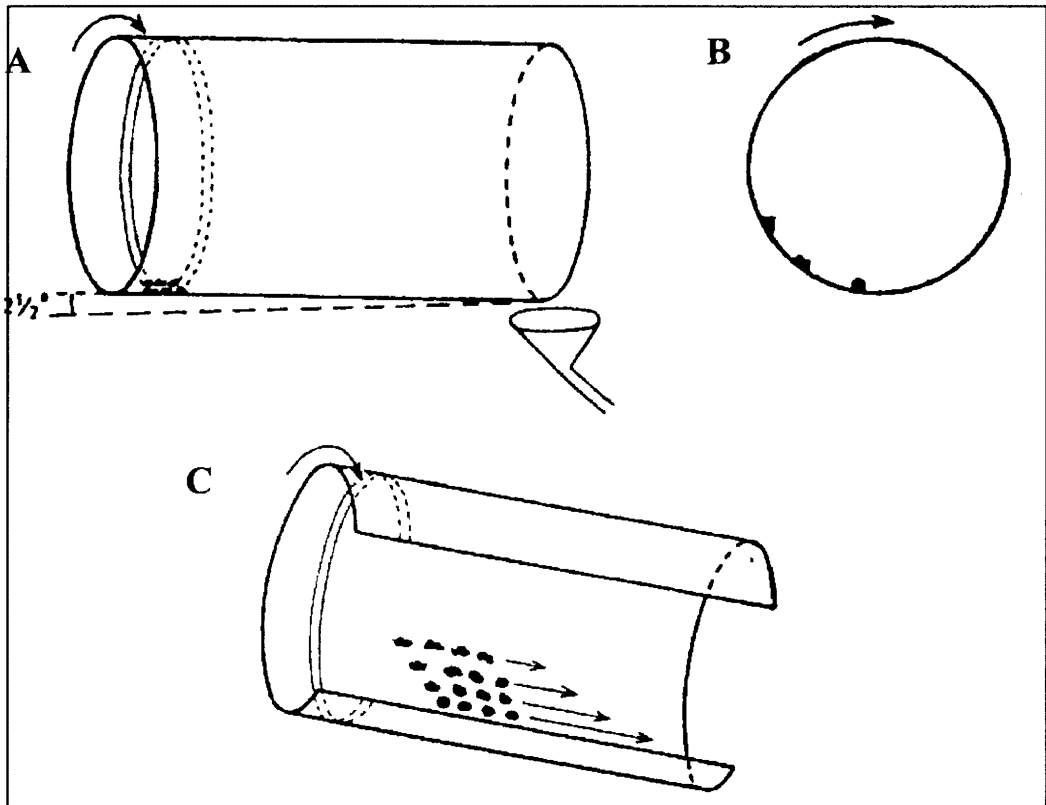


Figure 4.8: A) The configuration of the rollability apparatus. B) Lateral shape selection within the cylinder. C) Shape selection along the length of the cylinder (after Winkelmolen 1969).

One of the major limitations of rollability analysis is that it can only be used for sand sized sediments, as the weight of coarser materials emerging at the end of the cylinder would damage the electronic balance. Rollability analysis can therefore only identify areas supplying sand to the coastal system. On a mixed sediment beach such as Gore Bay, this is a severe limitation, as there is a large amount of sediment too coarse for rollability analysis. It is for this reason that a *multiple sediment analysis* approach has been used for this thesis, so that methods such as rollability, while not appropriate for analysis of the entire sediment population, can still be utilised where appropriate.

4.2.6 Data collection

Thirty-nine samples were taken from thirteen sites along a three kilometre stretch of Gore Bay (Figure 4.9). The selection of sample sites was determined by previous work undertaken at Gore Bay. Environment Canterbury have set up eleven beach profile monitoring sites along Gore Bay, which have also been used as profile sites for beach morphology analysis in this study (Chapter Five). It was decided that sediment samples would be taken from these sites so that the analysis of beach sediments and beach morphology could be related. In addition to these eleven sites, samples were taken from two other sites (H5825 and H5952) to gain a more comprehensive coverage of sediment data for interpolation. The numbering scheme of Environment Canterbury has been retained and refers to the distance north of the Waipara River, in tens of metres. For example, site H5658 is 56.58 kilometres north of the Waipara River and site H5867 is 58.67 kilometres north.

Samples were collected around low tide on the 7th July 2003 and each sample site was photographed prior to collection. At each site, samples of around five kilograms were taken from the fore-, mid- and back- shore, giving 39 sediment samples in total. Foreshore samples were taken from the mid tide water level, midshore samples from the high tide zone and backshore samples from above the highest line of storm debris. Samples were taken from the top 200mm of the beach deposit and taken back to the laboratory for sieve analysis.

Once returned to the laboratory, the sediments were washed and oven dried in preparation for sieving. After drying, each sample was weighed and then mechanically sieved for 15 minutes in a ro-tap sieve shaker. The sieves used in the initial sieving ranged in size from -4Ø (pebble) to -1Ø (granule), at a ½ Ø interval. The weights of sediment retained by each sieve was recorded and calculated as a percentage weight of the entire sediment sample that was sieved. The sizes of sediments that were coarser than the largest sieve aperture were recorded by passing the sediments through a 'gravelometer'. Sediment that was finer than the finest sieve aperture (sand sized sediment) was then weighed and recorded as a percentage of the total sediment sample weight. If the sand fraction was larger than 200 grams, the sample was then split (using a sample splitter) into an appropriate weight for sand

sieve analysis (100-150 grams) and a portion (around 1-2 grams) was set aside for later rollability analysis.

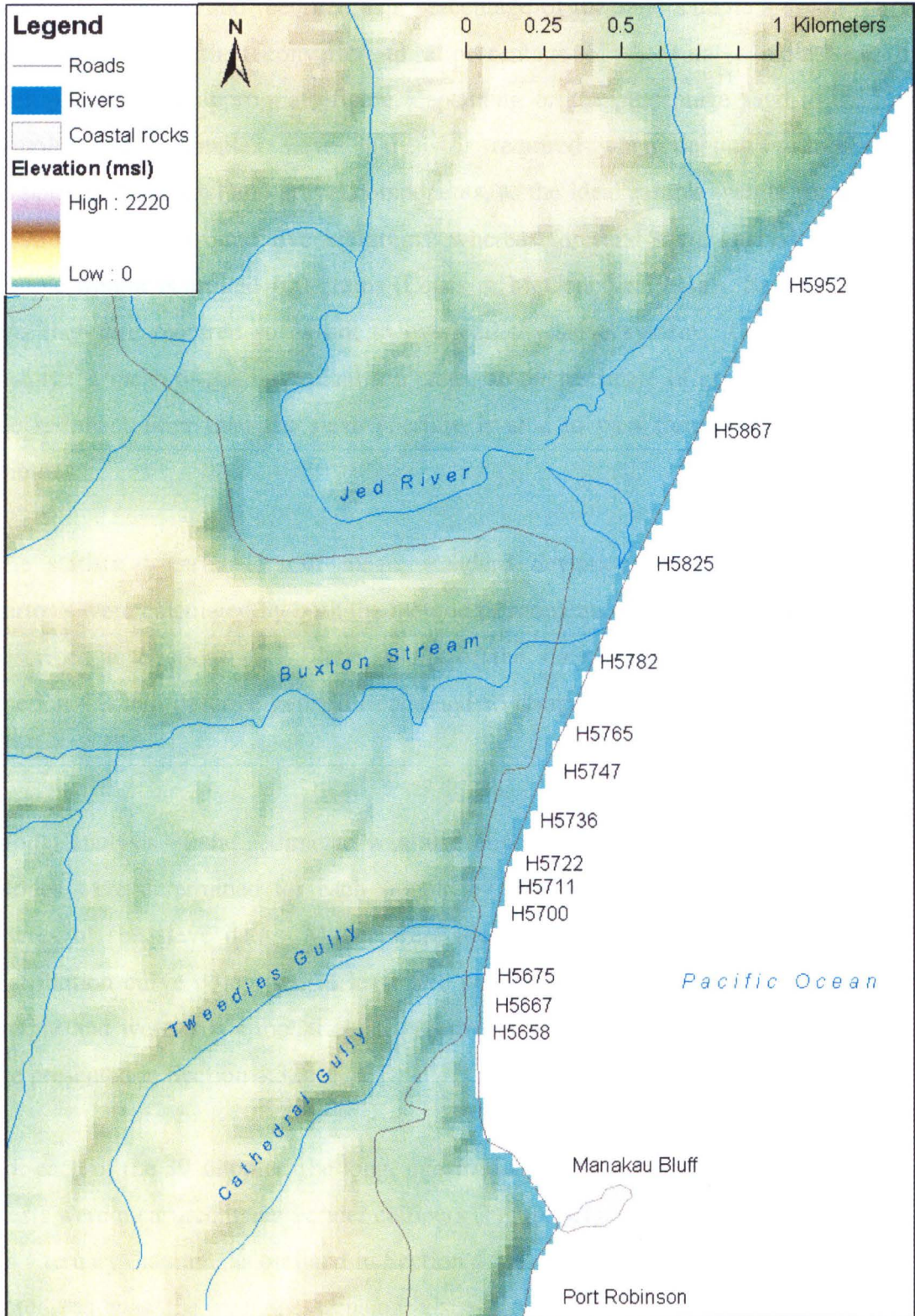


Figure 4.9: Map of Gore Bay, showing sites (H5658 – H5952) where sediment samples were taken from at low tide on 7th July 2003.

The sand sample was then put through a series of sieves at $\frac{1}{2} \phi$ intervals from -0.5ϕ (very coarse sand) to $+4.0\phi$ (very fine sand). The weight of sediment retained in each sieve was weighed and recorded as a percentage of the sand sample sieved. These percentages were then converted to a percentage of the total sample size, by multiplying by an appropriate figure, depending on the percentage sand in the total sample. This complex sieve analysis is required when dealing with samples comprising both sand and gravel components, as the ideal sample weight for a gravel sieve analysis is around five kilograms, whereas for sand sieve analysis, the ideal sample weight is around 100 grams (Lewis & McConchie 1994a). Sample splitting was therefore required so as not to overload the sieve system. Overloading may distort the mesh of the sieves and can cause an overestimate of grain size, as not all the sediment finer than the sieve aperture is able to pass through the sieve in 15 minutes.

The statistical parameters of mean, standard deviation (sorting), skewness and kurtosis were calculated by both the method of moments and graphical techniques, as described in Section 4.2.1. The results of the statistical analysis are reported in Section 4.3.1 to describe general trends and so comparisons can be made with other studies.

Modal analysis of the sediments was also conducted, as outlined in Section 4.2.3. Modes were determined for each sample by examining the frequency distribution curves of the sieve data. Modes were identified where peaks on the frequency distribution curve comprised at least five percent of the entire sediment sample by weight and were part a modal cluster (Curry 1960). The results of modal analysis are presented in Section 4.3.3.

For each of the 39 samples, the long, intermediate and short axes of the thirty largest clasts were measured using vernier callipers (Figure 4.1). This shape data was plotted on a ternary diagram, as outlined in Section 4.2.4. The composition of each clast was noted, as was the roundness, using visual comparison charts (Krumbein 1941). Results from morphological analysis are given in Section 4.3.4.

Rollability was measured using a 1-2 gram sample of unsieved sand. Although many studies measure the rollability of each $\frac{1}{2} \phi$ or $\frac{1}{4} \phi$ fraction and average the rolling times to get a rollability value for the entire sample, it is believed that an unsieved sample provides a more reliable value of rollability. This is because interactions between grains of different sizes are allowed to occur, as they do in nature. Winkelmoen (1982) stated that “it would be far better to omit size as a parameter when we aim at clarifying the processes of transport, selection and deposition of sediment particles”.

For each sample, the time taken for fifty percent of the sample by weight to pass through the rollability apparatus is recorded. The times of all samples are averaged to compute a mean rollability value for the entire suite of samples. The relative rollability for each sample is then expressed as a percentage lower or higher than the mean. Positive values are attached to those samples taking a shorter time to pass through the apparatus than the mean, i.e. those with high relative rollability, and vice versa. Relative rollability values were plotted as a distance north of the southernmost sample site to aid visualisation (Section 4.3.5). Areas of high relative rollability (positive values) indicate source areas, while low relative rollability (negative values) indicates sediment sinks. This is due to poorly rollable samples being more transportable, therefore being selectively eroded from source areas and concentrated in sink areas.

4.3 Sedimentary Analysis

This section fulfils one of the main aims of this thesis: to describe and interpret the nature of the sediments in Gore Bay. A *multiple sediment analysis* approach has been used to achieve this aim, whereby a variety of techniques are used to strengthen conclusions or disprove apparent trends in data which are based on sometimes invalid assumptions.

It is important to note that the following analysis has been undertaken on 39 samples taken from 13 sites along the length of Gore Bay at one point in time (7th July, 2003). It has been discussed earlier in this thesis that hydraulic factors influence the textural characteristics of a beach and therefore the patterns shown by this analysis are likely

to be influenced by the processes which have recently occurred. In the three days preceding collection of sediment samples at Gore Bay, a low pressure system to the south west of New Zealand caused a large southerly swell along the east coast and brought snow to low levels throughout the South Island. At Gore Bay, observed wave conditions during this time were of a solid southerly swell between four and six feet in height (Section 3.3.4). On the day of sampling, observed wave height had decreased to two to three feet and was from an east-north easterly direction. Therefore, any conclusions made on the basis of these results should take into account the post-storm nature of the beach.

4.3.1 Statistical grain size analysis

As discussed in Section 4.2, grain size data was obtained through sieve analysis of 39 sediment samples and plotted as cumulative frequency graphs. Frequency curves for each sample were also created to aid visualisation of sediment size distribution. These graphs are contained in Appendix C. The graphs reveal a large variation in the sedimentary characteristics between the north and south of the bay, which coincides with field observations (Figure 1.2). In the north, samples tend to be unimodal and generally coarser than in the south. In the northern samples there is a general pattern of lateral grading from coarse sediments on the backshore to finer sediment in the foreshore. This across shore pattern becomes complicated in the south, due to the bimodality of the samples.

Both the method of moments and the graphical technique were used to calculate summary statistics of the grain size data, shown in Appendix D. Figure 4.10 shows the results of both techniques plotted against each other. If the two methods gave exactly the same results, the relationship between the two for each of the parameters tested would be a straight line with a gradient of one and an origin through zero. It can be seen from Figure 4.10 that the relationship between the two methods for mean grain size (\diamond) and sorting (\circ) is close to perfect, however there is some scatter. On the other hand, the relationship between the methods for skewness (Δ) and kurtosis (\square) is far from perfect and in fact there is no relationship at all. It is therefore concluded that while either method can be used to calculate the mean and sorting of a sediment sample, the method used to calculate higher order parameters needs careful

consideration. This is in keeping with Balsillie *et al.* (2002), who also found considerable variation between methods for higher order parameters.

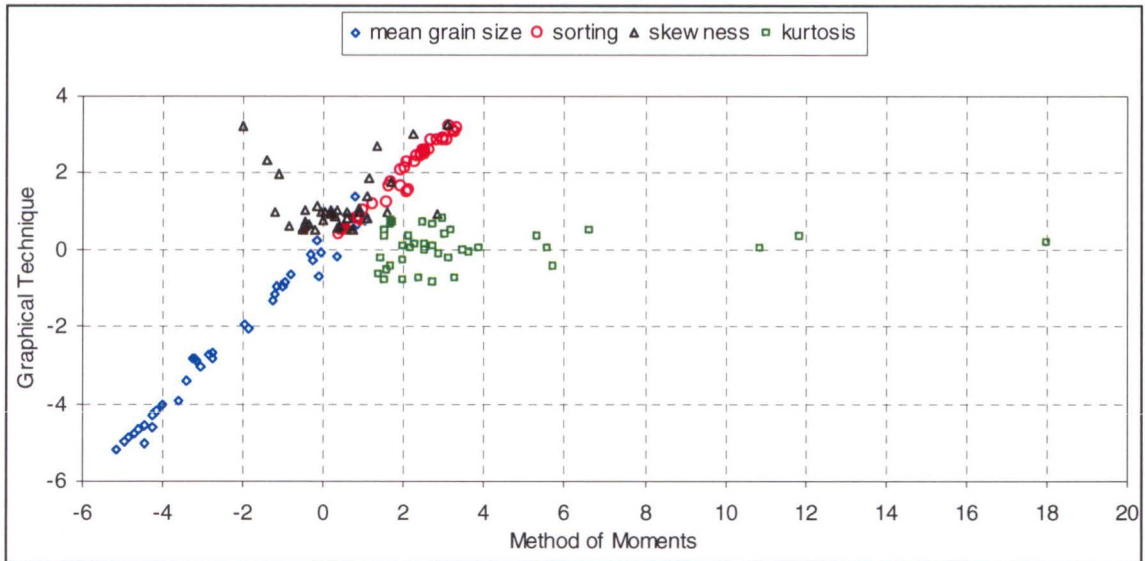


Figure 4.10: The relationship between values gained from the method of moments and graphical technique of calculating summary statistics, using 39 sediment samples from Gore Bay.

The usefulness of these parameters and the errors associated with the techniques have been discussed in Section 4.2.1 and it was concluded that these parameters would be used only to describe general trends, and as a comparative measure for other studies. Due to the wide variation between methods for skewness and kurtosis, these parameters will not be used further in this study. Mean grain size and sorting have been mapped in order to aid visualisation of trends and are presented in the following sections. Despite the fact that the previous discussion has indicated that the method of moments and graphical techniques yield similar results for these two parameters, the method of moments technique has been used, due to the belief that it is more mathematically correct (Blatt *et al.* 1980; Balsillie 2002).

Mean grain size

Figure 4.11 shows the mean grain size of the sediment samples mapped as a distance north of the southernmost sample site (H5658 in Figure 4.9) and as a distance landward of the foreshore sample site, which was taken from the mid tide water line on the 7th July 2003. Data has been interpolated between samples using the Kriging function of the software program Surfer 8.0. It can be seen that mean grain size varies between -6.0ϕ and $+1.0\phi$ and that the dominant pattern is one of across shore variation. For the majority of the beach, the backshore contains the coarsest mean

grain size, while the foreshore contains the finest. This is in agreement with the general trend observed from the frequency distribution curves (Appendix C). This seaward pattern of fining is interrupted only between about 250 and 500 metres from the southernmost sample site, where the mean grain size of the back- and mid- shore samples is considerably finer than elsewhere along the bay.

The mean grain size of the foreshore sediments tends to steadily increase along the bay, from approximately 0ϕ (very coarse sand) in the south to -3.5ϕ (small pebbles) in the north. However, the mean grain size of the backshore sediments decreases from -3.5ϕ (small pebbles) at the very south to $+0.5\phi$ (coarse sand) approximately 500 metres north. North of here, the mean grain size of the backshore sediments increases again, up to -4.5ϕ (medium pebble) by about 900 metres north. North of this, the mean grain size of the backshore sediments stays fairly stable at around -4 to -5ϕ .

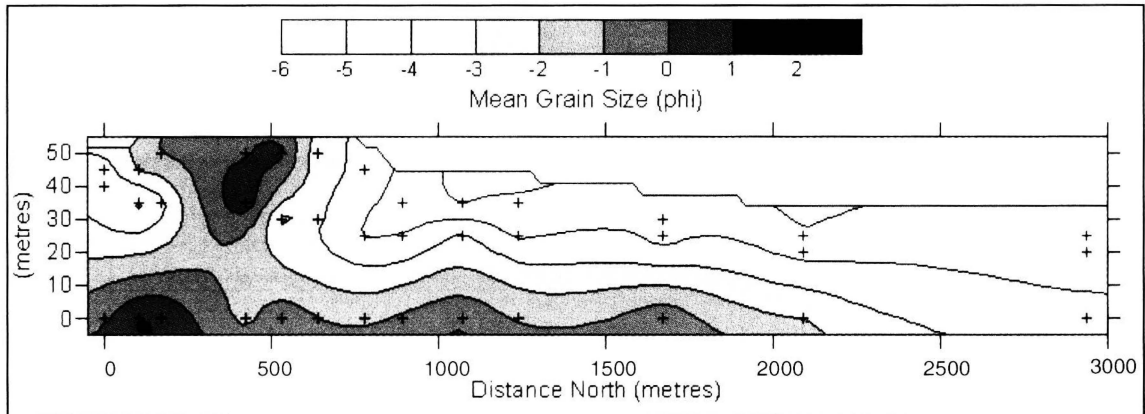


Figure 4.11: Mean grain size distribution contour map. The x-axis represents the distance north of the southernmost sample site (H5658), while the y-axis represents the distance landward of the foreshore sediment sample at each site. Locations of sample sites are indicated by crosses (+).

Sorting

The degree of sorting of a sediment sample is measured by calculating the standard deviation of the sediment distribution. Figure 4.12 shows the variation in standard deviation along Gore Bay, mapped and contoured in the same way as Figure 4.11. The lower the standard deviation, the better sorted the sample. The degree of sorting in Gore Bay ranges from very poorly sorted (3.5ϕ) to well sorted (0.5ϕ). In the north of Gore Bay, the degree of sorting improves from backshore to foreshore, while in the southern part of the bay almost all samples were very poorly sorted ($2.0 - 4.0\phi$) and there are no clear across shore trends.

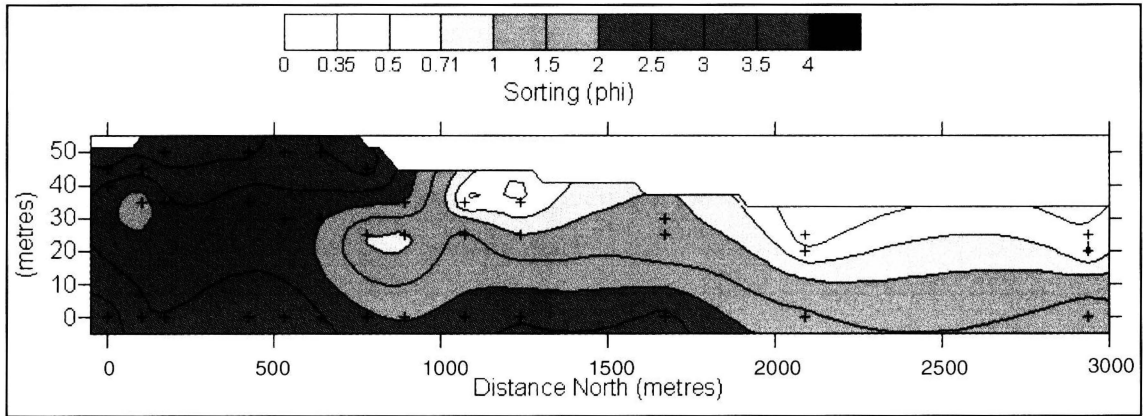


Figure 4.12: Standard deviation contour map. Base map and symbols as for Figure 4.11.

McLean and Kirk (1969) found that mean grain size was the main influence on the degree of sorting on a mixed sand and gravel beach. This can be said to be true of the northern section of Gore Bay, where a seaward decrease in mean grain size corresponds to a seaward decrease in the degree of sorting. It will be explained in the following section that both of these trends can be linked to the proportion of sand present.

4.3.2 Proportion of sand

The proportion of sand was calculated by determining the percentage weight of sand sized sediments in each sample. These were mapped in the same way as mean grain size and sorting, using the Kriging method of interpolation. Figure 4.13 shows that the proportion of sand increases from backshore to foreshore along the majority of Gore Bay, except for the area between 250 and 500 metres north of the southernmost sample site. In this area, the proportion of sand in the back- and mid- shore is much higher than along the rest of the bay. The patterns shown are very similar to the patterns seen in Figure 4.11. The implication of is that a reduction in mean grain size does not necessarily indicate that the sediments are all smaller in size, but simply that the proportion of sand has increased, “dragging down” the mean grain size. This concept highlights the difficulties of using mean grain size to describe mixed sediment beaches.

The darker lines in Figure 4.13 indicate the boundaries between the textural classifications suggested by Folk *et al.* (1970), discussed in Section 4.2.2. It can be seen that the back- and mid- shore samples in the northern two-thirds of the bay can be classified as “gravel” (<20% sand), while the majority of the rest of the samples

fall within the “sandy gravel” classification (20-70% sand), with only small areas of “gravelly sand” (70-95% sand) and “gravel”. Using this classification, Gore Bay can be described as a sandy gravel beach, backed by a gravel ridge in the north. This is similar to the description of Gore Bay given by De Groot (1979, p4) of a “sandy beach backed by a gravel ridge in the north”.

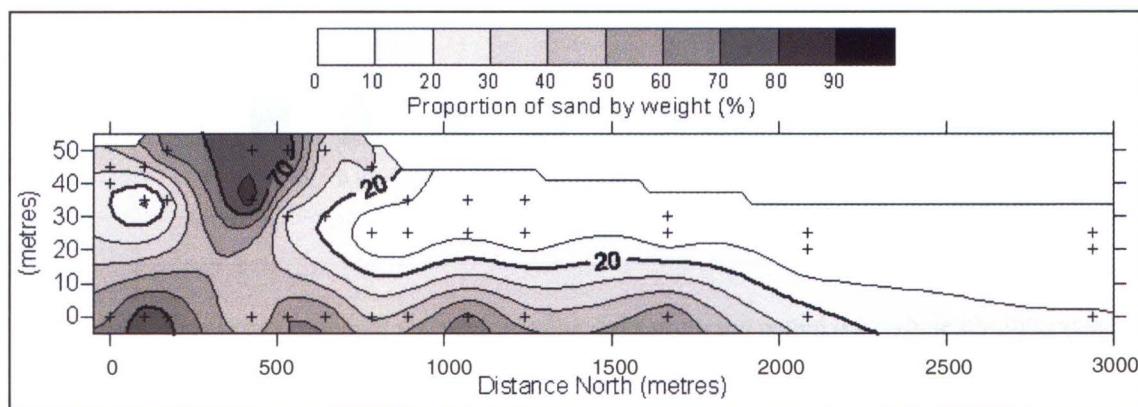


Figure 4.13: Percentage sand contour map of Gore Bay. Base map and symbols as for Figure 4.11.

4.3.3 Modal analysis

Section 4.2.3 introduced the method of modal analysis, concluding that the frequency distribution curves obtained directly from sieve data were accurate enough to allow the identification of modes and that the complex mathematical derivations of Brotherhood and Griffiths (1947) were not necessary. Modes were identified visually from the frequency distribution curves presented in Appendix C. Of the 39 samples taken from Gore Bay for sedimentary analysis, 56% (22) were identified as polymodal and 44% (17) were unimodal.

Figure 4.14 shows the frequency of modes identified from unimodal samples from Gore Bay, grouped into whole phi classes. It can be seen that all unimodal samples have modes between -2ϕ and -6ϕ (small to large pebbles) and that the dominant mode is between -5ϕ and -4ϕ (large pebbles). Figure 4.15 shows the frequency of modes in each phi class from all samples in Gore Bay. It can be seen that while the dominant mode is between -6ϕ and -3ϕ (pebbles), there is a secondary peak between 0ϕ and $+3\phi$ (fine to coarse sand). The dominant sediment populations in Gore Bay are therefore composed of pebbles and medium sand respectively.

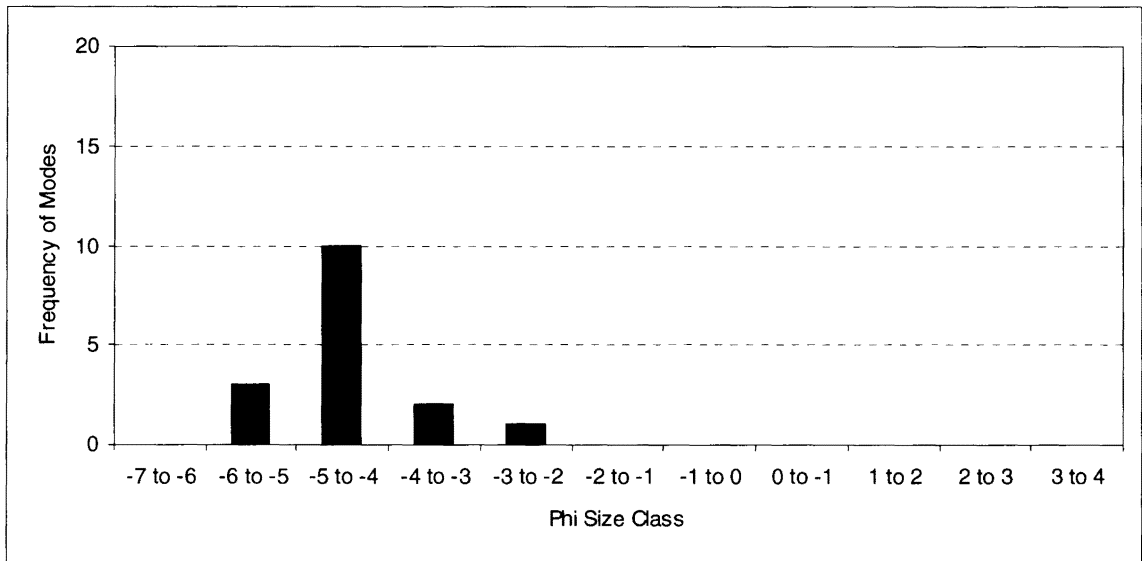


Figure 4.14: Frequency of modal classes for unimodal samples grouped into whole phi intervals.

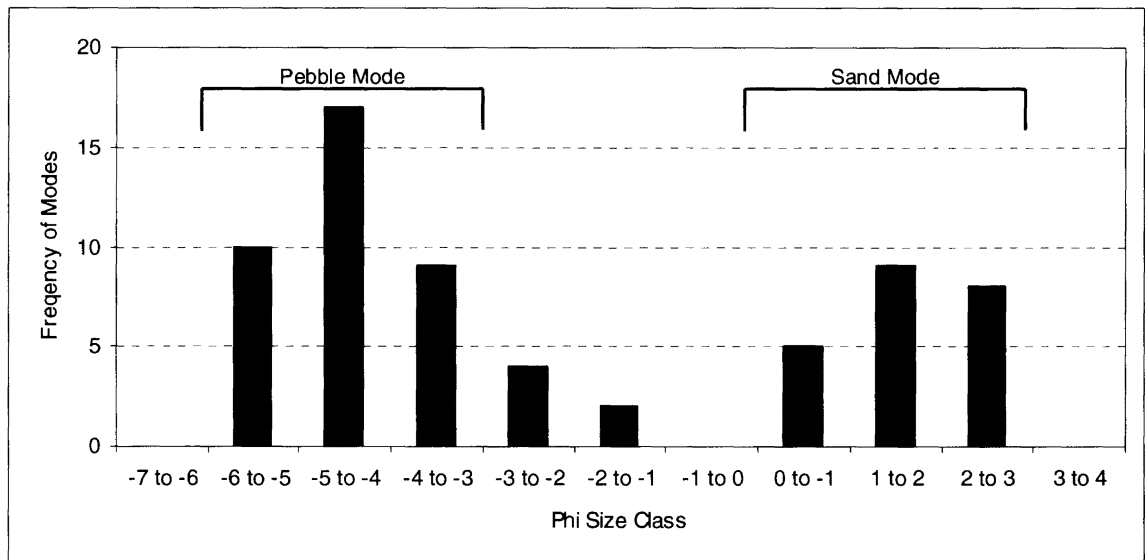


Figure 4.15: Frequency of modal classes for all samples grouped into whole phi intervals. It can be seen that there are two primary modes, a pebble mode (-6 ϕ to -3 ϕ) and a sand mode (0 ϕ to +3 ϕ).

Analysis of the number of modes present in each sample reveals variations along the length of Gore Bay. Eight out of the nine northernmost samples (north of H5872) were unimodal, while 14 out of the 15 southernmost samples (south of H5722) were polymodal. Of the 15 samples taken from the middle of the bay (between H5722 and H5782 inclusive), there was a mixture of uni- and poly- modal samples (see Appendix C). As Figure 4.14 shows that unimodal samples only have modes of pebble sized sediment, it can be surmised that the amount of sand present in Gore Bay decreases

towards the north. This is in agreement with observations (Figure 1.2) and with the analysis of the proportion of sand present in the samples (Figure 4.13).

While general trends of modality can be used to support conclusions made through observations and other methods of analysis, the main reason for modal analysis is to determine the spatial distribution of the different sediment populations, in order to determine source areas and the direction of transport. Figure 4.16 shows the distribution of modal sizes along Gore Bay, distinguished by the position of the sediment sample across shore. The two discrete sediment populations can be easily identified, and are indicated by the boxes within the graph. The pebble mode is present along the entire beach, while the sand mode is present only in the south of the bay.

There is also variation within modes. Overall, the pebble mode is coarser in the backshore than the midshore, which is generally coarser than in the foreshore. It was shown in Sections 4.3.1 and 4.3.2 that the analysis of mean grain size showed a similar variation, but that the validity of mean grain size, and therefore the conclusions made from its analysis, was questioned. However, the repetition of the seaward fining pattern by modal analysis strengthens the earlier conclusion.

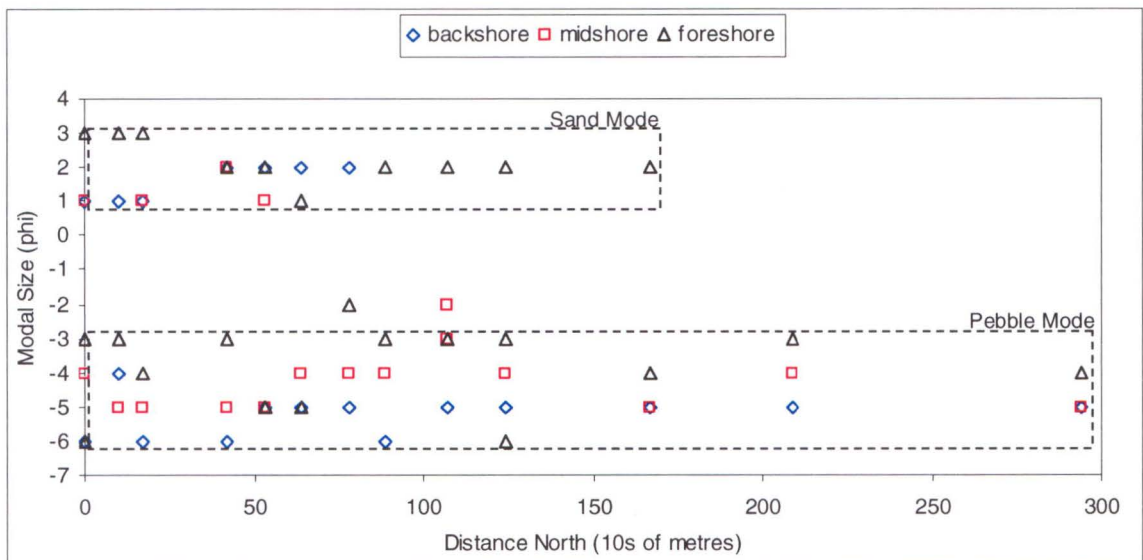


Figure 4.16: The alongshore distribution of modal sizes in Gore Bay.

4.3.4 Grain morphology

Section 4.2.4 introduced the idea that in addition to grain size statistics, the morphology of individual particles is also a significant property of sediments that can be used to help determine source areas and hydrodynamic processes within the coastal environment. This section looks at the shape, roundness and composition of the coarsest gravels present in the 39 sediment samples taken from Gore Bay.

Particle shape

As discussed in Section 4.2.4, sphericity is a measure of the equality of the three axial dimensions of a particle and is commonly plotted on a ternary diagram. Results of the sedimentary investigation into Gore Bay are shown in Figure 4.17. Figure 4.17a shows the sphericity of the 30 largest clasts for all foreshore samples taken from Gore Bay, while b) and c) show the same for the midshore and backshore respectively. Figure 4.18 shows the frequency distribution of clasts in each shape class.

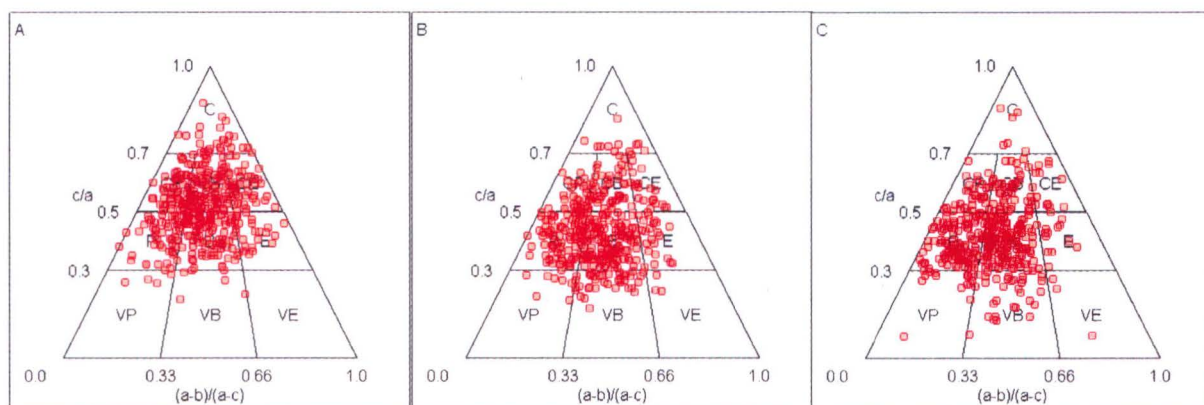


Figure 4.17: Ternary plots of clast shape for a) foreshore sediments, b) midshore sediments and c) backshore sediments (Sneed & Folk 1958). See Figure 4.7 for meanings of abbreviations.

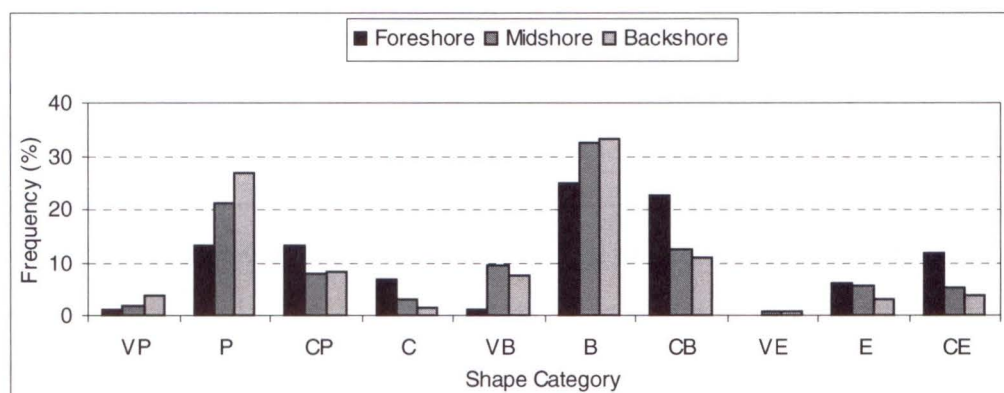


Figure 4.18: Histogram of clast shape data for foreshore, midshore and backshore sediments. See Figure 4.7 for meanings of abbreviations.

From analysis of these figures, it can be seen that while the shape of clasts in the back- and mid- shore are very similar, foreshore sediments show some subtle but distinct differences. The majority of back- and mid- shore clasts tend to be either bladed (B) or platy (P), while the majority of foreshore clasts are either bladed (B) or compact bladed (CB). This is illustrated in Figure 4.17 by a shift of the cluster of samples upwards and to the right.

Concentrations of platy clasts high on a beach have been noted by several authors (Van Andel *et al.* 1954; Bluck 1967; Single & Hemmingsen 2000). One hypothesis for how this occurs is that platy clasts are concentrated high on the beach by selective sorting. Platy shapes are more susceptible to suspension by wave turbulence, so are thrown higher on the beach by waves than more bladed, elongate or compact clasts. Platy shapes are also less susceptible to rolling by backwash, so they remain high on the beach while other more compact clasts roll back down the beach slope (Bluck 1967; Dobkins & Folk 1970; Orford 1975).

Roundness

It was stated in Section 4.2.4 that one of the most important roundness characteristics to look for in coastal environments is a trend of changing roundness alongshore, which may be used to infer the direction of sediment transport. To investigate if any such trends were present in Gore Bay, average roundness values were calculated for each sample and plotted as a distance north of the southernmost sample site (Figure 4.19). Average roundness for all samples fell between 0.64 and 0.76, and showed a slight trend of increasing roundness to the north. There were no discernable trends in average roundness values across shore. This may indicate a northwards transport direction for the gravels; however the trend shown is not strong enough for this to be a solid conclusion.

Another important characteristic to look for is unexpected differences within the local population, such as differences in roundness between grains of different sizes, which may indicate unusual histories or multiple sources for the sediment (Lewis & McConchie 1994b). Analysis of the data showed no such trends, although this may be due to the fact that only the thirty largest clasts were sampled, meaning that in many samples there was not a large size range for which to determine any trends.

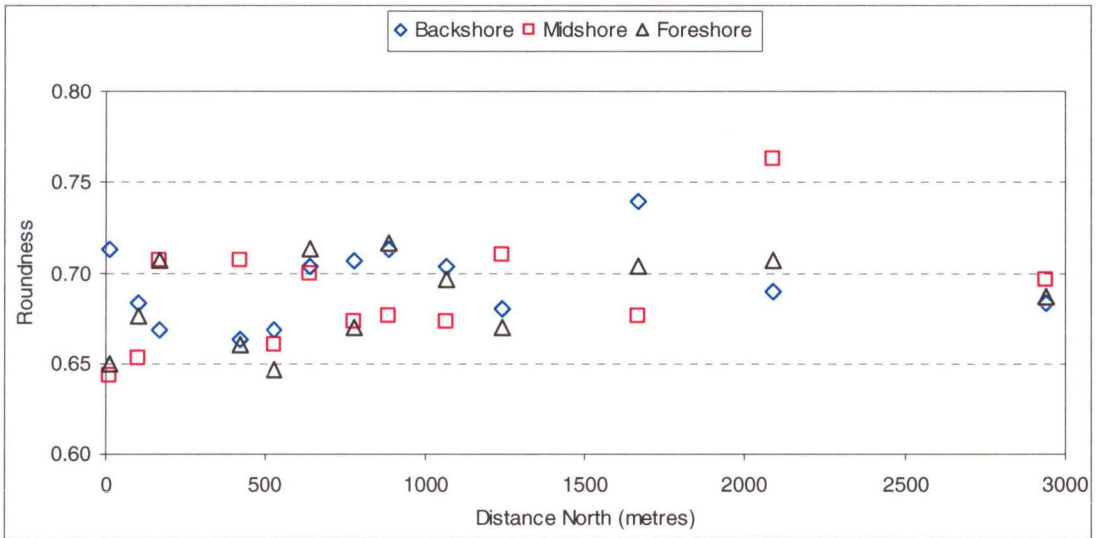


Figure 4.19: Average roundness of the thirty largest clasts in each sediment sample, differentiated by sample position. Scale of roundness is based on the silhouette comparison chart of (Krumbein 1941), shown in Appendix B.

Composition

The majority of clasts in Gore Bay are indurated sandstones of the Torlesse Super Group, commonly known as greywacke. However, there are also minor populations of chert (red and green), limestone (Amuri), siltstone (Greta) and glauconitic sandstone (Waipara) present on the beach. In general, subordinate lithologies were less common in the north of the bay, indicating that these clasts are derived from the outcrops of Manakau Bluff. Several clasts of limestone and siltstone were significantly bored, indicating a long residency period underwater. It is suggested that these clasts have come from the reef extending off Manakau Bluff. Sand samples from Gore Bay are quartzo-feldspathic, with high shell content and some lithic fragments.

4.3.5 Rollability

Rollability analysis was conducted on 33 of the 39 sediment samples taken from Gore Bay. The remaining six samples did not contain enough sand sized sediment to undertake rollability analysis. The samples for which no analysis was completed were H5952-B, H5952-M, H5867-B, H5867-M, H5782-B and H5765-B, all of which contained 0.01% sand by weight or less.

The values gained through relative rollability analysis were mapped and contoured using the Kriging function of the Surfer 8.0 software program, as shown in Figure 4.20. Negative relative rollability values indicate that a particle is more easily transported and positive values indicate less easily transportable particles. Therefore, sediment sinks are shown by negative relative rollability and sediment sources by positive relative rollability. The direction of sediment transport is inferred as occurring from source areas to sink areas, as selective transport removes the less rollable (more transportable) grains from the source area, concentrating them in the sink area.

It can be seen in Figure 4.20 that there are two main source areas (positive) and two main sink areas (negative) within Gore Bay and that the main pattern seen is one of across shore variability. In the southern two-thirds of the bay, foreshore samples tend to be less rollable than midshore samples. This indicates a movement of sand from the midshore to the foreshore. It is likely that the sand may have moved even further offshore, however without nearshore samples, this cannot be confirmed. This pattern may be related to the fact that sediment samples were taken shortly after a period of large southerly swells in Gore Bay (Section 3.3.4). The response of a beach to storm conditions involves a complex relationship between processes, sediments and morphology and will be discussed further in Chapters Five and Six.

Another small but important feature shown in Figure 4.20 is the gradient from the source area in the central midshore of the bay, to the small sink area in the southern backshore of the bay, indicating a landward movement of sediment. This sink area corresponds to the area of backshore containing a high proportion of sand (Figure 4.13). It seems unlikely that sand would be deposited by wave action in this area, as only the largest storm waves reach the backshore, which would tend to concentrate larger clasts rather than sands. A more likely scenario is that this sand has been deposited by aeolian processes. This conclusion is supported by observations of incipient dunes forming amongst the marram grass and ice plant in the backshore in this area. North easterly winds are frequent in Gore Bay (Section 3.3.2) and during low tides the midshore area is often dry enough to allow erosion of sand by the wind.

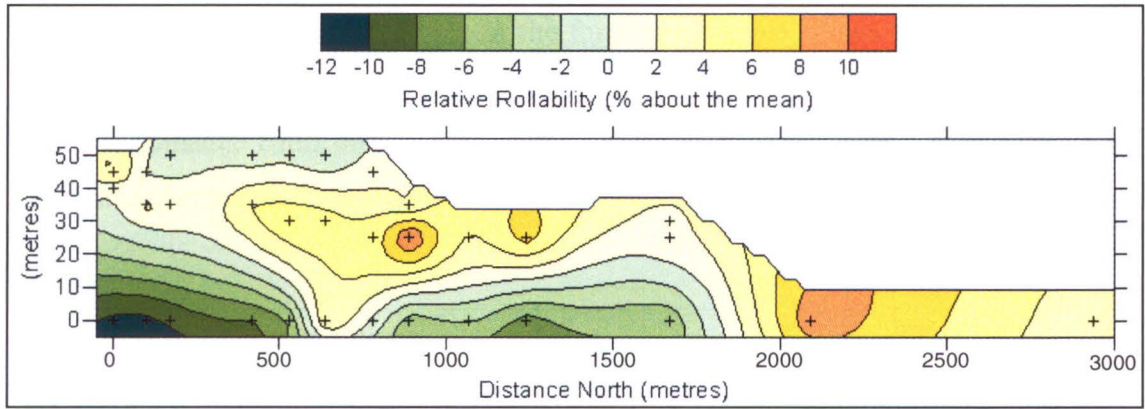


Figure 4.20: Relative rollability contour map. Base map as for Figure 4.11.

Rollability analysis can also be used to determine whether possible sediment sources provide sediment to the coastal system. It was noted in Chapter Three that possible sources of sediment to the Gore Bay coastal system included the Jed River and Buxton Stream, the Tweedies and Cathedral gullies, the conglomerate facies in Manakau Bluff and perhaps some finer sediment from longshore transport, from either the Hurunui River to the south or the Waiau River to the north.

The Jed River mouth is located approximately 1700 metres north of the southernmost sample site. Relative rollability values in the back- and mid- shore are slightly positive, indicating that the Jed may supply some sand to the system. The mouth of Buxton Stream is located approximately 1400 metres north of the southernmost sample site. The back- and mid- shore in this area also show positive relative rollability values.

The Tweedies and Cathedral gullies are located approximately 300-400 metres north of the southernmost sample site and show negative relative rollability values in the backshore. This is due to the presence of wind blown deposits, as explained above. As samples were not taken directly from the outlets of these stream beds, it is unknown whether or not they supply sand to the coastal system. However, due to the ephemeral nature of the gullies, it is unlikely that a significant contribution is made.

Manakau Bluff forms the southern boundary of Gore Bay and meets the beach approximately 100 metres south of the southernmost sample site. If the bluff were a supplier of sand to the coastal system, relative rollability values in the southernmost sample site would be positive. The back- and mid- shore samples in the very south of

the bay are slightly positive, however the foreshore sample shows extremely positive relative rollability, explained above. Although mainly comprised of siltstones and gravels, Manakau Bluff does contain some sandstone and may supply a small amount of sand to the beach.

4.4 Temporal Variations

The results presented in Section 4.3 have dealt with variations found between samples taken from Gore Bay at one point in time. However, one of the major features of Gore Bay is the temporal variation in sedimentary characteristics. For example, local residents will tell that the southern end of the bay near the village is generally much sandier during the summer than the winter and that the passage of a storm along the east coast of New Zealand will result in a lot more gravel being present on the beach (Sorenson 2003, pers. com.).

While the results presented in the preceding sections are still useful for understanding the origin and nature of the sediments within Gore Bay, it is likely that the trends and relationships shown may not be present at all times. This is especially true of the patterns shown by rollability analysis, which are proposed to be the result of preceding wave conditions, rather than a permanent feature of the beach sediments.

It was shown in Figure 4.16 that there are two main sediment populations within Gore Bay, a pebble mode and a sand mode. At the time of sampling, the pebble mode was present along the entire length of Gore Bay, while the sand mode was only found in the south. However, it was obvious to the author during visits to the field area that the distribution of sand varied temporally as well as spatially. It is hypothesised that the distribution of sand and gravel is linked to variations in the process environment and morphology of the beach as per the process-response model (Krumbein 1963).

Because time restrictions prevented regular repetition of the sedimentary analysis techniques described in Section 4.3, a more qualitative method of describing the sedimentary characteristics of the beach was adopted. This involved photographing the beach from a vantage point above the village whenever the author visited Gore Bay. The distribution of surface sediments could clearly be seen in these

photographs, as shown by the light (sand) and dark (gravel) areas in Figure 4.21. By taking numerous photographs from the same vantage point throughout the study period, temporal changes in the distribution of the sand and gravel can be tracked and linked to changes in beach morphology and the process environment. This is undertaken in the following chapter.



Figure 4.21: Distribution of sand (light coloured) and gravel (dark coloured) along Gore Bay, June 13th 2003.

4.5 Chapter Summary

Chapter Four has reviewed various methods of interpreting beach sediments, concluding that a multiple analysis technique is best for mixed sediment beaches. This is due to the uncertainties and limitations of various sedimentological techniques when dealing with a wide range of sediment sizes.

Thirty nine sediment samples were taken from Gore Bay and sieved to determine frequency distribution curves for each sample. Both the graphical technique of Folk and Ward (1957) and the method of moments technique (Van Orstrand 1925) were

used to calculate the summary statistics for each sample, however it was found that while both methods gave similar results for mean grain size and sorting, there was no relationship between the two methods for skewness and kurtosis. Due to the inconsistencies between these methods and the irrelevance of mean grain size for a largely bimodal sediment population, these statistics were not used to interpret the sediments of Gore Bay. However, they were provided as a means for comparison to other studies which have used summary statistics to describe mixed sediment beaches.

The proportion of sand was determined for each sample, and it was found that the majority of Gore Bay is comprised of sandy gravel, although the back- and mid- shore in the north of the bay is almost pure gravel. Two discrete sediment populations were identified through modal analysis, a pebble mode with a peak at around -5ϕ and a sand mode with a peak around $+1\phi$. The pebble mode was present along the entire length of Gore Bay and tended to be coarser in the backshore than the foreshore. The sand mode was only present in the southern portion of the bay at the time of sampling. Modes were determined by eye directly from the frequency distribution curves calculated from the raw sieve data. It was shown that these simple methods gave the same results as more complex methods of curve derivation and mode identification (Brotherhood & Griffiths 1947; Van Andel 1973; Dias & Neal 1990).

Analysis of the shape, roundness and composition of the thirty largest clasts in each sample showed that bladed clasts are the most common, with back- and mid- shore samples also having a high proportion of platy clasts. Foreshore samples did not have such a concentration of platy clasts, due to the way in which clasts of different shapes are entrained and deposited in the swash zone. There was a slight trend of decreasing roundness with distance northward along Gore Bay. While this could be indicative of a northward transport direction for the gravels, the trend shown was very slight and needs confirmation through some other means to be validated. The gravels of Gore Bay are predominantly Torlesse greywacke, although several subordinate lithologies are also present, sourced from the Manakau Bluffs and associated reef. A northward reduction in the number of non-Torlesse clasts supports the conclusion that gravels are transported northwards in Gore Bay.

Rollability analysis of the sand population in Gore Bay found that sand moved from the midshore to the foreshore. However, due to the post-storm nature of the beach at the time of sampling, it is believed that this pattern simply shows the response of the beach to the storm conditions, rather than permanent patterns of sand transport. This belief will be further discussed in Chapters Five and Six when beach response to changes in the process environment is investigated. Due to the large imprint of recent storm activity on rollability values, the determination of source areas to the beach was unable to be quantified through rollability analysis.

In addition to the findings summarised above, Chapter Four also investigated temporal and spatial variations in the distribution of sand and gravel along Gore Bay through photographic analysis. Results of this investigation are presented in Chapter Five, where they are linked to changes in beach morphology and the process environment.

CHAPTER FIVE

BEACH MORPHOLOGY

5.1 Introduction

This chapter addresses one of the main objectives of this thesis: to describe and interpret the beach morphology of Gore Bay. In Chapter One it was recognised that beach morphology is the ultimate response element of the coastal system, affected by the textural properties of the beach materials, which in turn are dependent on source area characteristics and hydraulic factors (McLean & Kirk 1969). Therefore, it is important to examine spatial and temporal variations in beach morphology.

The analysis of beach profiles has long been used as an effective means of describing changes in beach morphology and is one of the most direct and accurate methods of assessing geomorphic changes on the shore face (Gorman *et al.* 1998). Variability in cross shore elevation patterns and volume change is revealed by repeated surveys of the same profile, while differences between adjacent profiles can be linked to alongshore variation in sediments and processes. With a long term monitoring program, seasonal variations and the impact of storms can be identified. In addition to being fundamental to understanding the morphodynamics of beaches, the spatial and temporal behaviour of the beach profile has direct application for beach nourishment projects and the siting of coastal structures (Larson & Kraus 1994).

Changes in beach morphology are also important for coastal management. It is change in beach shape and position which results in damage to property and concern about erosion by residents, local and regional authorities. Beach morphology changes in response to the ever variable wave conditions. These short term changes typically involve large quantities of sediment and result in large variations in beach height, width and slope. By repeated surveying of beach profiles, it is possible to define the *envelope* which contains the range of forms taken by the beach. In the longer term, there may be a displacement of this short term *envelope of change* in a landward or seaward direction, indicating erosion or accretion respectively (Kirk 1982).

Often, coastal hazards arise when assets are located within the envelope of change. The “erosion” that threatens the assets is not actual erosion (i.e. a permanent loss of material from the shore) but is simply the beach adjusting naturally within its envelope of change. The determination of the envelope of change for a beach is therefore a necessary part of any coastal investigation.

5.2 Data Collection and Treatment

Environment Canterbury has set up eleven beach monitoring sites along Gore Bay, where beach profiles have been measured annually since 1993 (Figure 5.1). The location and details of the benchmarks are described in Appendix E. The benchmarks are referenced to the 1937 Lyttelton Datum (hereafter datum) which is approximately 1.1 metres below mean sea level (Land Information New Zealand 2003). It can be seen from Figure 5.1 that profile sites are concentrated in the southern portion of the bay, near the township. It was deemed logical that profiles measured for this study would be taken at the same sites so that comparisons with the yearly profile data could be made. This thesis has retained the profile numbering system used by Environment Canterbury, shown in Figure 5.1, which relates to the distance north of the Waipara River.

Environment Canterbury supplied data from the annual surveys of the eleven profile sites. The profiles were surveyed twice in the initial year of data collection (1993), once in May and again in December. Data from all the other years was collected in December, up to and including December 2002. Environment Canterbury also supplied survey data from profiles surveyed in 1934 (H5667 and H5675), 1936 (H5736 and H5747) and 1948 (H5700, H5722, H5736 and H5747).

In addition to the annual survey data, the eleven profiles were resurveyed at approximately monthly intervals, from February to September 2003 inclusive. At one of the sites (H5867) the data from the May 2003 survey was omitted due to operator error. Surveys were completed using a Sokkia 4B total station theodolite and prism staff. The profiles extended from the Environment Canterbury benchmarks (in the backshore) as far seaward as safety permitted, usually to around one metre below datum.

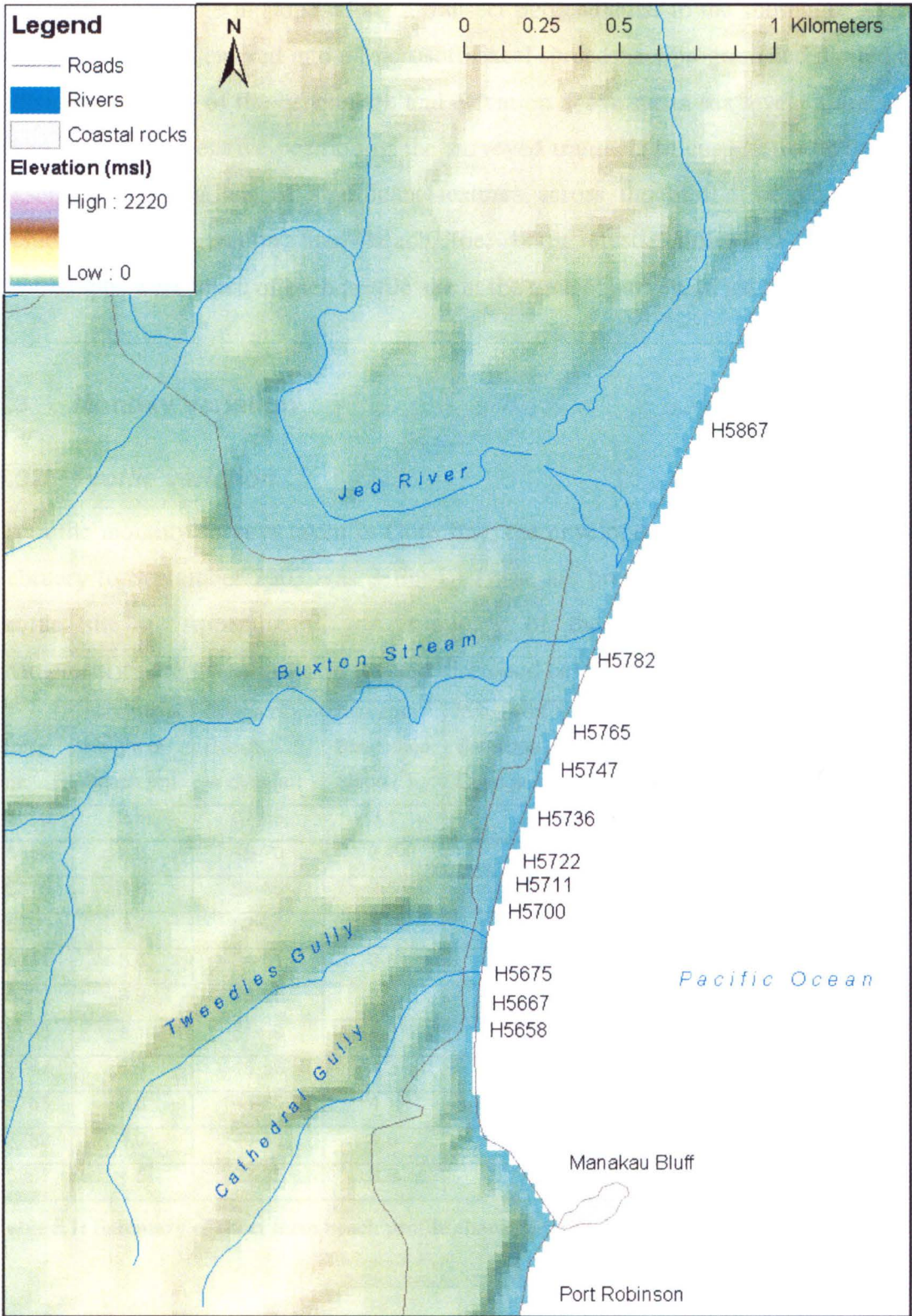


Figure 5.1: Location of beach profile sites, set up by Environment Canterbury, and utilised in this thesis. Descriptions of benchmarks can be found in Appendix E.

Measurements of the distance and elevation relative to the benchmark were taken at every (major) change in slope, along a transect perpendicular to the shoreline. Once collected, data was entered into a Microsoft Excel spreadsheet program and plotted as a distance seaward of the benchmark and elevation above mean sea level. Care was taken to note the relative position of the surveyed transects to cusp horns or bays if present. The locations of significant features across the profile were recorded, including the vegetation line, beach toe, berm crests, driftwood lines, etc. Photographs were taken of each profile site at the time of survey, to aid interpretation.

5.3 Monthly Variation

5.3.1 Profile variation

From the monthly surveys taken in Gore Bay, the envelope of change for the period February to September 2003 was defined. These are presented graphically for each profile site in Appendix F. A summary of the short term morphological characteristics are given in Table 5.1 and discussed below.

| Profile Site | Maximum Height of Beach (m) | Range of Beach Widths (m) | Average Beachface Slope (°) | Volume of Envelope of Change (m ³ .m ⁻¹) | Maximum Horizontal Excursion (m) | Maximum Vertical Excursion (m) |
|--------------|-----------------------------|---------------------------|-----------------------------|---|----------------------------------|--------------------------------|
| H5658 | 2.8 | 37-65 | 3.1 | 22 | 0.7 | 28 |
| H5667 | 2.8 | 48-70 | 2.7 | 22 | 0.8 | 22 |
| H5675 | 3.6 | 54-66 | 3.5 | 17 | 0.7 | 16 |
| H5700 | 3.4 | 52-65 | 3.2 | 14 | 0.8 | 13 |
| H5711 | 3.6 | 54-61 | 3.6 | 20 | 1.0 | 10 |
| H5722 | 3.9 | 55-66 | 3.7 | 28 | 1.2 | 14 |
| H5736 | 4.1 | 51-59 | 4.3 | 24 | 1.1 | 11 |
| H5747 | 3.9 | 45-58 | 4.3 | 25 | 1.1 | 14 |
| H5765 | 3.6 | 45-55 | 4.1 | 21 | 1.0 | 10 |
| H5782 | 4.0 | 40-59 | 4.6 | 24 | 0.9 | 19 |
| H5867 | 4.5 | 23-35 | 8.8 | 17 | 1.3 | 13 |

Table 5.1: Summary of short term beach profile characteristics, listed from south to north.

Profiles in the south of the bay (H5658 to H5747) are backed by a scarp which rises more than three metres above the backshore. This scarp has been cut into the dune field on which the village has been developed. The scarp is vegetated and has not changed position throughout the study period. Any changes in scarp position shown

in the graphs are due to placement of the survey staff within the vegetation at the base of the scarp.

The maximum height of the beach varied between 2.8 and 4.5 metres above datum and generally increased to the north. Beach width was measured as the horizontal distance between the beach toe and where the profile crossed zero datum. Due to the changing nature of the beach profiles, beach width varied by approximately 10 to 30 metres at any one site. The average beach width generally decreased to the north. The northernmost profile (H5867) was significantly narrower than all the other profiles, with the maximum width being 35 metres, which is smaller than the narrowest of all other profiles.

Beachface slope was measured as the average slope between the highest storm berm and where the profile crossed zero datum. In general, southern sites had shallower profile slopes than those sites to the north. Once again, the northernmost profile (8.8°) was significantly different to the other profiles ($2.7 - 4.6^\circ$). The majority of profiles are concave upward in appearance.

The volume of sediment contained within the envelopes of change within Gore Bay was calculated for that part of the profile above zero datum. However it must be noted that there was significant variation in profile shape and position below this level due to the presence of nearshore trough and bar systems. This arbitrary level was chosen because not all surveys extended deeper than zero datum. The volume of the beach envelopes for the eleven sites ranged between 14 and 28 cubic metres per metre of beach ($\text{m}^3 \cdot \text{m}^{-1}$), with no clear alongshore pattern. Maximum horizontal excursion refers to the greatest distance in a horizontal plane between the upper and lower bounding surfaces of the beach envelope. Maximum vertical excursion refers to the greatest vertical difference between the bounding surfaces of the envelope. Horizontal excursion was generally lower for those profiles in the centre of the bay, while vertical excursion generally increased to the north.

Through analysis of beach profiles on a survey by survey basis, it was found that there were no clear seasonal trends in beach profile response in Gore Bay. In the south of the bay, winter profiles tended to contain less volume than summer profiles, however

this pattern was not seen at all sites. Instead, profile shape and volume seemed to vary with changes in the process environment, as described in the following section.

5.3.2 Beach response to wave conditions

The previous section has outlined the variability in profiles at Gore Bay between January and September 2003, but the pressing concern to those involved in managing the beach is what drives the variability and whether there is a change in the position of the beach envelope in the long term. Chapter Three described the process environment within Gore Bay and outlined the variations in wave height and direction observed in Gore Bay in 2003. Chapter Four identified variations in the distribution of sediment within Gore Bay, which are hypothesised to be linked to changes in beach morphology under the influence of the process environment. This section combines the knowledge gained throughout this investigation, by attempting to find patterns of beach morphology and sediment distribution which relate to changes in the process environment.

The characteristic response of the beach to various wave conditions is outlined, highlighting alongshore differences in profile response and sedimentary characteristics. The reasons for these responses and variations will be discussed in Chapter Six, where the complex interaction between beach processes, sediments and morphology of Gore Bay will be discussed in detail and related to the current literature on mixed sediment beaches.

Low energy conditions

During low energy conditions, waves in Gore Bay tend to come from a north easterly direction. During these conditions, sediment accumulates in the nearshore (just below zero datum) along the whole bay and also in the lower foreshore in the south of the bay. This is illustrated in Figure 5.2 which shows the change in profile for the northern and southernmost profiles between August 28th and September 27th. As discussed in Section 3.3.4, wave conditions between these two surveys were fairly calm, with observed wave height in the two weeks preceding the September survey rarely exceeding two ‘feet’ (refer to Section 3.3.3 for explanation of the term ‘feet’).

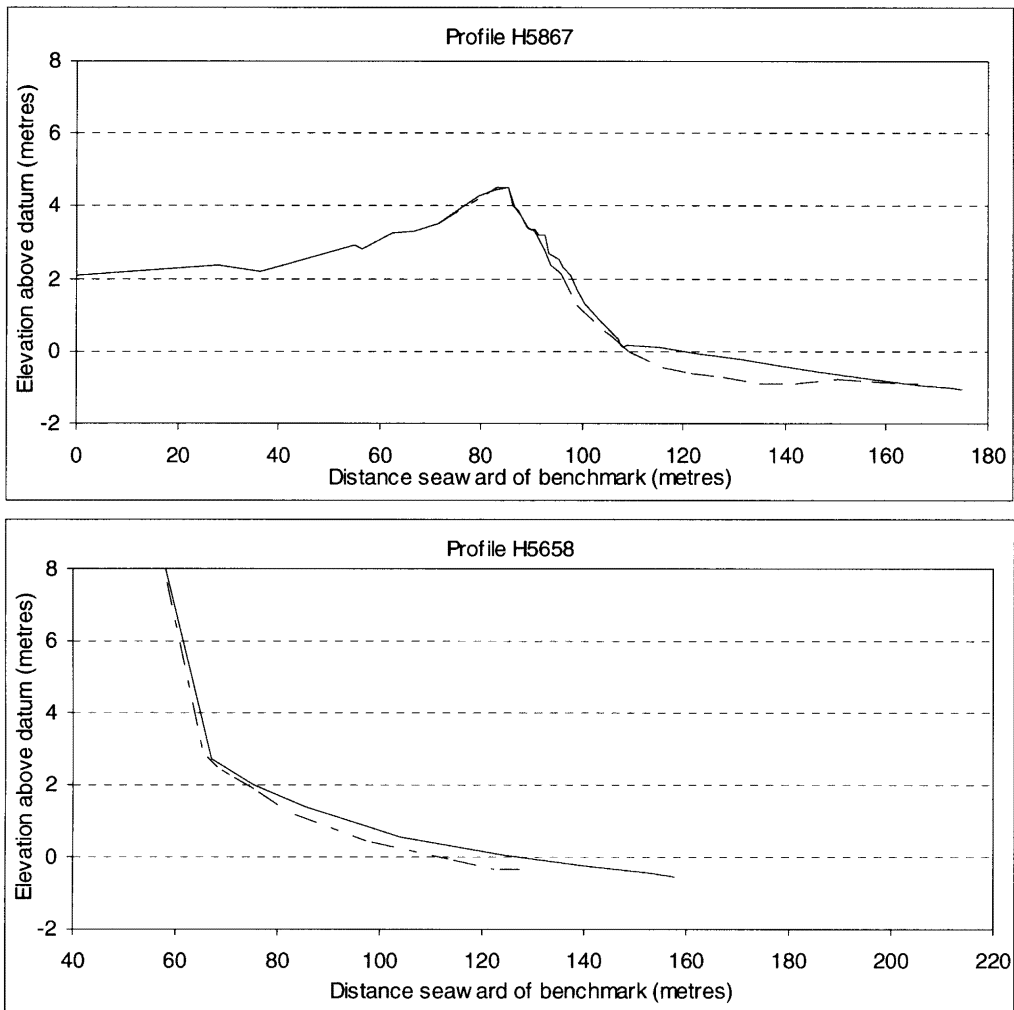


Figure 5.2: August (dashed) and September (solid) profiles for H5867 and H5658.

The bulk of the sediment accumulating under low energy conditions is sand. In the south, the proportion of sand on the visible foreshore increased dramatically between August 28th and September 27th (Figure 5.3).

In the north, there was a distinct change in sediments and slope from the steep, slightly sandy gravel beach face to the shallow low tide terrace, which was predominantly sand (Figure 5.4). The terrace contained a ridge and runnel system, where waves breaking at the outer limit of the terrace would occasionally wash over the ridge and flow alongshore in the runnel, toward the south of the bay.



Figure 5.3: Looking landward from the low tide mark at site H5658 (A) before (28th August) and (B) after (27th September) a period of low energy north easterly waves.



Figure 5.4: (A) North Gore Bay after a period of low energy north easterly waves, showing the presence of a sandy low tide terrace. (B) The boundary between the gravel foreshore and sandy low tide terrace.

Large southerly waves

During periods of large southerly waves, the beach in the north of Gore Bay tends to steepen. This occurs through the building up of a secondary berm and through the lowering of the lower foreshore and nearshore. In the south of Gore Bay, the effect of southerly waves on the beach is less than in the north. These responses are illustrated

in Figure 5.5 which shows the change in beach profile between June 13th and July 31st for a profile in the north (H5747) and south (H5675).

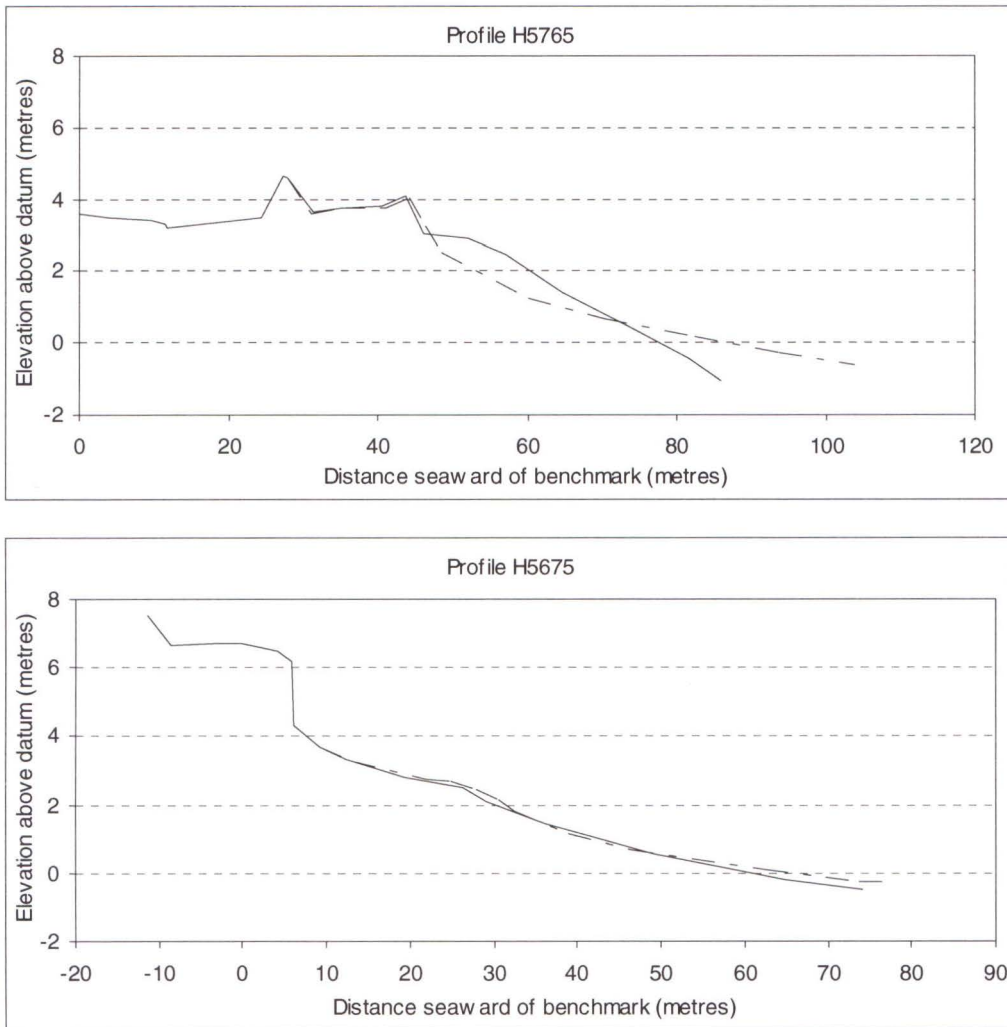


Figure 5.5: June (dashed) and July (solid) profiles for H5747 and H5675.



Figure 5.6: Gore Bay (A) before (July 2nd) and (B) after (July 6th) the passage of a storm which brought waves up to 5-6 ‘feet’ from a southerly direction.

Large southerly waves also result in a lot more gravel being present on the beach. Figure 5.6 shows photographs of Gore Bay immediately before and after the passage of a large southerly storm in July 2003. It can be seen that there is much less sand (light coloured) exposed on the beach after the storm. In addition, there is an extra line of breakers in the post-storm photograph, indicating the presence of an offshore bar.

Large easterly/north easterly waves

Large waves from an east or north easterly direction initiate a different response to that of large southerly waves, highlighting the concept that wave direction, as well as magnitude, is important when describing the coastal process environment. In the north of Gore Bay, large easterly waves remove sediment from the berms and deposit it in the lower foreshore and nearshore, resulting in a reduction in beachface slope (Figure 5.7). This is in direct contrast to the effect of large southerly storm waves.

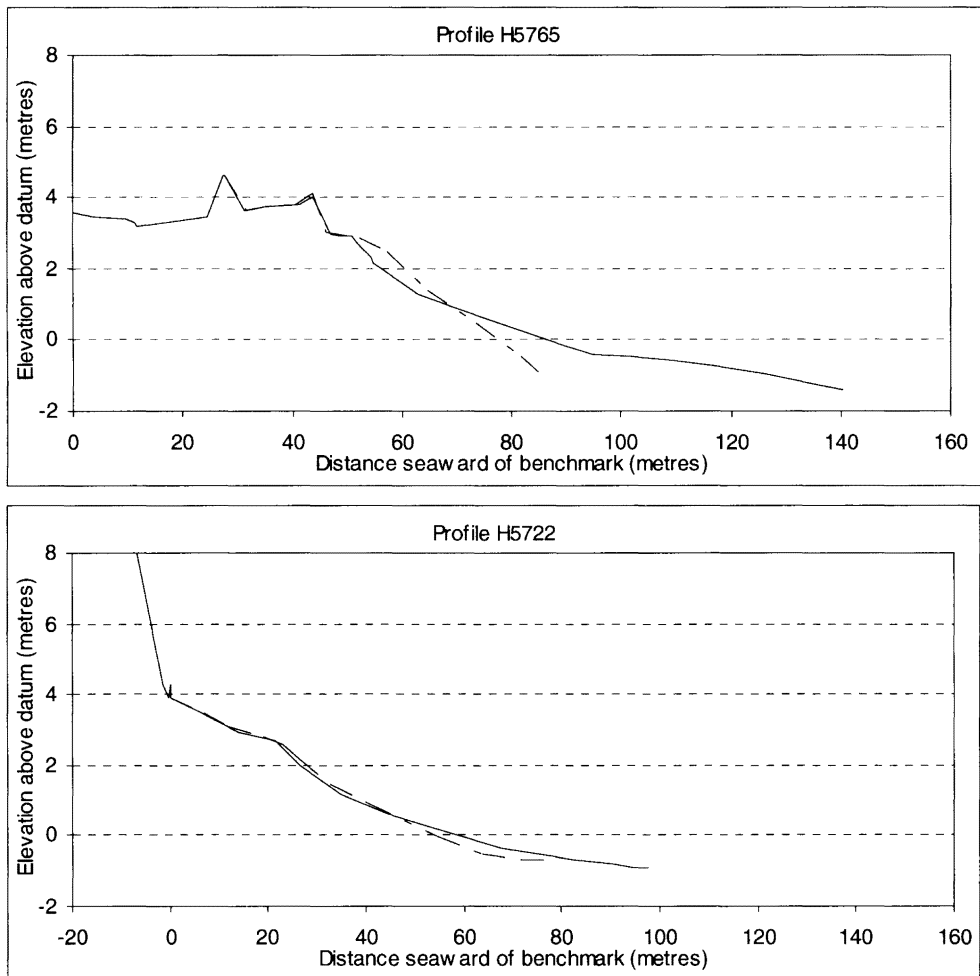


Figure 5.7: July (dashed) and August (solid) profiles for H5765 and H5722.

In the south of Gore Bay, the effect of large easterly waves on beach morphology is negligible, with only a slight build up of sediment in the nearshore. Under large easterly wave conditions, the foreshore in the north of Gore Bay becomes less sandy, while the south of the bay becomes slightly sandier.

It has been shown in the previous discussion that both the magnitude and direction of waves occurring at Gore Bay influence the way in which the beach responds, both in terms of beach profile variation and in the distribution of sand and gravel along the beach. Interaction between processes, sediments and morphology in the coastal environment is a complex relationship and is discussed further in Chapter Six, where it is also linked to the relevant international literature.

5.4 Long Term Variation

5.4.1 Annual profile variation

Using the data supplied by Environment Canterbury, beach profiles were graphed for the eleven sites between May 1993 and December 2002. Figure 5.8 shows the annual profile variations for three sites within Gore Bay and the other eight are presented in Appendix G. The thin coloured lines represent the range of profile forms between May 1993 (blue) and December 2002 (red). The thick black lines represent the upper and lower bounding surfaces of the envelope of change containing the monthly profile variations for February to September 2003.

At Site H5700, the long term envelope of change is much larger than the short term envelope, with a maximum horizontal excursion of more than 35 metres and a maximum vertical excursion of 2.2 metres (Figure 5.8a). The position of the scarp has not changed since 1993, there have only been changes in the form of the beach itself. The beach was at its lowest in 1995 and has shown a general pattern of accretion since then. However, it must be noted that the annual profile lines are based on a single survey and could be at an extreme edge of the short term envelope of change. Nevertheless, because the short term profile variation is so small compared with the long term changes, it can be stated with some authority that this site is accretional.

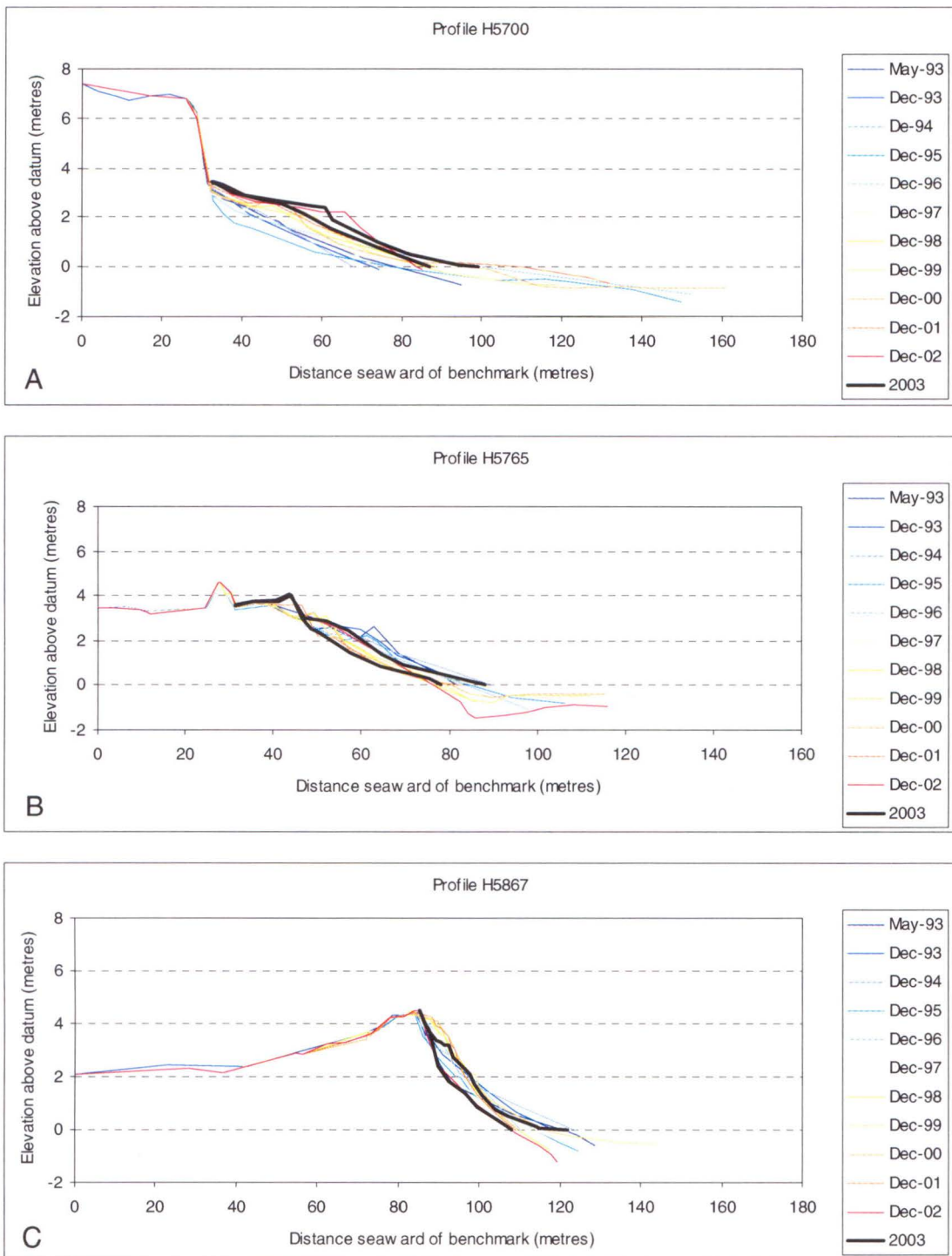


Figure 5.8: Profile variation between May 1993 and December 2002 for A) Site H5700, B) Site H5765 and C) Site H5867. Dark solid lines represent the beach envelope containing profile variation for 2003 profiles.

At Site H5765 the general pattern is one of landward retreat, especially of the lower foreshore (Figure 5.8b). However, the short term variation is such that long term trends may merely reflect movement within the short term envelope of change. Consider for example the profile line for December 2002. This profile seems to buck

the trend of landward retreat of the profile, due to the large berm at around three metres above datum. However, the 2002 profile is very similar to the upper bounding surface of the 2003 envelope of change. If 2002 has a similar short term envelope of change, then any pattern of retreat is masked due to the profile having been surveyed at a time when the beach was most accreted. Although the annual profiles were surveyed at a similar time of year (December), Section 5.3.1 has already shown that there is little seasonal pattern to beach profile changes. It is concluded that for this site, any net change in beach position is not significant enough to determine a trend from yearly surveying of beach profiles.

At Site H5867, the short term profile changes are almost as variable as the long term changes and there is no clear pattern of accretion or erosion (Figure 5.8c). Between 1996 and 2001 the crest of the beach ridge was up to five metres further seaward than it was in the early 1990s, however since 2002 the crest has returned to its former position. The beach has tended to be steeper in recent years. It cannot be concluded that there is any pattern of beach change at this location, especially when one considers the large short term variability in profile shape. It can be seen that the short term envelope of change is negligible above 3.5 metres. This indicates that profile change above this height occurs only in the largest storms.

Long term profiles for all profile sites are given in Appendix G. The majority of these also show little or no long term patterns of beach profile retreat or advancement. No significant movement of the backshore scarp has occurred at any site since 1993.

5.4.2 Annual volume variation

The volume of the beach (in cubic metres per metre of beach) was determined for each profile site for each survey by calculating the area under each profile line, between the beach toe and zero datum. The mean volume for each site was calculated and the volume of each survey expressed as a volume above or below the mean. The variation about the mean was expressed as a change in actual volume about the mean (in cubic metres) rather than as a percentage of the mean volume for the site, to allow direct comparison of the size of beach volume changes between sites.

Figure 5.9 shows the variation in beach volume for each profile site over time. Each dashed horizontal line in the diagram shows the location of a profile along the coast,

which remains fixed over the study period. The dashed horizontal line also represents the measured means of the beach volume for their respective profiles. Each tick mark on the y-axis of the graph represents $10 \text{ m}^3 \cdot \text{m}^{-1}$ of volume, as well as 50 metres alongshore. For each profile, the variation in volume over time is shown as a curve (solid) fluctuating around the mean. Because the variations are expressed as cubic metres of volume, the amplitudes of the volume fluctuations can be directly compared between sites and over time.

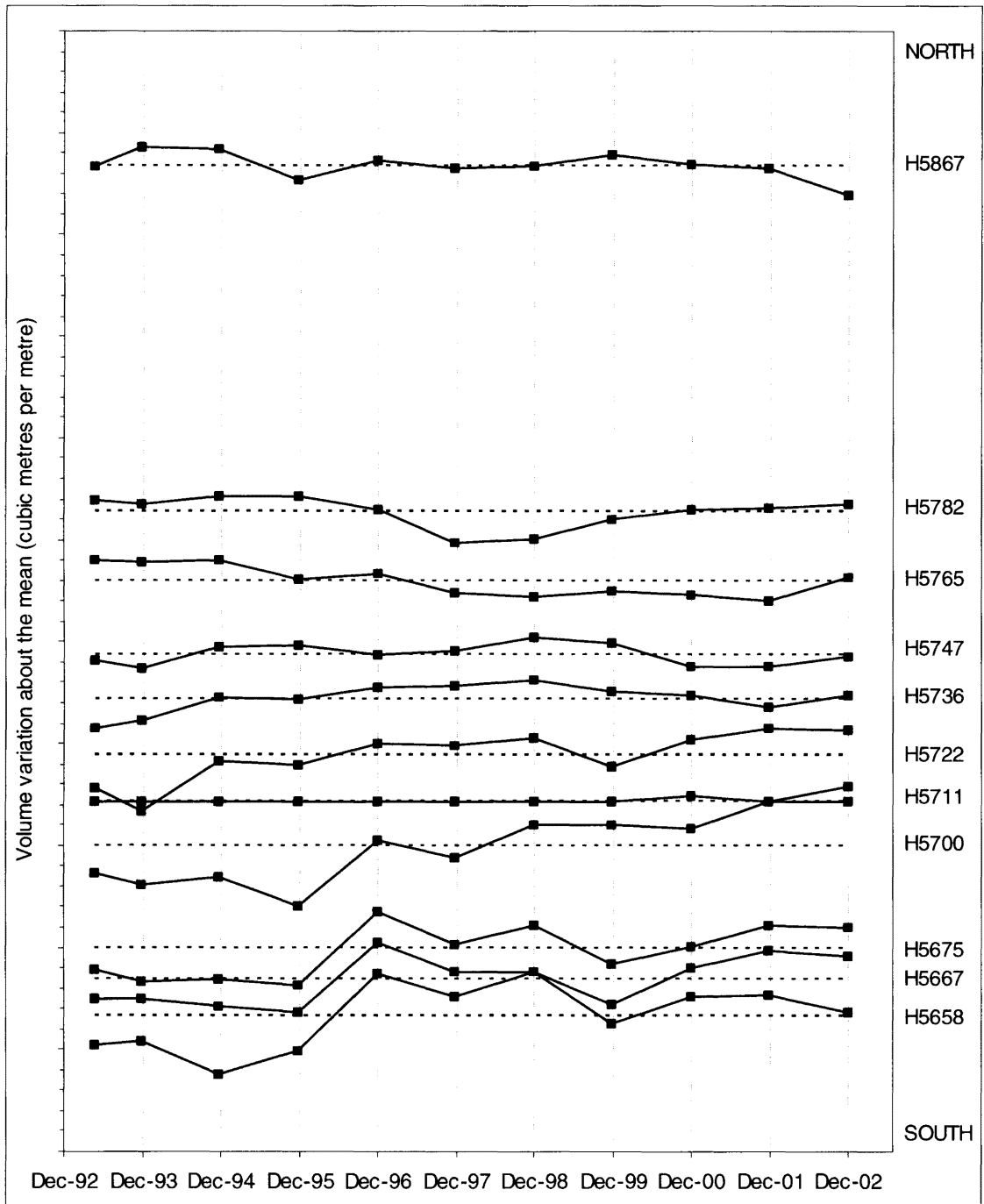


Figure 5.9: Long term variation in beach volume. See text for explanation.

The most striking feature of Figure 5.9 is the large volume deficit that existed in the southern portion of Gore Bay between 1993 and 1995. This deficit was probably caused by the passage of three large southerly storms over a four month period in 1992 (Table 3.3). If this is the case, it indicates that beach recovery from large storm events may take several years. Between the 1995 and 1996 surveys, the southern profiles showed an increase in volume of more than $30\text{m}^3.\text{m}^{-1}$. Between 1998 and 1999 the majority of southern profile sites showed a decrease in beach volume, due to the passage of a large southerly storm in July 1999. Since 1999 the southern sites have shown a general pattern of increasing beach volume, despite the occurrence of several large storms. In the central and northern portions of Gore Bay, there are no clear patterns of volume variation and the magnitude of volume variation is generally smaller than in the south.

It can also be seen from Figure 5.9 that profiles short distances alongshore from one another can show significant differences in profile response over the same time period. For example, between December 1993 and December 1994, site H5658 showed a loss of volume of more than 15 cubic metres. However, during the same period, site H5722 showed a gain of volume of around 30 cubic metres. These sites are only 640 metres apart. This indicates that beach response to the process environment is not constant alongshore. Such variations have been noted elsewhere. On two gravel-bearing beaches in South Wales, Caldwell and Williams (1985) demonstrated that while similar morphological changes were sometimes observed concurrently at a number of beach positions, often considerable morphological differences were found between profile sites less than twenty metres apart. In Gore Bay, it is suggested that this variation is due to the complex relationship between processes, sediments and morphology, which will be discussed in Chapter Six. This relationship includes potential longshore transfers of sediment within the Gore Bay system.

It is important to remember the variable nature of the coastal system when assessing patterns in beach volume. Section 5.3.1 showed that the short term envelope of change at Gore Bay varied from 14 to $26\text{m}^3.\text{m}^{-1}$, despite the relative lack of storms throughout 2003 compared with other years (Table 3.3). In many cases, the short term changes in beach volume outweigh the long term fluctuations. This is in keeping

with the findings of Thom (1973), who stated that high frequency changes in beach morphology could be of higher amplitude than long term variability. In order to quantify trends in beach volume and morphology, a more comprehensive monitoring program is required, both spatially and temporally (Clarke & Eliot 1988). While ongoing monthly surveys at Gore Bay are unlikely, it is suggested that another short period of monthly surveys could be undertaken in the near future, so that the short term variability of beach changes at Gore Bay can be substantiated under a wider range of wave conditions. This would allow more detailed interpretation of annual profile data.

5.4.3 Historical beach change

The previous two sections of this chapter have discussed variations in beach morphology through the analysis of beach profiles surveyed monthly between February and September 2003 and annually between 1993 and 2002. It was found that the beaches of Gore Bay are largely stable, with any slight trends of erosion or accretion masked by the large magnitude of short term changes. However, Gore Bay has a documented history of coastal erosion problems, as discussed in Chapter Three. Anecdotal evidence suggests that an area the size of a football field has been lost to the ocean to the south of the village (Department of Lands and Survey 1986). This section reviews the historical position and morphology of the beach at Gore Bay, as documented by the analysis of historical beach surveys and aerial photography.

Beach profiles were surveyed in the 1930s and 1940s at a number of locations in the southern part of Gore Bay. The present benchmarks from which the annual and monthly profiles are surveyed have been placed as closely as possible to the position of these original surveys to enable comparison (Cope 2003, pers. com.).

The original survey lines were also resurveyed in 1979 and 1984 (de Groot 1979; Slark 1984), however inconsistencies in the data and lack of benchmark information have prevented the direct comparison of these profiles to the 1993-2002 profiles. The conclusions made in these reports are still useful and the information can be used qualitatively to provide a picture of the historical changes in beach morphology and shoreline position.

De Groot (1979) surveyed six profiles in Gore Bay, roughly corresponding to sites H5667, H5675, H5711, H5722, H5736 and H5747. The profiles showed that erosion between 1948 and 1978 was concentrated in the south of the bay and was mainly in the form of bank retreat. At site H5667, the backshore scarp retreated by more than ten metres, with an average reduction in beach elevation of 0.6 metres. Site H5675 showed scarp retreat of almost 15 metres and beach lowering of more than three metres. North of this, (between sites H5711 and H5747) there was little change in beach elevation between 1948 and 1978 and only slight retreat of the sand dune face. De Groot (1979) noted that the amount of scarp retreat shown by the profiles was a minimum estimate, as various materials had been placed along the bank in order to protect the road (Table 3.4).

As stated previously, there were various inconsistencies in the 1979 surveys. For example, De Groot (1979, p.8) states that erosion at Gore Bay was mainly in the form of bank retreat rather than beach lowering. While the majority of profiles supported this conclusion, at one site (approximately H5675) there was a reduction in beach elevation of more than three metres below the 1948 level. This placed the beach surface more than six metres below the reported mean high water mark, which means that the beach would have been covered by at least three metres of water even in spring low tide conditions, an unlikely if not impossible scenario. De Groot (1979) stated that the positions of the two southernmost profiles were estimated using measurements from the 1948 map, because survey pegs could not be located. It is therefore suggested that the profile changes shown in the two southernmost profiles (equivalent to sites H5667 and H5675) may not be an accurate portrayal of beach change between 1948 and 1978.

Slark (1984) resurveyed the same six profiles in 1984, however missing pages from the original report means that data for only two of these (equivalent to H5711 and H5722) were available. The results and conclusion sections of the report were still present and can be assumed to be based on findings from all six profiles. It was revealed that there was relatively little net change in the beach profiles between 1978 and 1987. The position of the scarp had not retreated and was reported to be “fairly well vegetated and in a stable position” (Slark 1984, p.3). A slight build up of sediment had occurred in the upper regions of the beach (backshore), resulting in an

increase in beach slope. The two profiles for which data exists shows an increase in backshore elevation of up to 0.8 metres.

Data for the 1934, 1936 and 1948 profiles have been tied in to the modern day profile lines as accurately as possible (Cope 2003, pers. com.) and are presented in Appendix H. Table 5.2 summarises the changes in beach morphology shown by these profiles. Beach width has increased dramatically since the original profiles were surveyed. In 1934/36, beach width averaged around 20 metres. In 1948, beach width ranged from 50 metres at site H5736 to 0 metres at site H5700 where there was no beach present above water level. These very different values of beach width were recorded less than 400 metres apart. Since 1993, beach width along the southern stretch of Gore Bay has averaged around 55 to 60 metres. In association with increasing beach widths, the slope of the beach has decreased since these original profiles were surveyed and beach volume has substantially increased. It can be concluded that the present beach at Gore Bay is in a much better position to withstand a series of large storms than it has been in the past.

Table 5.2: Summary of beach changes between 1934, 1936, 1948 and present.

| | H5667 | H5675 | H5700 | H5722 | H5736 | H5747 |
|--|-------|-------|----------|-------|-------|-------|
| 1934/1936 beach width | 20m | 15m | - | - | 25m | 23m |
| 1948 beach width | - | - | no beach | 42m | 50m | 25m |
| Present beach width | 59m | 59m | 60m | 61m | 55m | 52m |
| 1934/1936 beach slope | 6.8° | 10.2° | - | - | 9.9° | 7.2° |
| 1948 beach slope | - | - | no beach | 5.0° | 5.4° | 9.3° |
| Present beach slope | 2.7° | 3.5° | 3.2° | 3.7° | 4.3° | 4.3° |
| Change in scarp position between 1934/1948 and present | -10m | -15m | +6m | -1.5m | -4m | +3m |

It can be seen that at the majority of sites with data from the 1930s or 1940s, the position of the scarp has translated landward (negative value), indicating erosion. The maximum scarp retreat occurred at site H5675 with landward translation of the scarp of more than 14 metres. At sites H5700 and H5747 the position of the scarp is now further seaward than it was in 1948 (positive values). While this would usually indicate accretion, it must be noted that at these two sites, artificial fill was placed along the bank to protect the road, so that the accretion shown is human induced, not natural beach response. De Groot (1979) found similar amounts of scarp retreat had

occurred at sites H5667 and H5675 between 1948 and 1978 as this study has found between 1934 and 1993. While this may indicate that little change in scarp position has occurred since 1978, the aforementioned uncertainties in de Groot's study (1979) mean that these conclusions must be treated with caution.

Analysis of aerial photographs taken of Gore Bay in 1955, 1965, 1979, 1988 and 1993 shows no distinguishable change in the position of the scarp, suggesting that the majority of scarp retreat occurred prior to 1955. However, it must be noted that the scale of these photographs is not large enough to permit detailed measurement of shoreline change or determine the placement of artificial fill. Stereoscopic analysis of the aerial photographs indicates that the beach is steeper and narrower in 1979 than in 1965 or 1988, although there is little change in scarp position.

5.5 Chapter Summary

Chapter Five has discussed the beach morphology of Gore Bay on a variety of time scales. Short term changes in beach morphology were determined through the analysis of beach profiles surveyed approximately monthly between February and September 2003. It was shown that there are along shore variations in the way in which the beach responds to changes in the process environment. Both the height and direction of incident waves were important in determining the response of the beach, and it was suggested that the sedimentary characteristics of the beach influence and are influenced by changes in beach morphology. This interaction between processes, sediments and morphology will be discussed in Chapter Six and related to the international literature on the morphodynamics of mixed sediment beaches.

Long term changes in beach morphology were determined through profile and volume analysis of annual beach surveys between 1993 and 2002. It was found that the majority of the beach has been relatively stable over the last ten years, although some sites in the south of the bay show slight patterns of accretion. Difficulty was found when interpreting longer term patterns of beach change, as often the magnitude of short term variations exceeded the long term trends apparent from the annual survey data. It was suggested that a more temporally comprehensive surveying program is needed for quantitative analysis of beach volume trends.

Historical beach changes were investigated using data from Environment Canterbury, de Groot (1979) and Slark (1984). Inconsistencies in the data made analysis difficult, however it was tentatively concluded that the position of the scarp has remained fairly constant since 1979, while beach volume and width have increased considerably since the 1930s. This building up of the foreshore means that while erosion at Gore Bay cannot be ruled out in the future, the beach is now better equipped to deal with a series of high seas and storms than it was in the late 1970s.

CHAPTER SIX

THE GORE BAY COASTAL SYSTEM

6.1 Introduction

The preceding chapters of this thesis have investigated various components of the Gore Bay coastal system. For ease of writing up the results, it has been necessary to distinguish between the investigations into the process environment, beach sediments and beach morphology throughout the thesis. This was done by adopting the theory of the ordered control model (McLean & Kirk 1969) to provide some structure to the investigation. However, it was noted in Chapter One that complex interactions and feedback mechanisms occur between these three components, as acknowledged in the process-response model (Krumbein 1963). It is the aim of this chapter to bring together the findings of the preceding chapters, using knowledge gleaned from the international literature to determine the ways in which the coastal system at Gore Bay operates.

In Chapter Two, it was recognised that there are several types of mixed sediment beaches and a classification scheme for determining beach type was outlined and critiqued. This chapter uses the knowledge gained throughout the investigation to determine where Gore Bay sits in the spectrum of mixed sediment beach types. The usefulness of such classification schemes is discussed and implications for other New Zealand mixed sediment beaches are presented.

6.2 Morphodynamic Implications

There is an alongshore variation in sediments, morphology and processes in Gore Bay. Such variations are not uncommon and have been described on many beaches around the world (Bascom 1951; Carr 1969; Finkelstein 1982; Dawe 2000; Boorer 2002). Beaches sheltered at one end from the prevailing wave direction generally have mean grain size, beachface slope and wave energy increasing away from the sheltered end (Krumbein 1947; Bascom 1951), while the degree of sorting decreases.

Finkelstein (1982) found a similar pattern, although grain size, beachface slope and wave energy were found to decrease slightly between the centre of the beach and the exposed end. The characteristics of embayed beaches vary in conjunction with the distribution of wave energy.

Gore Bay is sheltered from the prevailing southerly waves by Point Gibson and the reef associated with Manakau Bluff to the south of the bay. Grain size, beachface slope and wave energy are greater at the northern end (exposed to prevailing waves) than at the southern (sheltered) end of the bay, similar to the findings of Krumbein (1947) and Bascom (1951). However, the degree of sorting improves away from the sheltered end of Gore Bay, due to the decreased proportion of sand in the north (Section 4.3.2).

In general, high wave energy is expected to decrease the beachface slope, as the stronger backwash associated with large waves is able to move most available sediment offshore, thereby flattening the beach (King 1972). However, in some instances beachface slope increases with higher wave energy, due to fine material moving along or offshore, leaving behind coarser, better sorted sediments on the beachface. This increases the permeability of the beachface, resulting in more infiltration and less powerful backwash (Finkelstein 1982; Packwood 1983; Everts *et al.* 2002). This in turn results in a steeper beachface slope, because clasts moved up the beach by the strong swash flow are unable to be transported back down the beach by the weaker backwash (Quick 1991). This series of events occurs at Gore Bay under large southerly wave conditions, when sand is moved offshore to form a bar, leaving gravels on the beach to form a steep ($4-9^{\circ}$) berm face in the north of the bay (Figure 5.5). In the south of the bay, the steepness of the berm is less ($<4^{\circ}$), due in part to the sheltering effect of Point Gibson and to the higher proportion of sand, which decreases the degree of sorting and limits the maximum slope the beachface can maintain.

6.2.1 Beach response to wave conditions

In Section 5.3.2 it was shown that while large waves from the south cause a steepening of the beach profile, large waves from the north east or east cause the profile to flatten. Wave height is therefore not the only factor influencing beach

response at Gore Bay. Southerly waves are generated in the South Pacific and tend to be longer period than the locally generated north easterly waves (Section 3.3.2). Data from the Environment Canterbury wave buoy tends to support this statement, with typical periods for southerly waves between four and twelve seconds, with four to eight seconds for north easterly waves.

Shorter period waves arrive at the beach more frequently than long period waves, therefore the timing between the backwash of one wave and the incoming swash of the next is reduced. If the backwash has not completely cleared the beach by the time the next swash arrives, the pore spaces of the beach will still be filled with water and the incoming swash will not be able to percolate through the beach. The returning backwash will therefore be strong enough to transport coarse sediment down the beach face, flattening the beach profile.

Kirk (1975) identified the importance of the degree of interaction between incoming waves and outgoing backwash on mixed sand and gravel beaches, based on the concept of “phase difference” (Kemp 1960). This concept recognises that as the period of the swash-backwash cycle approaches that of the incoming waves, interaction between the two will increase turbulence in the swash zone and enhance erosion of the beach sediments. Therefore, it is not just the size of the wave arriving at Gore Bay that determines whether the beach will erode or accrete. The period of the wave and the interaction of the swash and backwash are also important factors in beach response.

6.2.2 Alongshore variations in beach response

At Gore Bay, large southerly (long period) wave conditions cause a steepening of the beach profile by the building of berms and lowering of the nearshore bed (Section 5.3.2). The foreshore also tends to become more gravelly after a period of large southerly waves, and an offshore bar is often present. Beach response is stronger in the north of the bay than the south, where only small berms form. This may be due to refraction effects reducing wave energy in the south of the bay (Figure 3.9) but may also be due to the differences in sedimentary characteristics along Gore Bay.

Coarser sediment is more permeable than finer sediment and therefore any berms formed will have steeper faces due to the reduced power of the backwash (Quick 1991). Well sorted sediment is also more permeable than poorly sorted sediment, with the same effect. Because the north of the bay is both coarser and better sorted than the south of the bay, large southerly waves will cause steeper berms in the north. This concept is supported by the nature of beach response to large easterly (short period) waves. Beach response to easterly waves is also greater in the north of Gore Bay than in the south (Section 5.3.2). The southern end of the bay is not sheltered from easterly waves, so the lack of beach response in the south must be due to some other factor, such as sedimentary characteristics.

At Gore Bay, sand behaves as it would on a pure sand beach. Under large, long period waves the sand moves offshore to form a bar, thereby causing waves to break earlier, dissipating some of their energy. This was illustrated by the rollability analysis of sand samples (Section 4.3.5). Samples were collected the day after a large southerly storm had passed through Gore Bay and analysis showed a strong offshore movement of sand, especially in the south of the bay. Under calmer conditions, the sand moves back onshore, depositing in the lower foreshore and nearshore, as evidenced by analysis of beach profiles and qualitative observations (Figure 5.2, 5.3 and 5.4). In the north of the bay, a sandy low tide terrace is often present after periods of low energy wave conditions. The behaviour of the sand population of Gore Bay is relatively straightforward; however the presence of gravel on the beach at Gore Bay complicates the morphodynamics of the system.

In the south of Gore Bay, the proportion of gravel is much less than in the north, especially in the back- and mid- shore regions (Figure 4.13). This is due to the sheltering effect of Point Gibson and the reefs to the south of the bay. As sand is moved offshore under high energy conditions, gravel remains on the foreshore as a lag deposit. Although there is a concentration of gravels on the surface of the beach, this layer is thin and the permeability of the beach remains low due to the sand underneath. Backwash velocities are therefore relatively strong, meaning that the beachface slope remains fairly shallow and the gravels do not form a distinct berm, as they do in the north. At times, the gravel may concentrate in the horns of beach cusps, which have steeper slopes than the sandy cusp troughs. Under calm conditions,

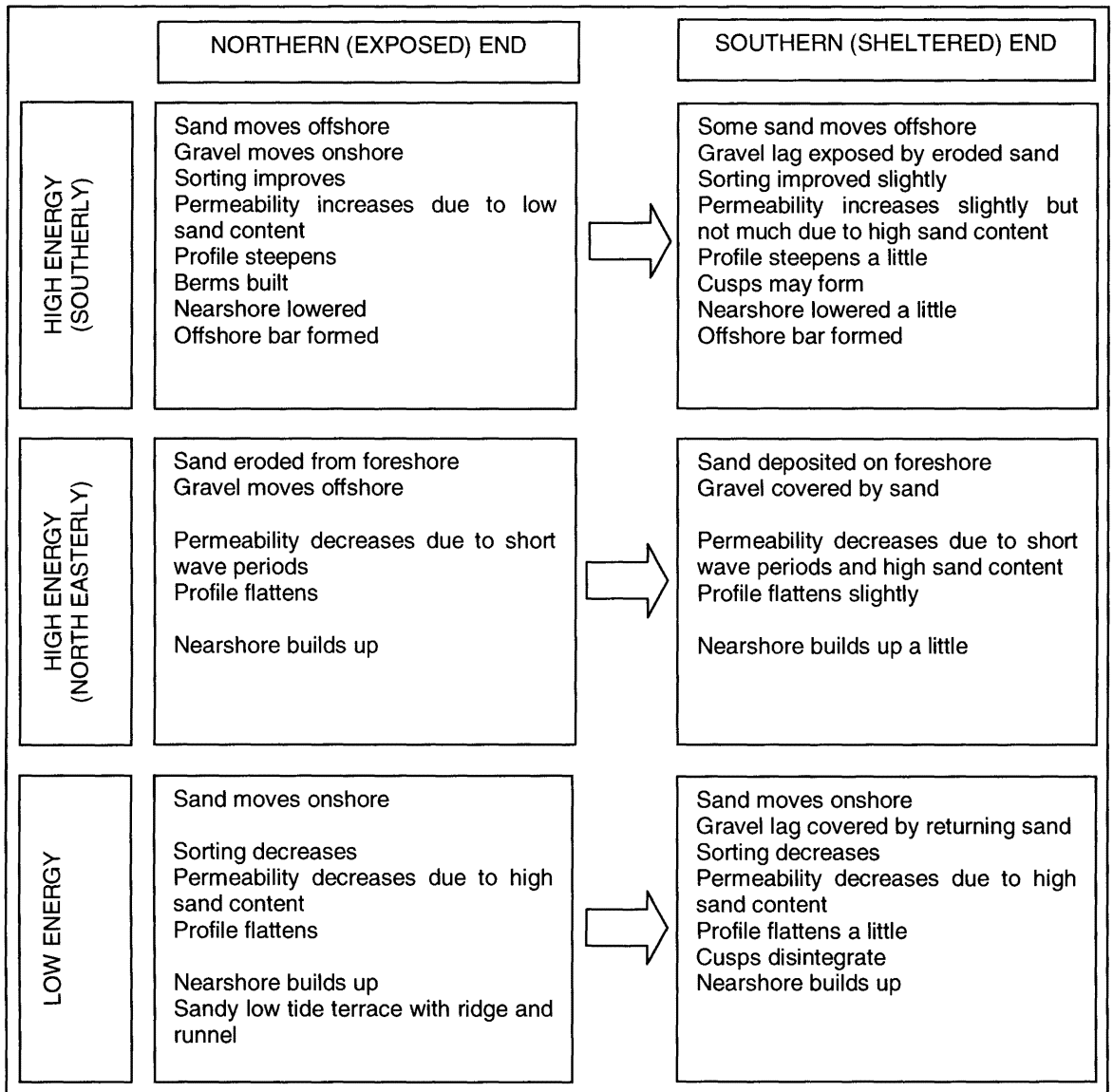
the beach cusps disintegrate and sand is moved back onshore, covering the gravel lag in a layer of sand.

In the north of Gore Bay, the proportion of sand in the back- and mid- shore is much less than in the south. Average grain size is coarser and the degree of sorting is better (Section 4.3.1) resulting in a much higher level of beach permeability. Large waves transport the sand offshore, removing sand from the interstitial spaces of the gravel. Sorting is therefore improved and permeability increases further. As a result, backwash velocities are reduced and are unable to transport the gravel seawards, resulting in accretion of gravels at the top of the swash zone and a steepening of the beach profile. Under low energy conditions, waves transport the sand onshore, decreasing the degree of sorting of the gravels, which decreases permeability. The backwash is therefore relatively strong and can transport the gravels seawards, flattening the beach profile.

The contrasting behaviour between the sand and gravel populations in response to the process environment has also been noted on composite gravel beaches in southern California (Everts *et al.* 2002). At Gore Bay, the characteristics of beach sediments have a strong control on the morphological behaviour of the beach, but the morphological state of the beach also determines the distribution of sediment on the beach at any point in time.

Figure 6.1 illustrates the morphological behaviour of Gore Bay and highlights the alongshore variations in beach response to varying wave conditions. This diagram provides a simple summary of the coastal system, but there are several questions left unanswered. For example, only three types of wave conditions are considered: high energy southerly waves, high energy north easterly waves and low energy waves. However, Gore Bay is subject to a wide spectrum of wave heights, directions and periods, to which the beach responds slightly differently. Further study is required to investigate the morphological and sedimentary response to a wider range of wave conditions. Short and Wright (1984) linked various morphodynamic states observed on sand beaches to the wave power that created them. More quantitative wave data and beach profiles extending throughout the entire surf zone would be required to do this at Gore Bay.

Figure 6.1: The variation in beach response of Gore Bay to three possible wave conditions.



6.3 What Sort Of Beach Is Gore Bay?

Now that the morphodynamics of the coastal system have been identified, Gore Bay can be compared to the other mixed sediment beaches identified in Chapter Two. It is important to determine what sort of beach Gore Bay is, so that knowledge gained at similar beaches can be applied. This comparative experience is an important part of coastal management, as it is impossible to study every aspect of every beach. However, it is imperative that direct relationships are only inferred for beaches which operate in similar ways.

Jennings and Shulmeister (2002) devised a classification scheme for gravel beaches (Section 2.5) with three end member states: pure gravel, mixed sand and gravel and composite gravel beaches. Some problems were found with this classification scheme, especially in the large overlap in the range of discriminating parameters for each beach type (Table 2.1) and in the use of mean grain size on beaches which may have bimodal sediment populations.

6.3.1 Visual classification

The first stage of Jennings and Shulmeister's (2002) classification is to visually classify the beach into one of the three beach types. This is a problem at Gore Bay, as the beach does not fit neatly into any of the categories. One of the major issues with visually classifying Gore Bay is the large temporal and alongshore variation in beach characteristics. The outcome of a visual classification at Gore Bay will therefore depend on what part of the beach one is looking at, as well as what morphodynamic state the beach is in at the time of classification.

The first category in the classification scheme is a pure gravel beach. Gore Bay is not a pure gravel beach, as there is a large proportion of sand, especially in the southern end (Figure 4.13). Even at the northern end, sand is often present in the lower foreshore and nearshore. There is a wide surf zone and the profile is often dissipative with a sandy low tide terrace. Pure gravel beaches are highly reflective at all stages of the tidal cycle and surf zone processes are absent (Jennings & Shulmeister 2002). Gore Bay is therefore not a pure gravel beach by visual classification.

Gore Bay has been described as a mixed sand and gravel beach in the literature (Slark 1984) although it displays very few of the characteristic features (Kirk 1980). A steep nearshore face does not exist at Gore Bay, in either the monthly profiles surveyed as part of this investigation, or in the annual survey data obtained from Environment Canterbury (Appendix F and G). This face is a permanent feature of mixed sand and gravel beaches (Kirk 1980; Single & Hemmingsen 2000). The presence of a nearshore face prevents onshore-offshore cycling of sediments on mixed sand and gravel beaches and forces waves to break in a single line. However, onshore-offshore cycling of sediment is an important feature of the Gore Bay coastal system (Section

6.2) and a wide surf zone exists under all but the calmest wave conditions. Gore Bay cannot be visually classified as a mixed sand and gravel beach.

The third category in the classification scheme is a composite gravel beach. These beaches are characterised by a sharp demarcation between a steep gravel upper foreshore and low gradient sandy low-tide terrace (Jennings & Shulmeister 2002). The terrace is exposed at low tide, resulting in a profile dissipative of wave energy. At high tide, the steep gravel berm causes wave energy to be reflected. Parts of Gore Bay sometimes appear like a composite beach. North of site H5765 there is a gravel berm which has been permanent throughout this investigation. Sedimentary analysis of the berm showed low sand content (Section 4.3.2). There is always a sharp contrast in slope between the berm face and the lower foreshore along this section of Gore Bay, as is typical on a composite beach, but the lower foreshore is not always composed of sand sized sediment (Figure 6.2).

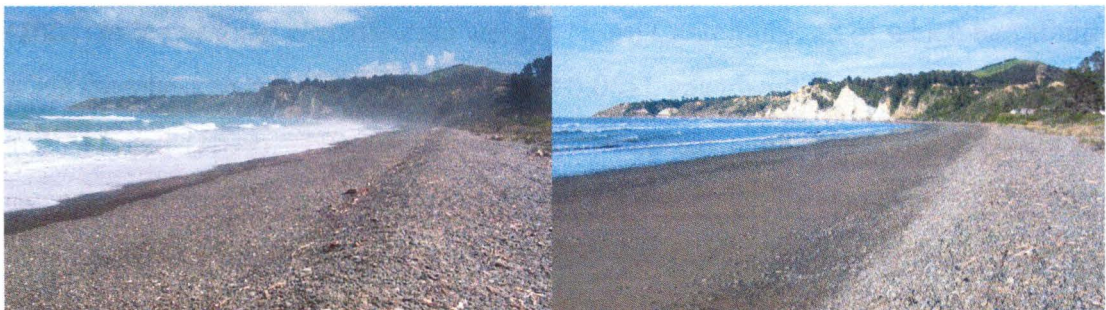


Figure 6.2: Looking south from site H5782 on A) 5th December 2002 and B) June 14th 2003.

In the south of Gore Bay, there is not a gravel berm or an abrupt change in slope across the profile, as expected on a composite gravel beach. The foreshore contains a similar amount of gravel to the backshore and the beach is dissipative of wave energy at all stages of the tidal cycle.

Of the three end members of Jennings and Shulmeister's (2002) classification, the one most appropriate to Gore Bay by visual determination is the composite gravel beach. However, is really only applicable in the northern section of the bay. The southern section of the bay does not fit into any of the three end member categories, as there is a large proportion of sand across the whole profile and the beach is dissipative at all stages of the tidal cycle.

6.3.2 Confirmation of visual assessment

The second stage of Jennings and Shulmeister's (2002) classification is confirmation of the visual assessment through the measurement of some basic parameters. The parameters of most importance for distinguishing between different beach types are the Iribarren number, beach width, average grain size and storm berm height (Jennings & Shulmeister 2002).

The Iribarren number (ξ) is a function of beachface slope ($\tan \beta$) and wave steepness (H_{∞}/L_{∞}), given by the equation:

$$\xi = \frac{\tan \beta}{(H_{\infty}/L_{\infty})^{1/2}}$$

Wave steepness requires both the offshore wave height and offshore wave length. Unfortunately, these parameters were not measured at Gore Bay as part of this investigation. However, twelve of the beaches used by Jennings and Shulmeister (2002) in the original classification were in North Canterbury, all of which had similar wave steepness values (between 0.059 and 0.065), calculated using data from Pickrill and Mitchell (1979). For calculation of the Iribarren number at Gore Bay, a wave steepness value of 0.062 was used. Beachface slope ($\tan \beta$) was taken as the angle between the top of the highest berm to the low tide mark. Due to the multiple surveys taken at Gore Bay, a range of beach slopes was determined for each profile site, which resulted in a range of Iribarren numbers for each site.

Beach width is the distance between beach toe and the low tide mark, taken at Gore Bay to be approximately equal to zero datum (1.1 metres below mean sea level). Multiple surveys of the same profile site lead to the calculation of a range of beach widths for each site. Jennings and Shulmeister (2002) do not give values of the height of storm berm heights for the three beach types, or for individual study sites. Storm berm height is therefore disregarded as a discriminating parameter in the classification of Gore Bay.

At Gore Bay, mean grain size was calculated by averaging the mean grain sizes of the backshore, midshore and foreshore sediment samples for each site, as calculated from

sieve analysis. Jennings and Shulmeister (2002) used sieve analysis only for the foreshore sediment samples, measuring the b-axis of 50 randomly selected clasts in the back- and mid- shore samples to determine mean grain size. This method was not possible at Gore Bay, due to the high proportion of sand in many of the back- and mid- shore samples.

Table 6.1 shows the Iribarren numbers, beach widths and mean grain size, as calculated for each profile site at Gore Bay. These values were compared with the range of possible values given to each beach type by Jennings and Shulmeister (2002) (Table 2.1). Sites were only classified overall as a particular beach type in Table 6.2 if all three of the measured parameters for that site fitted within the range given for that beach type.

Table 6.1: Discriminating parameters measured at Gore Bay. Sites are listed from south to north.

| Site | Range of Iribarren Numbers | Range of Beach Widths | Mean Grain Size |
|-------|----------------------------|-----------------------|-----------------|
| H5658 | 0.69-1.22 | 37-65 | -2.3 |
| H5667 | 0.65-0.94 | 48-70 | -1.7 |
| H5675 | 0.88-1.12 | 52-66 | -1.1 |
| H5700 | 0.83-1.02 | 54-66 | -0.2 |
| H5711 | 0.95-1.08 | 54-61 | -1.0 |
| H5722 | 0.95-1.14 | 55-66 | -2.2 |
| H5736 | 1.12-1.30 | 51-59 | -2.8 |
| H5747 | 1.08-1.40 | 45-58 | -3.1 |
| H5765 | 1.06-1.29 | 45-55 | -2.7 |
| H5782 | 1.09-1.61 | 40-59 | -3.4 |
| H5867 | 2.07-3.16 | 23-35 | -3.7 |

Of the eleven sites investigated at Gore Bay, only six fitted all of the parameters for one of the three beach types. For example, sites H5722 to H5782 fitted all three parameters for mixed sand and gravel beaches; however they only fitted one or two of the parameters for composite or pure gravel beaches. They are therefore classified as mixed sand and gravel beaches. Site H5867 fits all parameters for a pure gravel beach type and only one parameter for the other beach types. It is therefore classified as a pure gravel beach. Sites H5658 to H5711 fit two out of three of the mixed sand and gravel parameters and one of the composite gravel parameters. These sites do not fit

neatly into any of the beach type classifications described by Jennings and Shulmeister (2002).

Table 6.2: Classification of Gore Bay.

| Site | Iribarren Number | | | Beach Width | | | Mean Grain Size | | | Beach Type |
|-------|------------------|-----|----|-------------|-----|----|-----------------|-----|---|------------|
| | | | | | | | | | | |
| H5658 | - | - | CG | - | MSG | - | PG | MSG | - | |
| H5667 | - | - | CG | - | MSG | - | - | MSG | - | |
| H5675 | - | MSG | CG | - | MSG | - | - | - | - | |
| H5700 | - | MSG | CG | - | MSG | - | - | - | - | |
| H5711 | - | MSG | CG | - | MSG | - | - | - | - | |
| H5722 | - | MSG | CG | - | MSG | - | - | MSG | - | MSG |
| H5736 | - | MSG | CG | - | MSG | CG | PG | MSG | - | MSG |
| H5747 | - | MSG | CG | - | MSG | CG | PG | MSG | - | MSG |
| H5765 | - | MSG | CG | - | MSG | CG | PG | MSG | - | MSG |
| H5782 | - | MSG | CG | - | MSG | CG | PG | MSG | - | MSG |
| H5867 | PG | - | - | PG | | CG | PG | MSG | - | PG |

Even for those sites which can be classified by the discriminating parameters, the beach type indicated is different to that indicated by visual classification. Gore Bay displays few of the characteristic features of a mixed sand and gravel or pure gravel beach and has many characteristics that are very different to the typical features of these beach types. The southern part of Gore Bay, which cannot be classified through analysis of the discriminating parameters, is also the section of the bay that was unable to be classified visually.

According to the classification scheme of Jennings and Shulmeister (2002), Gore Bay is not a pure gravel, composite gravel or mixed sand and gravel beach. Visually, parts of Gore Bay sometimes appear to be a composite gravel beach, but other parts bear no visual resemblance to any of the beach types. The north of Gore Bay has parameters that are within the range of mixed sand and gravel beaches, despite displaying significant variations to the morphodynamics of such a beach. The characteristics of southern Gore Bay are different to all three beach types recognised in the scheme. The classification scheme of Jennings and Shulmeister (2002) is not easily applied to the beaches of Gore Bay, which may be more similar to the transitional sand and gravel beaches of northern Pegasus Bay than to the end members of the classification scheme.

6.3.3 Transitional sand and gravel beach

The characteristic features of a transitional sand and gravel beach are described in Section 2.4. Gore Bay is similar to the transitional sand and gravel beaches of northern Pegasus Bay because there is no nearshore face preventing the onshore-offshore cycling of sediments. The distribution of sand and gravel varies both spatially and temporally and there is an alongshore variation in beach morphology and sedimentary characteristics. A morphodynamic model was created for transitional sand and gravel beaches; however it was found that beach response to the changing process environment varied alongshore and that the model was not applicable to the entire range of beaches found in northern Pegasus Bay (Hall 1995). Pescini (2000) found that sedimentary characteristics have a strong influence on the way in which beaches respond to changes in the process environment. This same conclusion was reached at Gore Bay, where alongshore differences in sedimentary characteristics result in varying responses to changing wave conditions.

The morphodynamic model for transitional sand and gravel beaches suggests that increasing wave power results in erosion of gravels from the fore- and mid- shore areas, leaving a gravel backshore with scarped cusps, fronted by a sandy terrace with a few pebbles scattered in the midshore (Hall 1995). Pescini (2000) notes that the sandy foreshore results from the highly turbulent swash zone during storm events, which forces the sand population into suspension, while the gravels settle through the sands to a scour plane. As wave energy decreases after the storm, the sand settles out of suspension and is deposited on top of the gravel.

Periods of low wave energy lead to the accretion of gravels in the midshore, forming large sets of well developed cusps. The majority of the beach above water is characterised by gravels, while a small ridge and runnel system may be apparent at the low tide mark. Pescini (2000) notes that the dominance of gravels during low energy conditions is because waves do not have enough energy to suspend the sand particles, but the energy is sufficient to displace the sand, causing a mixing of sand and gravel populations and a visual dominance of gravel above the water line.

At Gore Bay, high energy events are characterised by high proportions of gravel, due to the offshore movement of sand and the landward movement of gravels (Section 6.2.1). Low energy events at Gore Bay result in higher proportions of sand being exposed on the beach surface, due to the return of sand from the offshore bar. This pattern of beach response is different to that shown in the morphodynamic model for a transitional sand and gravel beach (Hall 1995) and is caused by different processes to those suggested by Pescini (2000). However, Hall (1995) noted that the model was not representative of the morphodynamics in the very north or very south of her study area. Variations to the model were described, which better coincide with the dynamics of the Gore Bay coastal system.

In the southern part of northern Pegasus Bay, beaches are mostly sand and a fully accreted beach state is characterised by a sandy profile with ridges and runnels at the foreshore and a sand berm near the high tide mark. A fully eroded beach state results in coarse gravels being found in significant abundance on the foreshore. Cusps are not found on these sandier beaches. Shulmeister and Kirk (1997) and Pescini (2000) found that high energy events result in the exposure of a gravel lag deposit in the southern part of northern Pegasus Bay, due to the erosion and seaward transportation of sands. The northernmost beaches of the study also showed variation to the model. The backshore is comprised of gravels in all beach states and is characterised by cusps. When accreted, the foreshore is mainly sand, with a ridge and runnel system at the low tide mark. An eroded beach state results in a more gravelly foreshore, due to the erosion and seaward transportation of sands by high energy waves.

The morphodynamic model created for the transitional sand and gravel beaches of northern Pegasus Bay could not be directly applied to Gore Bay, however, some of the variations to the model, described for those beaches at either end of northern Pegasus Bay, are similar to the way in which the Gore Bay coastal system operates. No attempt has been made in this thesis to extend Hall's (1995) model to reflect the spatial variations in the morphodynamic response of transitional sand and gravel beaches, because more quantification of the process-response system is needed before such a model can be delineated. In particular, the dynamics of the surf zone need to be investigated and beach profiles extended to beyond the depth of closure. The

response of the beach to intermediate wave conditions also needs further investigation.

Transitional sand and gravel beaches are not widely recognised in published literature. Similar variations to the typical mixed sand and gravel beach have been acknowledged in unpublished reports and theses, such as Pescini (2000) in northern Pegasus Bay; Tranz Rail (1996) in Clifford Bay and Single (1985) at Napier. However, the differences between ‘mixed sand and gravel’ and ‘transitional sand and gravel’ beaches have not been explicitly defined. The following section attempts this quantification, by comparing the features of a typical mixed sand and gravel beach to Gore Bay.

6.3.4 Differences between mixed sand and gravel and transitional sand and gravel beaches

Transitional sand and gravel beaches are different to the typical mixed sand and gravel beach described by Kirk (1980). But are they different enough to be considered a separate beach type, or are they simply a variation to the typical mixed sand and gravel beach? Table 6.3 compares and contrasts the major features of mixed sand and gravel beaches, taken from the literature, with the features of a transitional sand and gravel beach, as evidenced by the findings of this investigation. This comparison will determine which features of a mixed sand and gravel beach are present on a transitional sand and gravel beach and which features are not. This knowledge will allow the determination of the process-response principles of mixed sand and gravel beaches that can be applied to Gore Bay. The process-response principles that are not applicable to Gore Bay will also be determined.

In Gore Bay, there is a distinct variation in beach characteristics from north to south, caused by the sheltering effect of Point Gibson and the reefs to the south of the bay. As mixed sand and gravel beaches are generally exposed to the prevailing wave conditions, characteristics from the northern end of Gore Bay will be used in the comparison, to remove wave energy as a significant factor. The typical features of a pure sand beach have also been included in the comparison, to highlight the idea that transitional sand and gravel beaches display characteristics of both pure sand and mixed sand and gravel beaches.

Table 6.3: Comparison of transition sand and gravel beaches with mixed sand and gravel beaches and pure sand beaches.

| Mixed sand and gravel beach | Transitional sand and gravel beach | Pure sand beach |
|---|---|---|
| Contain a wide range of sediment sizes from sand to boulders. | Contain a wide range of sediment sizes from sand to cobbles. | Contain a narrow range of sediment sizes from very fine sand to very coarse sand. |
| Consist mainly of greywacke clasts. | Consist mainly of greywacke clasts. | Usually consist of some combination of quartz, feldspar and lithics. |
| Comprise of entirely intermixed sand and gravel across the entire profile. | Distribution of sand and gravel is temporally and spatially variable. | Comprise entirely of sand. |
| Bladed clasts are dominant, with platy shapes the next most common. | Bladed clasts are dominant, with platy shapes the next most common. | Particle shape is difficult to measure and not as important as particle size. |
| Sediment is often bi- or poly-modal, so mean grain size is often irrelevant. | Sediment is often bi- or poly-modal, so mean grain size is often irrelevant. | Sediment can be bimodal, but the modes are close together. |
| Backed by Pliocene and Holocene alluvial plains and fans often crossed by major rivers. | Backed by an ancient dune field and prograded coastal plain. | May be prograding or eroding, backed by dunes or cliffs or plains. |
| The foreshore is moderately steep (5 – 12°). | The foreshore at the northern end is around 4-8°. In the sheltered southern end, foreshore slope is between 2 – 4°. | The foreshore is shallow (0.5 – 1.5°). |
| Beach profiles are typically convex upwards. | Beach profiles are typically concave upwards. | Beach profiles are typically linear or slightly concave upwards. |
| There are often tiers of berms related to deposition and erosion episodes of differing magnitudes. | There are often tiers of berms, often with well developed cusps. | Berms are often poorly defined due to low foreshore gradient. |
| There is usually a step between the mixed sediments of the foreshore and the fine sand low gradient nearshore seabed. | At no times was a step observed between the foreshore and nearshore seabed. | Sand beaches do not usually have a nearshore step. |
| Are exposed to high energy waves of an East Coast Swell Environment. | The northern end is exposed to high energy waves of an East Coast Swell Environment. The southern end is largely sheltered from the prevailing waves. | May be exposed to high energy or low energy waves. |
| Surf zone is narrow, most often consisting of one line of breakers which show little horizontal translation during the tidal cycle. | A wide surf zone (100-300m) is present under all but the calmest conditions. | A wide surf zone is generally present |
| Breakers are usually of the plunging type. | Breakers ranged from spilling to plunging. | Breakers can be collapsing, spilling or plunging. |
| The profile is dominated by swash and backwash processes. | Surf zone processes and swash-backwash processes play a large role in determining beach morphology. | The profile is dominated by surf zone processes. |

It can be seen from Table 6.3 that the sedimentary characteristics of mixed sand and gravel beaches are similar to those of transitional sand and gravel beaches. Pure sand beaches have very different sedimentary characteristics. Morphologically, transitional sand and gravel beaches occur somewhere between the steep, reflective mixed sand and gravel beaches and the shallow, dissipative sand beaches.

While the sediments of mixed sand and gravel beaches may be similar to transitional sand and gravel beaches, it is the morphology seaward of the swash zone where the major differences occur. Transitional sand and gravel beaches have a surf zone, with offshore bars present after large storm events. The surf zone is therefore an important part of a transitional sand and gravel beach. In the surf zone, processes similar to pure sand beaches operate, where sediment is moved offshore during high energy conditions and onshore during low energy conditions. In the swash zone, gravels move onshore when beach permeability is high and offshore when beach permeability is low. The swash zone of a transitional sand and gravel beach is not usually as high energy as on a mixed sand and gravel beach, due to dissipation of wave energy in the surf zone.

In contrast, a mixed sand and gravel beach is dominated by swash zone processes as there is no surf zone. Plunging waves break in a single line at all stages of the tidal cycle due to the presence of the steep nearshore face. There is little or no offshore-onshore recycling of sediment. In the swash zone, foreshore slope depends on the permeability of the beach, as it does on a transitional sand and gravel beach. Factors influencing permeability are the same for both beach types and include grain size, sorting and the interaction between swash/backwash flows. However, transitional sand and gravel beaches have a much higher proportion of sand in the swash zone than mixed sand and gravel beaches, which is reflected in the beach morphodynamics.

From the above comparison, it can be concluded that transitional sand and gravel beaches are a distinct beach type and should be distinguished from the typical mixed sand and gravel beaches described by Kirk (1980). The presence of a surf zone means that the principles of a mixed sand and gravel beach cannot be directly applied to Gore Bay. The presence of a gravel component means that the principles of a pure sand beach also cannot be directly applied to Gore Bay. Several theories developed

for mixed sand and gravel beaches still hold true at Gore Bay, including the influence of grain size and sorting on beach permeability and the influence of permeability on beach slope. The behaviour of the sand component at Gore Bay appears to respond in a similar fashion to that of a pure sand beach, however this needs further investigation. It is concluded that transitional sand and gravel beaches like Gore Bay are a distinct environment and should be treated as such.

In order to effectively manage transitional sand and gravel beaches, knowledge of the spatial and temporal variation in sediments and morphology and the complex process-response relationship are required. Gore Bay does not operate in the same way as a mixed sand and gravel beach or a pure sand beach. Rather, it possesses some characteristics of both, which results in a complex morphodynamic system that cannot be understood without site specific investigation, including spatial and temporal descriptions of processes, sediments and morphology.

6.4 Chapter Summary

By combining knowledge gained through investigations into the processes, sediments and morphology of Gore Bay, the morphodynamics of the coastal system were determined. The sand and gravel components of the system respond separately to the process environment, with the response of the gravel dependent on the behaviour of the sand. As a result, the morphology of the beach is heavily dependent on the sedimentary characteristics, which vary both spatially and temporally. Due to the large alongshore variation in sedimentary characteristics, the north and south of Gore Bay respond differently to changes in the process environment. The sand component behaves as it would on a pure sand beach, moving offshore during high energy events to form an offshore bar and returning onshore during low energy periods. The behaviour of the gravel depends on the level of permeability of the beach. Beach permeability is dependent on the proportion of sand, the size of the gravels and the interaction of the swash and backwash.

Through the application of a gravel beach classification scheme (Jennings & Shulmeister 2002), the northern end of Gore Bay can be visually classified as a composite gravel beach, but the southern end does not fit the visual description of any

of the three end members. When basic parameters were measured at Gore Bay and compared to the typical values associated with each beach type, the north of Gore Bay was similar to a mixed sand and gravel beach, while the southern end did not match the typical parameters of any of the beach types, as determined by Jennings and Shulmeister (2002). This indicates that the classification scheme is not robust enough to enable classification of all gravel-bearing beaches. While the classification scheme provides a good description of the main characteristics of the three end member beach types, there is significant overlap of discriminating parameters which suggests that the categories are not entirely discrete.

Gore Bay is a transitional sand and gravel beach, similar to those of northern Pegasus Bay. Lack of recognition in the published literature of a transitional type of gravel beach has led to such beaches often being described as mixed sand and gravel beaches (Siemelink 1984; Slark 1984; Hall 1995; Pescini 2000), which are assumed to have the same morphodynamic characteristics as those described by Kirk (1980). This chapter has identified the differences between the two types of beach, concluding that a transitional sand and gravel beach is a distinct beach type, not simply a variation to the typical mixed sand and gravel beach. The presence of a surf zone and the combination of sand beach processes and mixed sand and gravel beach processes make transitional sand and gravel beaches such as Gore Bay unique. Management of transitional sand and gravel beaches therefore requires site specific investigation, rather than the application of “text-book” coastal principles.

CHAPTER SEVEN

CONCLUSIONS

7.1 Thesis Aims Revisited

This thesis has presented, described and interpreted the results of an investigation into the coastal system of Gore Bay, North Canterbury. Such an investigation is necessary for the effective management of any beach and until now has been lacking at Gore Bay. The purpose of this chapter is to summarise the main findings of the investigation with respect to the aims and objectives set out in Chapter One.

The primary aim of this thesis was to provide a thorough description of the Gore Bay coastal system, so that those involved in the management of coastal resources have an understanding of the environment and a benchmark with which to compare future studies. The secondary aim was to determine what type of mixed sediment beach Gore Bay is, so that knowledge gained from similar beaches can be used for management of the Gore Bay coastal system. Five objectives were set to achieve these aims:

- To identify and describe the processes operating within the Gore Bay coastal system.
- To describe and interpret the nature of the sediment in Gore Bay.
- To describe and interpret the morphology of Gore Bay.
- To identify and describe the interaction and feedback mechanisms between these three components.
- To compare the characteristics of Gore Bay to those of various “beach types” described in the literature.

7.2 Summary of the Main Findings

The first objective of this thesis was to identify and describe the processes operating within the Gore Bay coastal system. Processes identified included tides, currents,

waves, wind and human processes. Gore Bay has a semi-diurnal tidal cycle with a mean spring tidal range of around 1.5 metres. The prevailing offshore current is the Southland Current, which travels north along the east coast of the South Island at a rate of between 0.5 and 0.8 metres per second (Yetton & Garland 1988). Net longshore transport along the North Canterbury coast has been estimated at around 100 000 – 250 000 cubic metres per year (Gibb 1979). The continental shelf extends approximately 30 kilometres off the coast of Gore Bay, at a depth of around 130 metres. This width increases to the south of Gore Bay and decreases to the north.

The wave climate at Gore Bay consists of two main components: long period waves from a south or south east direction and shorter period, locally generated waves from an east or north east direction. Locally generated waves observed at Gore Bay are not always recorded by the Environment Canterbury deepwater directional waverider buoy, due to the large distance between the buoy and Gore Bay. It is recommended that future studies requiring quantitative information on wave conditions in North Canterbury should collect site specific wave data.

Observed wave height at Gore Bay varies from less than one “foot” (see Section 3.3.2 for definition) to more than six “feet”, with the majority of waves between one and three “feet”. Southerly waves are dominant, although easterly and north easterly waves are also common. The majority of large waves observed in Gore Bay come from a southerly direction, while less energetic conditions are typically associated with easterly or north easterly waves. Gore Bay is partially sheltered from southerly waves, by the reefs associated with Point Gibson and Manakau Bluff. Historically, periods of erosion at Gore Bay have been associated with extreme high seas caused by a combination of severe storm events and spring tides. The majority of large storms occur between April and August, although large waves can occur at any time of the year.

Wind patterns at Gore Bay reflect the large scale wind regime of New Zealand, with winds most commonly arriving from a north westerly, southerly or easterly/north easterly direction. Wind patterns observed at Gore Bay are better reflected by those recorded by the Cheviot climate station than the Kaikoura climate station, however there is some variation. North easterly winds can entrain sand from the midshore of

central Gore Bay, depositing it in the backshore where incipient dunes are forming. Wind is also important in modifying the wave environment, as reflected in the large number of locally generated, north easterly waves. Strong north easterly winds can offset the prevailing offshore current, thereby reducing its capacity to transport sediment (Yetton & Garland 1988).

Human activities have also been shown to be an active part of the process environment at Gore Bay. Foredunes were levelled and cleared of vegetation in the late 1800s to improve ocean views and increase the land area suitable for construction. Groynes were constructed which interrupted transfers of sediment along the beach. Breastwork and seawalls were constructed in the backshore and foreign material has been dumped along “at-risk” sections of the backshore scarp. Currently, the mouth of Buxton Stream is regularly bulldozed to prevent back up of the lagoon in times of high flow, which causes inundation of the adjacent land.

The second objective of this thesis was to describe and interpret the nature of the sediment in Gore Bay. A comprehensive sampling of Gore Bay yielded a suite of 39 samples from the back-, mid- and fore- shore. Analysis revealed that mean grain size and the degree of sorting generally decreases from north to south and from backshore to foreshore. These patterns were linked to the proportion of sand present on the beach, which generally increases from north to south and from backshore to foreshore. Summary statistics such as mean grain size and sorting are often not the best descriptors for mixed sediment beaches, due to the bimodality of many samples. The higher order summary statistics of skewness and kurtosis were not used in this thesis, due to the large discrepancies between the two widely used methods of calculating them.

Two discrete sediment populations were identified within Gore Bay, a pebble mode at around -5ϕ (32mm) and a sand mode at around $+2\phi$ (0.25mm). The pebble mode was identified along the entire length of Gore Bay, while the sand mode was only present in the southern part of the bay at the time of sampling. Pebbles in the backshore were found to be slightly coarser than those in mid- or fore- shore.

Blade shaped clasts are most common in Gore Bay, with a higher proportion of platy clasts in the back- and mid- shore than in the foreshore due to the way in which different shaped gravels are entrained and deposited by waves. There is a slight trend of decreasing roundness with distance northwards in Gore Bay, which indicates a net northward transport of beach gravels. This tentative conclusion is strengthened by observations of changing beach composition, where several subordinate lithologies sourced from the Manakau Bluff and associated reef at the south of Gore Bay are found in decreasing quantities to the north.

Rollability analysis found that sand is transported offshore under storm conditions. This conclusion was supported by photographic evidence which documented changes in the distribution of sand and gravel within Gore Bay. The distribution of sand and gravel was linked to the morphodynamic response of the beach.

The third objective of this thesis was to describe and interpret the beach morphology of Gore Bay. The majority of the beach at Gore Bay is backed by a scarp which has been cut into the dune field on which the village is developed. This scarp is vegetated and has not changed position throughout the study period. In the north of Gore Bay, the backshore scarp gives way to a washover surface, which slopes gently landward from the highest storm berm. Around the Buxton Camp area (Sites H5765 and H5782) an artificial bund has been constructed on the washover surface to prevent inundation of the land during storms. Beach height generally increases from south to north in Gore Bay, while beach width generally decreases. Beach slope correspondingly increases to the north. Monthly envelopes of change at Gore Bay contain between 14 and 28 cubic metres of sediment per linear metre of beach, with no clear alongshore trend in the size of the envelope. There are no clear seasonal trends in beach profile response in Gore Bay. Instead, profile changes were linked to the characteristics of recent wave conditions.

Gore Bay has shown little net change in beach position or volume over the last ten years, with the majority of annual change occurring within the short term envelope. At some sites in the centre of the village there has been a slight trend of accretion since 1993. In the long term, the position of the scarp appears to have remained fairly constant over the past twenty-five years, but prior to that had undergone significant

retreat. Beach volume and width have increased considerably since the 1930s, which means the beach is now better equipped to withstand attack from a series of high seas than it has been in the past.

The fourth objective of this thesis was to identify and describe the interactions and feedback mechanisms between the processes, sediments and morphology of the Gore Bay coastal system. There is a complex interaction between these three variables at Gore Bay, whereby the morphological response of the beach is dependent on both the characteristics of the wave environment and the distribution of sediments along the beach. The sand and gravel populations in Gore Bay respond differently to changes in wave conditions, with the response of the gravel dependent on the behaviour of the sand population. Sand behaves in a similar fashion to a pure sand beach, moving offshore to form a bar during high energy conditions and returning to the foreshore under low energy conditions. When the sand is offshore in a bar deposit, the gravel on the beach becomes better sorted and more permeable, so the gravel exposed by the eroding sand moves onshore under the strong swash flow, steepening the beachface. As the sand returns under lower energy conditions, the gravel lag is covered and the permeability of the gravel decreases, causing offshore movement of the gravel and a shallowing of the beachface slope. Because of the high sand content in the south of Gore Bay, the degree of sorting is always relatively poor and average grain size is smaller, resulting in shallower beach slopes than in the north of the bay.

Wave height is not the only factor influencing beach response at Gore Bay, as waves of similar heights from different directions cause different responses. This appears to be a function of the different periods of incoming waves. Southerly waves tend to be generated in the South Pacific and are long period swells by the time they reach the east coast of the South Island. North easterly waves tend to be locally generated, shorter period waves. The backwash of shorter period waves do not have as much time to clear the beach before the swash of the next wave arrives, resulting in less infiltration and relatively strong backwash compared to the swash flow. Gravels pushed up the beach by the swash are able to return down the beach with the backwash, thereby reducing beach slope.

A model was created to illustrate the alongshore variation in morphodynamics at Gore Bay, which incorporated beach response to three distinct wave conditions. More quantitative investigation of the process environment would allow the morphodynamic response to a wider range of wave conditions to be modelled, thereby enhancing the level of understanding of the Gore Bay coastal system.

The fifth objective of this thesis was to compare the characteristics of Gore Bay to those of various beach types described in the literature. The purpose of this objective was to determine whether it was appropriate to assume that the processes occurring at Gore Bay were the same as at other beaches, and therefore whether knowledge gained from these beaches could be utilised in the management of the Gore Bay coastal system.

A classification scheme for gravel bearing beaches was used to help determine what type of beach Gore Bay was. The scheme has three end members: pure gravel, mixed sand and gravel, and composite gravel beaches. Because Gore Bay has a high proportion of sand, a wide surf zone and is often dissipative of wave energy, it cannot be classified as a pure gravel beach. Similarly, the presence of a surf zone and absence of a nearshore face mean that Gore Bay does not operate in the same way as a mixed sand and gravel beach, despite having been referred to as such in the literature (Slark 1984). Parts of Gore Bay appear to be similar to a composite gravel beach at times, but Gore Bay does not fit the typical parameters for such a beach, as determined by the classification scheme of Jennings and Shulmeister (2002).

A fourth type of mixed sediment beach was identified in unpublished literature (Hall 1995), which was termed a transitional sand and gravel beach. Although differences were recognised between beach response at Gore Bay and the morphodynamic model created for the transitional sand and gravel beaches described by Hall (1995), some of the variations to the model match the way the Gore Bay coastal system operates. The characteristics of a transitional sand and gravel beach were compared to that of a mixed sand and gravel beach, in order to determine if they were distinct beach types or simply variations of the same beach type. Transitional sand and gravel beaches display many similar characteristics to mixed sand and gravel beaches, especially with regard to beach sediments. However, the presence of a surf zone and the process-

response feedback within both the surf and swash zones of a transitional sand and gravel beach allow transitional sand and gravel beaches to be considered a distinct beach type from mixed sand and gravel beaches. Management of transitional sand and gravel beaches requires site specific investigation rather than the application of “text-book” coastal principles.

7.3 Suggestions for Further Research

This thesis provides a thorough baseline description of the Gore Bay coastal system, the findings of which can be used to ensure that any management solutions are compatible with the way in which the coastal system operates. Gore Bay is a transitional sand and gravel beach, similar to those found in northern Pegasus Bay. While these beaches show some similarities to mixed sand and gravel beaches, the presence of a surf zone means that they are morphodynamically different. Although this thesis has achieved its aims, there is still much to be investigated, both with regard to the Gore Bay coastal system and in the wider context of mixed sediment beaches. This includes, but is not limited to:

- Further study of the process environment, including the role of wave refraction and a broader range of wave environment characteristics.
- Examination of the surf zone dynamics in greater detail, by extending profiles to the depth of closure.
- Developing the morphodynamic model of Hall (1995) to include more of the spatial and temporal variations seen on transitional sand and gravel beaches and to consider a wider range of wave conditions.
- Quantification of the sediment budget of Gore Bay.
- Investigation into the long term geomorphic evolution of Gore Bay, especially of the northern coastal plain.
- Reworking the classification scheme of Jennings and Shulmeister (2002) to include transitional sand and gravel beaches as an end member and using parameters better suited to the mixed sediment beach environment.

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APPENDICES

Appendix A

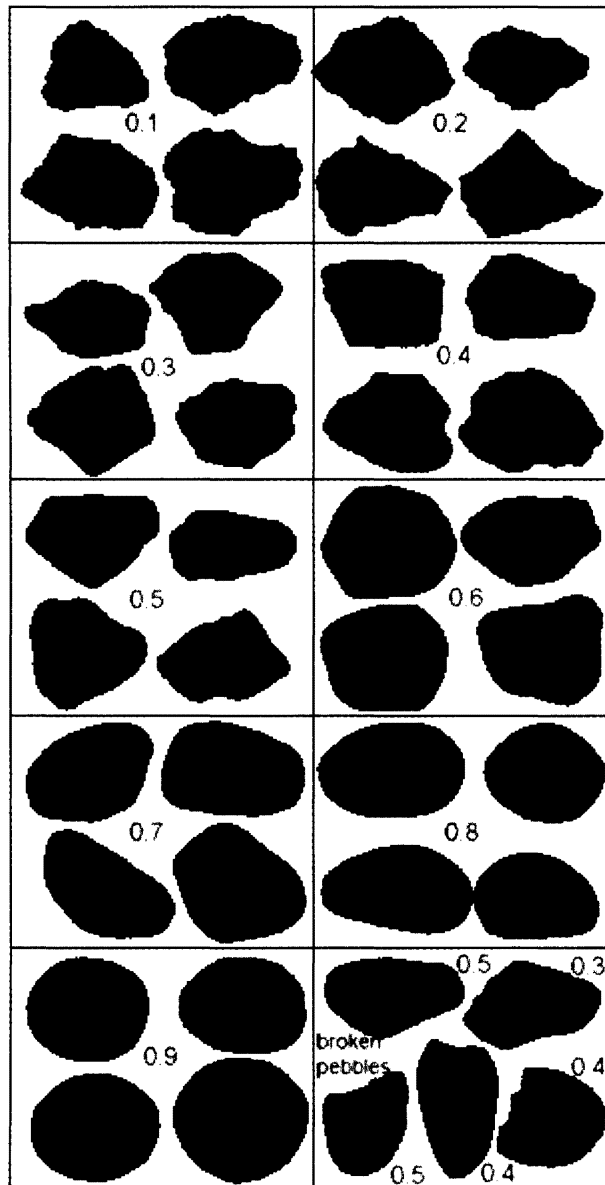
The Udden-Wentworth scale with the phi (ϕ) scale of Krumbein (1941).

The highlighted text is Wentworth's (1922) simplified classifications. The other nominal classifications are based on Udden's (1914) version.

| Grain Size (mm) | Microns | Phi Class (ϕ) | Nominal Classifications |
|-----------------|-----------|----------------------|---|
| 4098 – 2048 | | -12 to -11 | GRAVEL --- Boulder --- very large boulder |
| 2048-1024 | | -11 to -10 | large boulder |
| 1024-512 | | -10 to -9 | medium boulder |
| 512-256 | | -9 to -8 | small boulder |
| 256-128 | | -8 to -7 | --- Cobble --- large cobble |
| 128-64 | | -7 to -6 | small cobble |
| 64-32 | | -6 to -5 | --- Pebble --- large pebble |
| 32-16 | | -5 to -4 | medium pebble |
| 16-8 | | -4 to -3 | small pebble |
| 8-4 | | -3 to -2 | very small pebble |
| 4-2 | | -2 to -1 | --- Granule --- granules |
| 2.0-1.0 | 2000-1000 | -1 to 0 | --- SAND --- Sand --- very coarse sand |
| 1.0-0.5 | 1000-500 | 0 to 1 | coarse sand |
| 0.50-0.25 | 500-250 | 1 to 2 | medium sand |
| 0.25-0.125 | 250-125 | 2 to 3 | fine sand |
| 0.125-0.0625 | 125-62.5 | 3 to 4 | very fine sand |
| 0.0625-0.0311 | 62.5-31.1 | 4 to 5 | --- MUD --- Silt --- coarse silt |
| 0.311-0.0156 | 31.1-15.6 | 5 to 6 | medium silt |
| 0.0156-0.0078 | 15.6-7.8 | 6 to 7 | fine silt |
| 0.0078-0.0039 | 7.8-3.9 | 7 to 8 | very fine silt |
| 0.0039-0.0020 | 3.9-2.0 | 8 to 9 | --- Clay --- very coarse clay |
| 0.0020-0.00098 | 2.0-0.98 | 9 to 10 | coarse clay |
| 0.00098-0.00049 | 0.98-0.49 | 10 to 11 | medium clay |
| 0.00049-0.00024 | 0.49-0.24 | 11 to 12 | fine clay |
| 0.00024-0.00012 | 0.24-0.12 | 12 to 13 | very fine clay |
| 0.00012-0.00006 | 0.12-0.06 | 13 to 14 | extremely fine clay |

Appendix B

Silhouette images for the visual assessment of pebble roundness



Based upon Krumbein (1941)

Appendix C

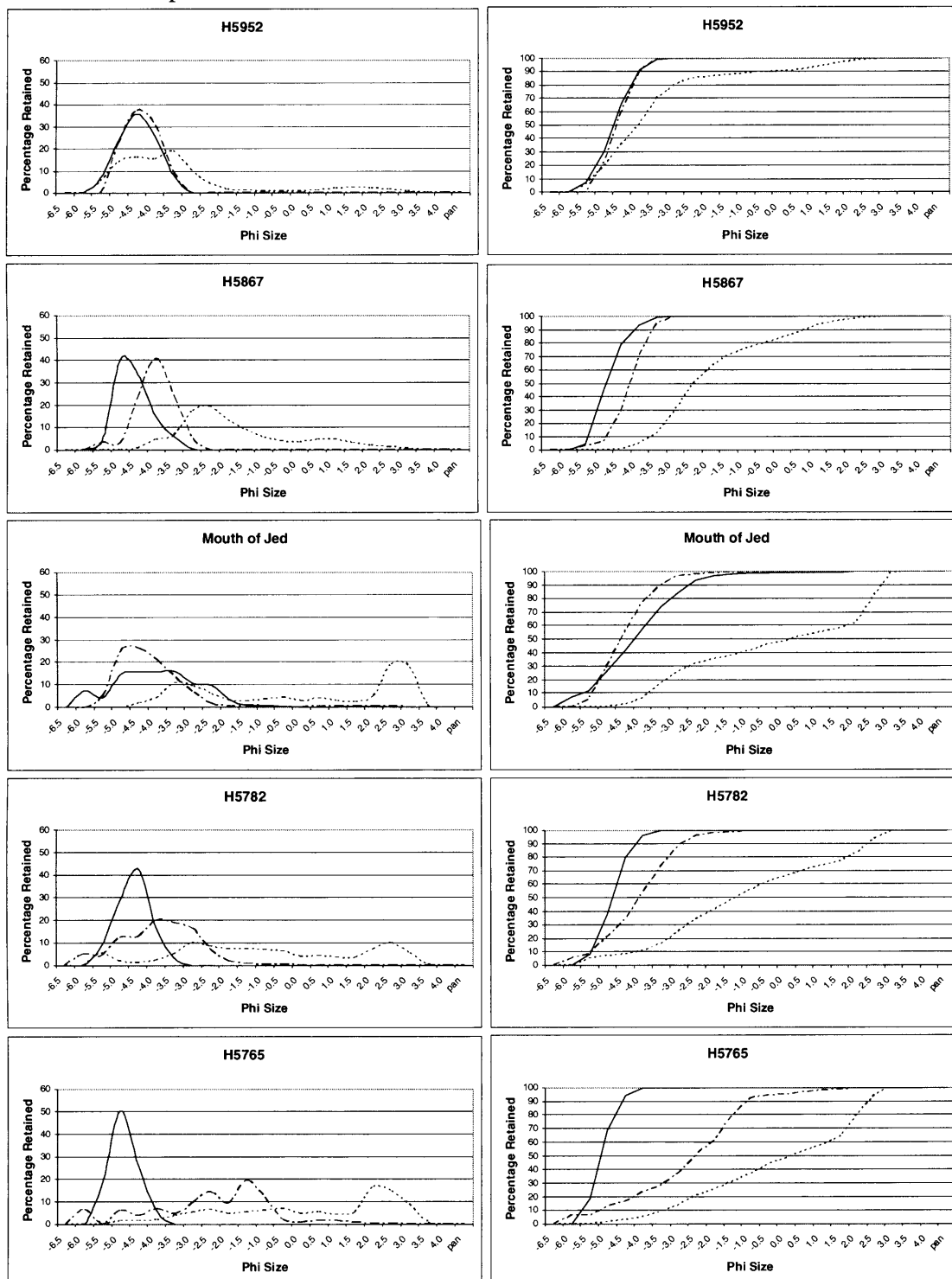
Frequency distribution curves and cumulative frequency curves for Gore Bay sediment samples

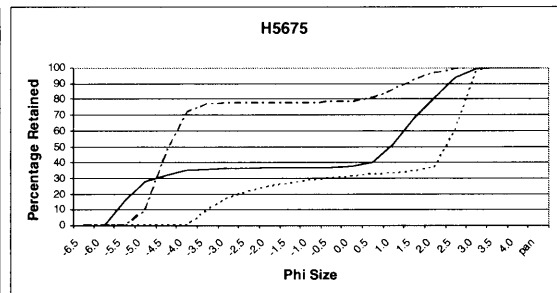
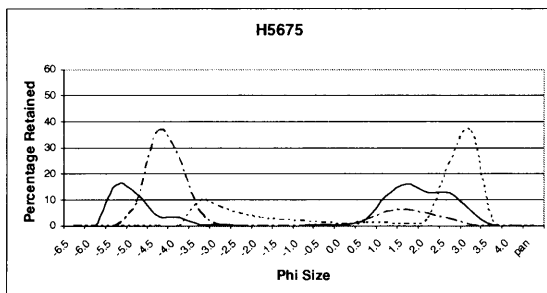
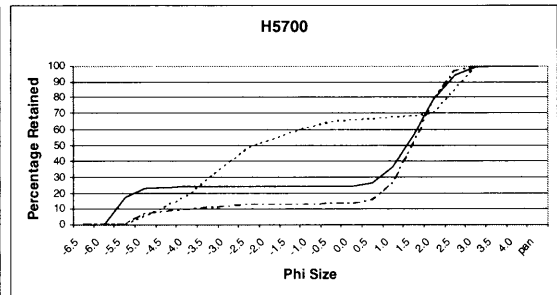
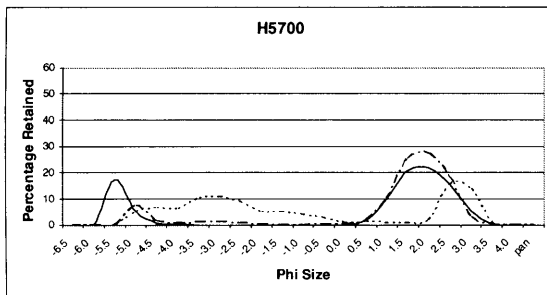
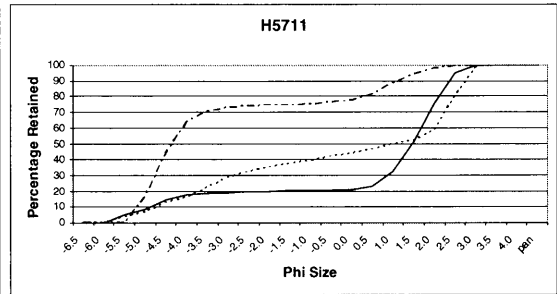
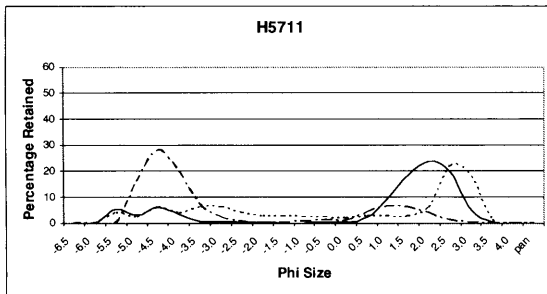
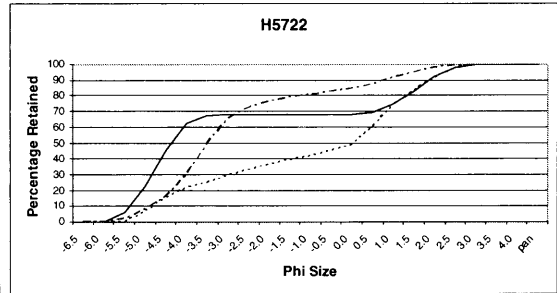
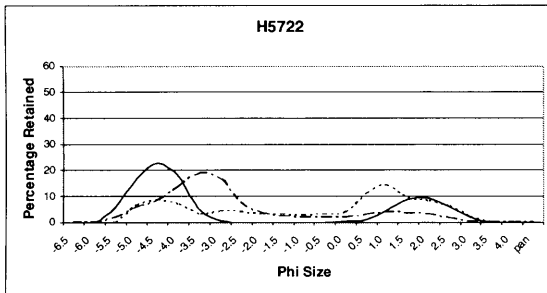
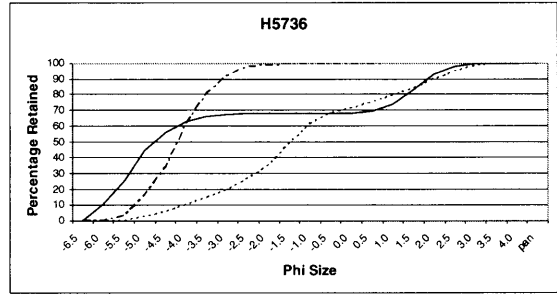
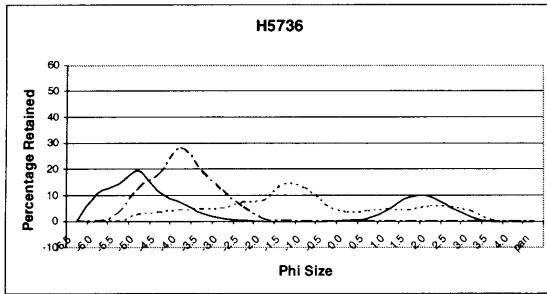
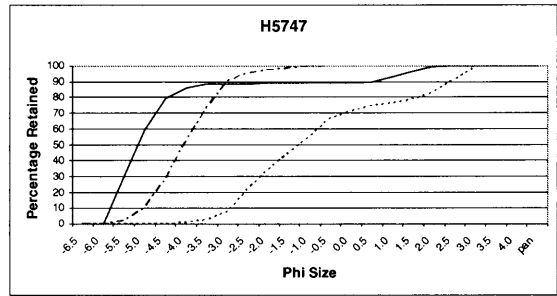
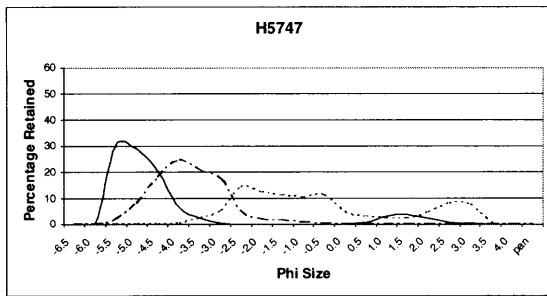
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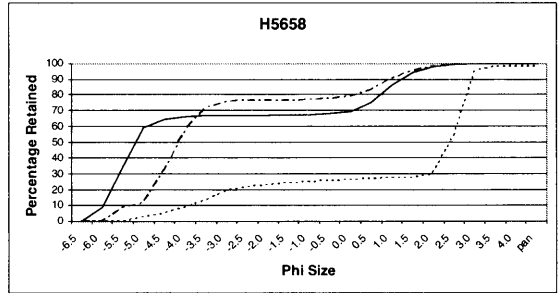
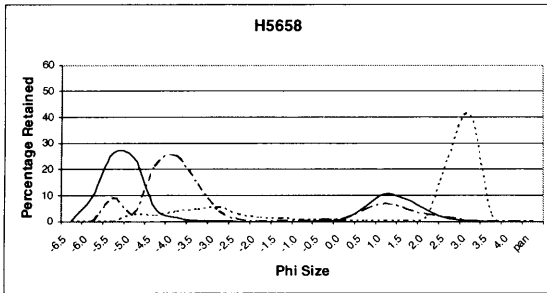
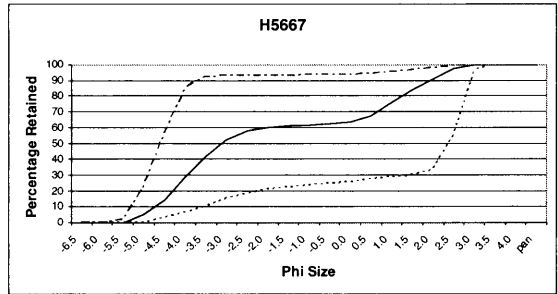
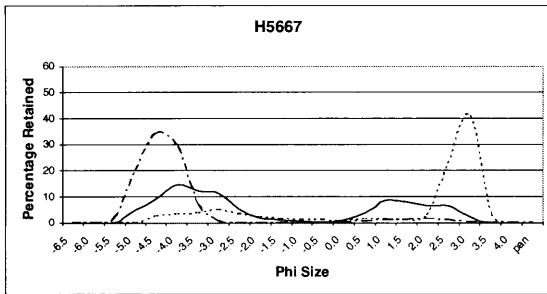
Backshore Samples – solid line

Midshore Samples – dashed line

Foreshore Samples – dotted line







Appendix D

Summary statistics for Gore Bay sediment samples

| Sample Site | Method of Moments | | | | Graphical Method | | | |
|-------------|-------------------|-------------|----------|----------|------------------|-------------|----------|----------|
| | Mean Size (Ø) | Sorting (Ø) | Skewness | Kurtosis | Mean Size (Ø) | Sorting (Ø) | Skewness | Kurtosis |
| H5952-B | -4.72 | 0.53 | 0.04 | 2.54 | -4.73 | 0.57 | 0.96 | 0.01 |
| H5952-M | -4.61 | 0.46 | 0.19 | 2.18 | -4.63 | 0.51 | 0.93 | 0.04 |
| H5952-F | -3.59 | 1.93 | 1.69 | 5.31 | -3.92 | 1.67 | 1.77 | 0.35 |
| H5867-B | -4.93 | 0.41 | 0.29 | 2.53 | -4.94 | 0.42 | 0.86 | 0.15 |
| H5867-M | -4.28 | 0.53 | -0.46 | 3.63 | -4.26 | 0.53 | 1.05 | -0.07 |
| H5867-F | -1.97 | 1.62 | 0.89 | 3.04 | -1.94 | 1.66 | 1.08 | 0.43 |
| H5825-B | -4.18 | 1.24 | 0.87 | 5.58 | -4.19 | 1.18 | 0.99 | 0.04 |
| H5825-M | -4.47 | 0.96 | 2.85 | 18.01 | -4.54 | 0.75 | 0.92 | 0.20 |
| H5825-F | -0.26 | 2.65 | -0.23 | 1.42 | -0.27 | 2.60 | 0.53 | -0.22 |
| H5782-B | -4.86 | 0.48 | 0.20 | 3.48 | -4.86 | 0.50 | 1.04 | -0.04 |
| H5782-M | -4.16 | 0.99 | -0.08 | 2.89 | -4.17 | 1.02 | 0.98 | -0.11 |
| H5782-F | -1.14 | 2.46 | 0.01 | 1.98 | -0.97 | 2.60 | 0.78 | 0.11 |
| H5765-B | -5.16 | 0.40 | 0.32 | 2.72 | -5.15 | 0.43 | 1.04 | 0.08 |
| H5765-M | -2.74 | 1.70 | -0.15 | 3.14 | -2.82 | 1.74 | 1.15 | -0.20 |
| H5765-F | -0.08 | 2.27 | -0.46 | 1.97 | -0.08 | 2.29 | 0.70 | -0.27 |
| H5747-B | -4.47 | 2.08 | 2.24 | 6.61 | -5.02 | 1.48 | 3.00 | 0.53 |
| H5747-M | -3.99 | 0.85 | 0.59 | 3.88 | -4.03 | 0.83 | 0.99 | 0.07 |
| H5747-F | -0.80 | 1.95 | 0.59 | 2.12 | -0.65 | 2.09 | 0.82 | 0.37 |
| H5736-B | -3.05 | 3.22 | 0.69 | 1.68 | -3.02 | 3.12 | 0.53 | 0.68 |
| H5736-M | -4.14 | 0.90 | 1.61 | 10.85 | -4.18 | 0.81 | 1.00 | 0.06 |
| H5736-F | -1.23 | 2.10 | 0.20 | 2.29 | -1.15 | 2.27 | 0.96 | 0.16 |
| H5722-B | -2.74 | 2.99 | 0.75 | 1.73 | -2.67 | 2.87 | 0.53 | 0.72 |
| H5722-M | -2.84 | 2.03 | 1.08 | 3.17 | -2.72 | 2.11 | 1.39 | 0.50 |
| H5722-F | -1.00 | 2.54 | -0.38 | 1.68 | -0.95 | 2.61 | 0.67 | -0.45 |
| H5711-B | 0.34 | 2.68 | -1.39 | 3.26 | -0.19 | 2.85 | 2.35 | -0.75 |
| H5711-M | -3.17 | 2.44 | 1.09 | 2.49 | -2.90 | 2.46 | 0.82 | 0.74 |
| H5711-F | -0.29 | 2.98 | -0.46 | 1.60 | -0.12 | 2.89 | 0.59 | -0.55 |
| H5700-B | -0.12 | 3.13 | -1.11 | 2.40 | -0.68 | 3.20 | 1.95 | -0.75 |
| H5700-M | 0.79 | 2.16 | -2.03 | 5.75 | 1.39 | 1.56 | 3.20 | -0.45 |
| H5700-F | -1.28 | 2.85 | 0.32 | 1.51 | -1.33 | 2.84 | 0.55 | 0.38 |
| H5675-B | -0.94 | 3.35 | -0.49 | 1.40 | -0.84 | 3.18 | 0.50 | -0.62 |
| H5675-M | -3.28 | 2.46 | 1.33 | 2.99 | -2.84 | 2.49 | 2.71 | 0.80 |
| H5675-F | 0.83 | 2.53 | -0.87 | 1.98 | 0.67 | 2.48 | 0.60 | -0.80 |
| H5667-B | -1.87 | 2.66 | 0.41 | 1.53 | -2.02 | 2.62 | 0.60 | 0.50 |
| H5667-M | -4.23 | 1.59 | 3.07 | 11.86 | -4.59 | 1.22 | 3.27 | 0.37 |
| H5667-F | 1.05 | 2.53 | -1.20 | 2.75 | 0.78 | 2.52 | 0.99 | -0.83 |
| H5658-B | -3.39 | 3.06 | 0.72 | 1.66 | -3.38 | 2.88 | 0.52 | 0.77 |
| H5658-M | -3.19 | 2.35 | 1.13 | 2.76 | -2.84 | 2.44 | 1.85 | 0.65 |
| H5658-F | -0.16 | 3.29 | -0.51 | 1.52 | 0.25 | 3.06 | 0.58 | -0.81 |

Appendix E

Benchmark Descriptions

Co-ordinates are in New Zealand Map Grid (NZMG).

Heights are expressed as metres above the Lyttelton Datum (1937) which is approximately 1.1 metres below mean sea level.

Site H5867

| | | |
|--------------|--------------------------|----------------------|
| | Fore site (+56.6 metres) | Benchmark (0 metres) |
| Northing: | 782174.968 | 782200.090 |
| Easting: | 348130.991 | 348080.295 |
| Height: | 2.835 | 2.115 |
| Description: | Iron rod in concrete | Old peg 50x50 |

Site H5782

| | | |
|--------------|--------------------------|----------------------|
| | Fore site (+50.9 metres) | Benchmark (0 metres) |
| Northing: | 781412.790 | 781424.287 |
| Easting: | 347800.777 | 347751.145 |
| Height: | 4.926 | 3.489 |
| Description: | Old peg 50x50 | Old peg 75x75 |

Site H5765

| | | |
|--------------|--------------------------|----------------------|
| | Fore site (+27.8 metres) | Benchmark (0 metres) |
| Northing: | 781255.125 | 781260.503 |
| Easting: | 347730.145 | 347702.848 |
| Height: | 4.613 | 3.468 |
| Description: | Old peg 50x50 | Old peg 75x75 |

Site H5747

| | | |
|--------------|----------------------------------|--------------------------|
| | Benchmark (0 metres) | Back site (-38.2 metres) |
| Northing: | 781086.564 | 781098.042 |
| Easting: | 347659.721 | 347623.286 |
| Height: | 5.632 | 7.978 |
| Description: | Old concrete benchmark with bolt | Iron rod in footpath |

Site H5736

| | | |
|--------------|--------------------------|--------------------------|
| | Benchmark (0 metres) | Back site (-11.6 metres) |
| Northing: | 780972.334 | 780975.836 |
| Easting: | 347622.357 | 347611.252 |
| Height: | 5.088 | 8.091 |
| Description: | Top of tramline (I beam) | Old peg 50x50 |

Site H5722

| | | |
|--------------|--------------------------|--------------------------|
| | Benchmark (0 metres) | Back site (-11.9 metres) |
| Northing: | 780841.389 | 780844.328 |
| Easting: | 347579.723 | 347568.386 |
| Height: | 4.297 | 11.471 |
| Description: | Top of tramline (I-beam) | Old peg 50x50 |

Site H5711

| | | |
|--------------|--------------------------|--------------------------|
| | Benchmark (0 metres) | Back site (-18.8 metres) |
| Northing: | 780741.357 | 780746.889 |
| Easting: | 347556.536 | 347538.583 |
| Height: | 3.516 | 10.217 |
| Description: | Top of tramline (I-beam) | Old peg 50x50 |

Site H5700

| | | |
|--------------|--------------------------|----------------------------------|
| | Fore site (+17 metres) | Benchmark (0 metres) |
| Northing: | 780639.101 | 780644.749 |
| Easting: | 347507.605 | 347491.602 |
| Height: | 6.915 | 7.387 |
| Description: | Old bridge spike in road | Old concrete benchmark with bolt |

Site H5675

| | | |
|--------------|-------------------------|--------------------------|
| | Fore site (+4.1 metres) | Back site (-11.4 metres) |
| Northing: | 780393.620 | 780396.425 |
| Easting: | 347460.609 | 347445.425 |
| Height: | 6.497 | 7.587 |
| Description: | Iron rod in concrete | Old peg 75x75 |

Site H5667

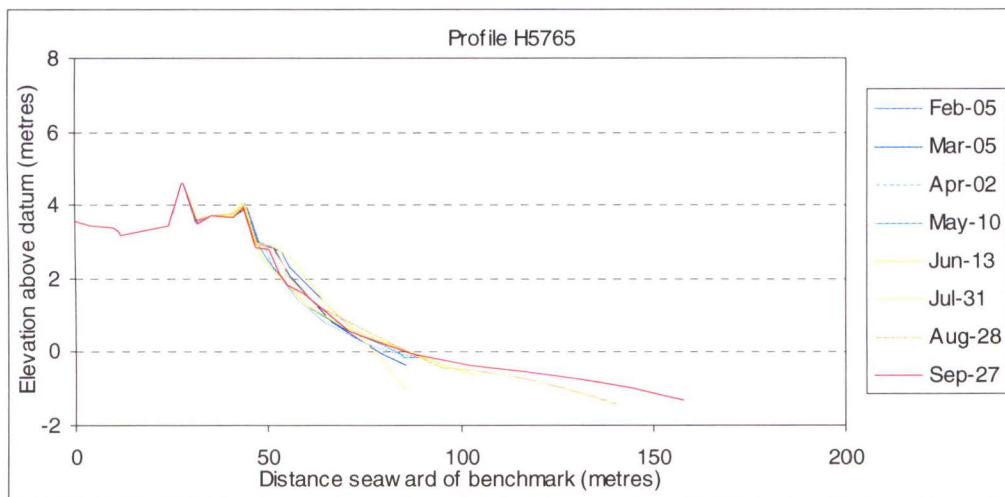
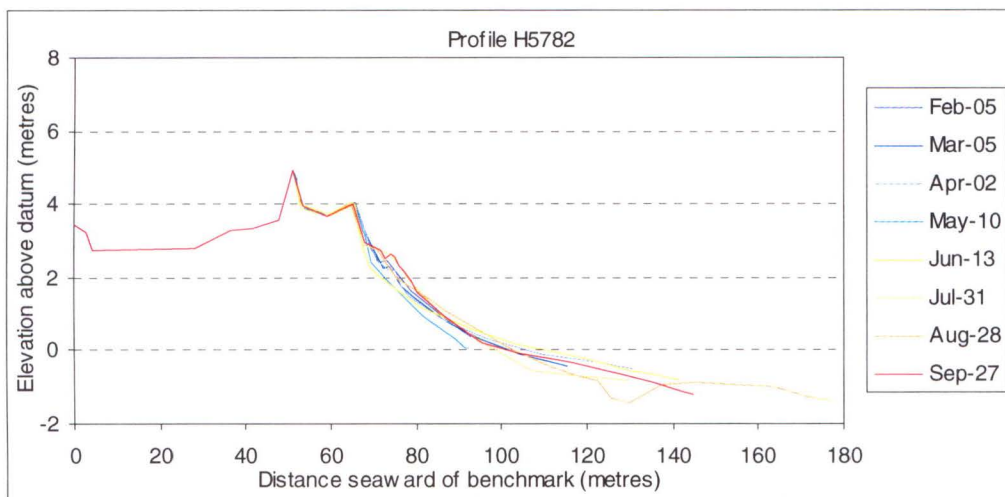
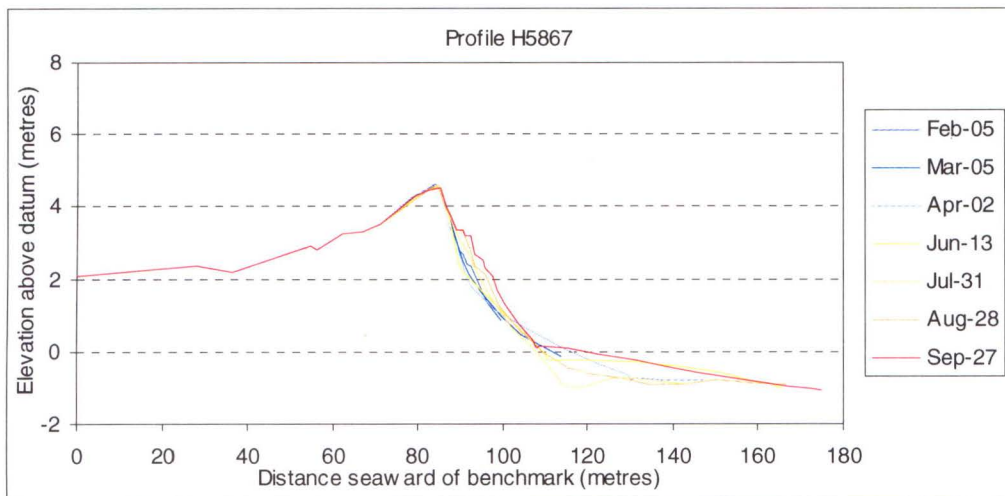
| | | |
|--------------|--------------------------|--------------------------|
| | Benchmark (0 metres) | Back site (-21.3 metres) |
| Northing: | 780325.756 | 780327.640 |
| Easting: | 347449.954 | 347428.700 |
| Height: | 6.825 | 6.974 |
| Description: | Old bridge spike in road | Old peg 75x75 |

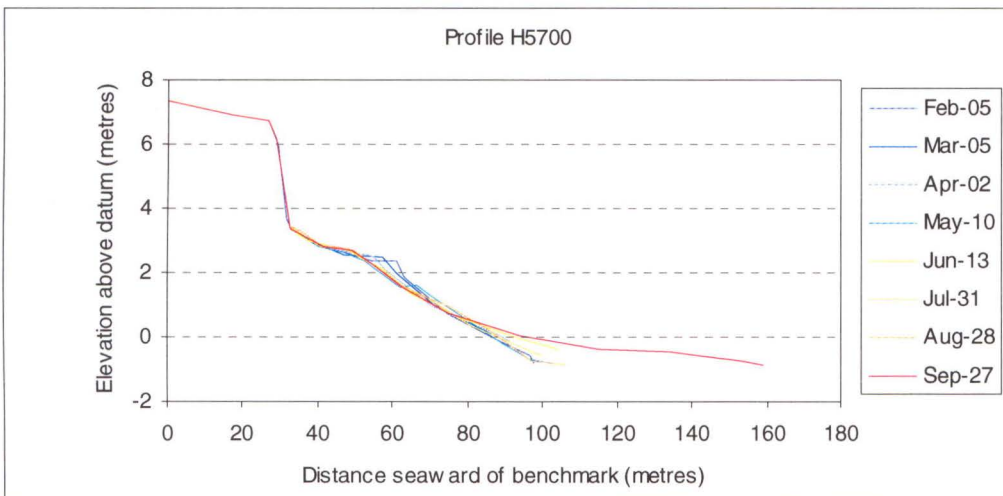
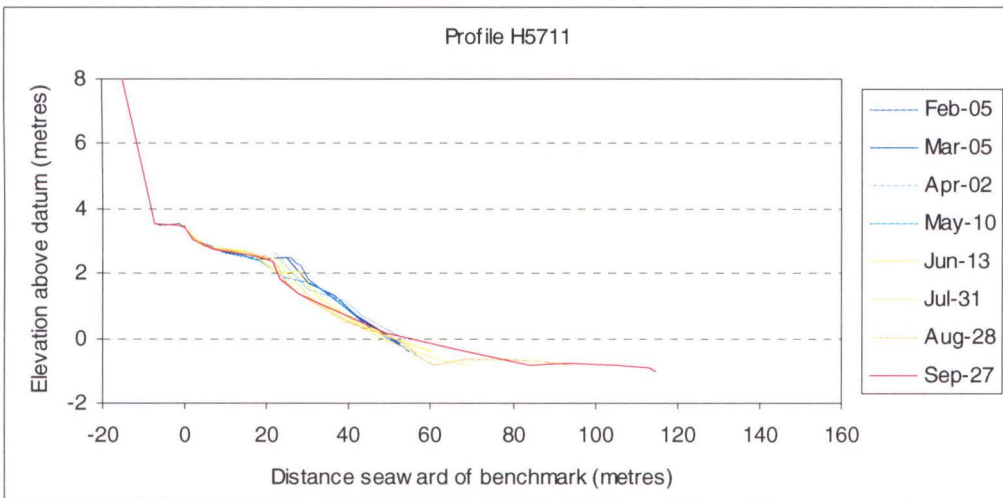
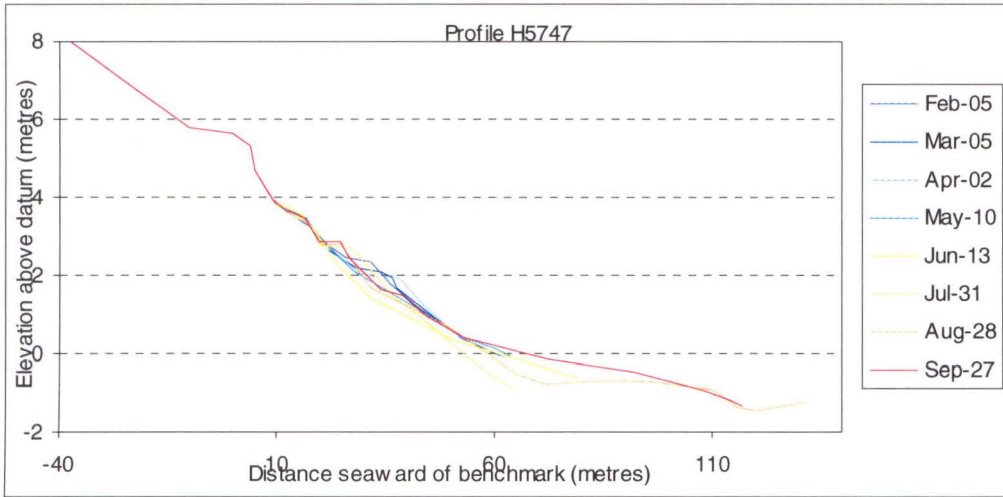
Site H5658

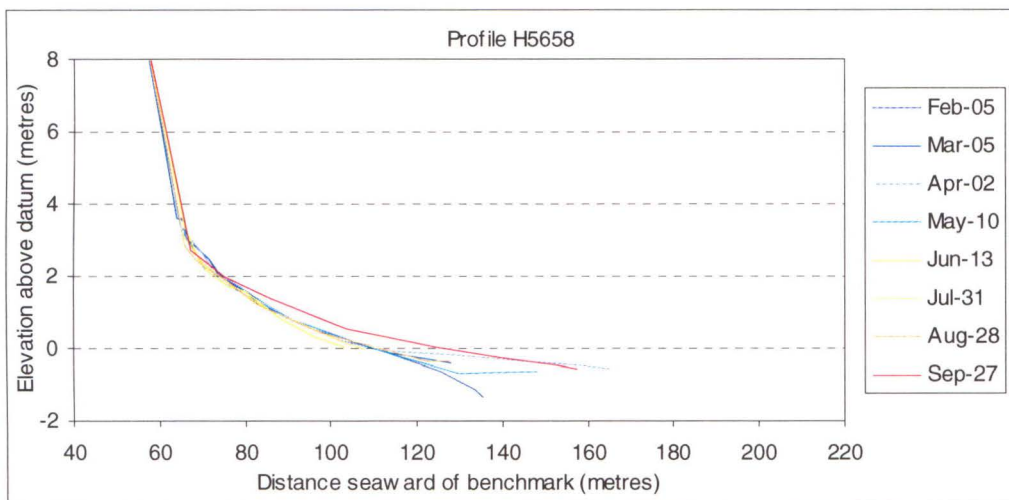
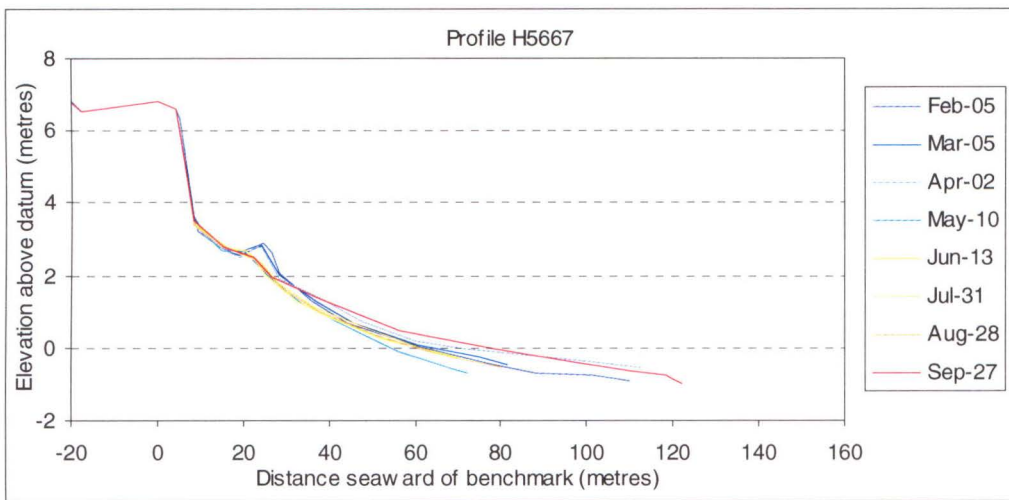
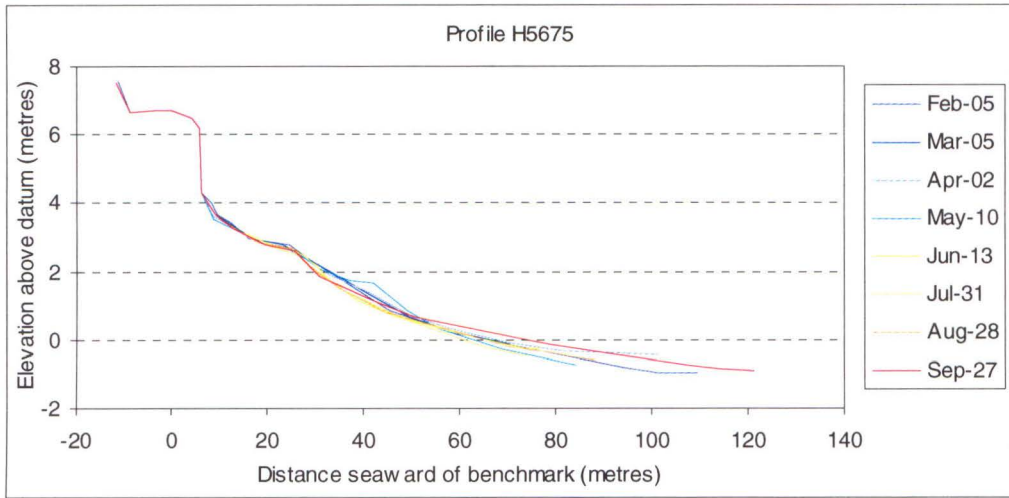
| | | |
|--------------|--------------------------|--------------------------|
| | Fore site (+50.6 metres) | Back site (-6.8 metres) |
| Northing: | 780288.249 | 780233.804 |
| Easting: | 347441.597 | 347384.450 |
| Height: | 9.656 | 15.799 |
| Description: | Iron rod in concrete | Old bridge spike in road |

Appendix F

Monthly profile variations at Gore Bay - February to September 2003

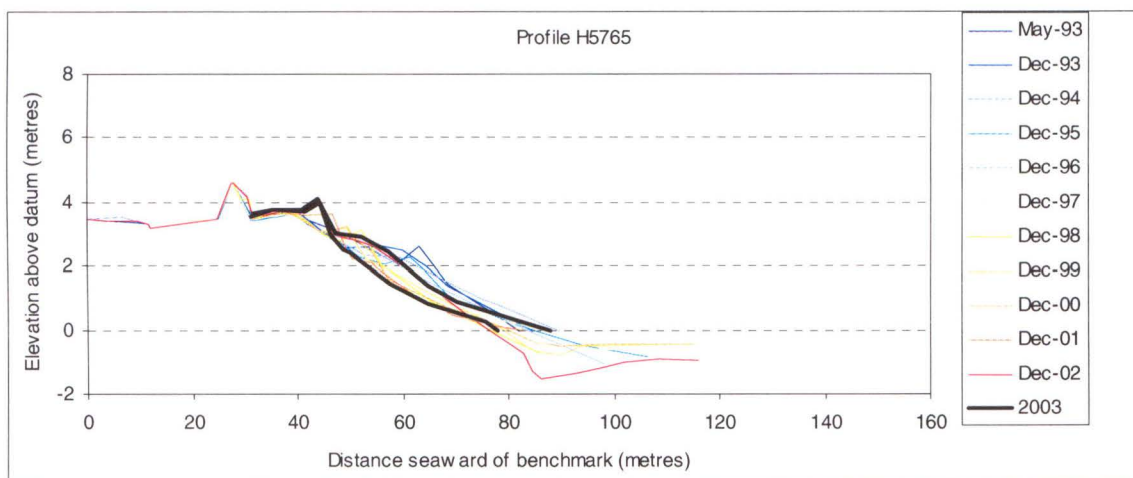
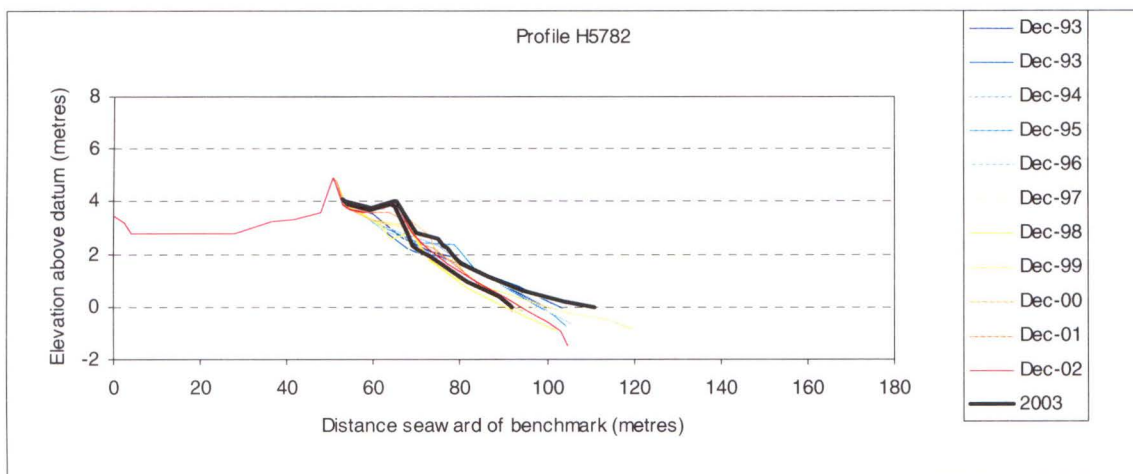
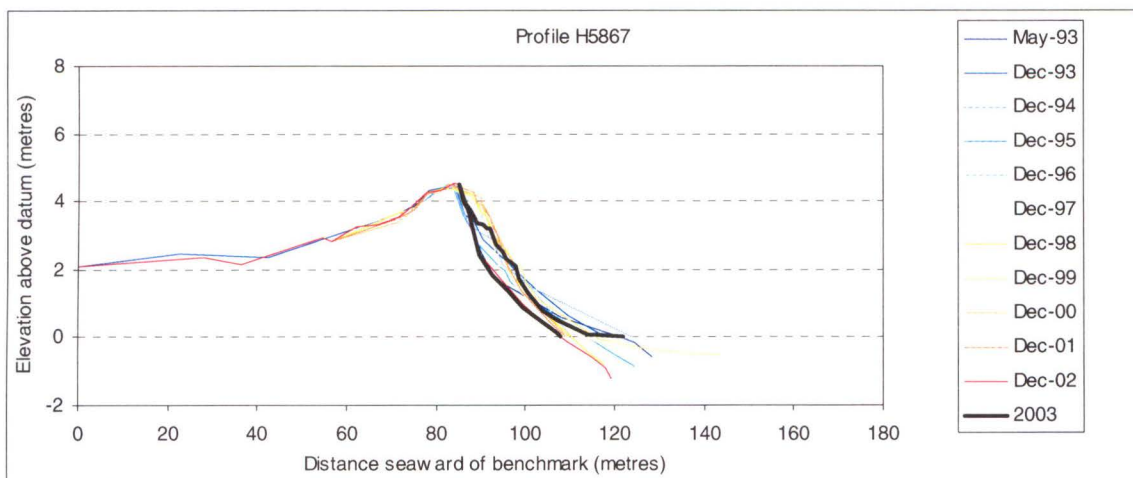


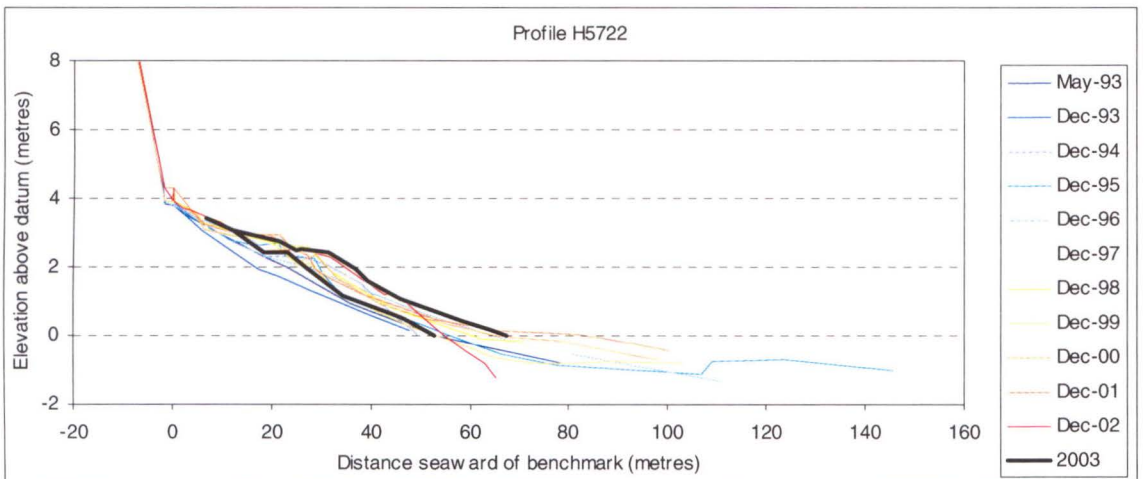
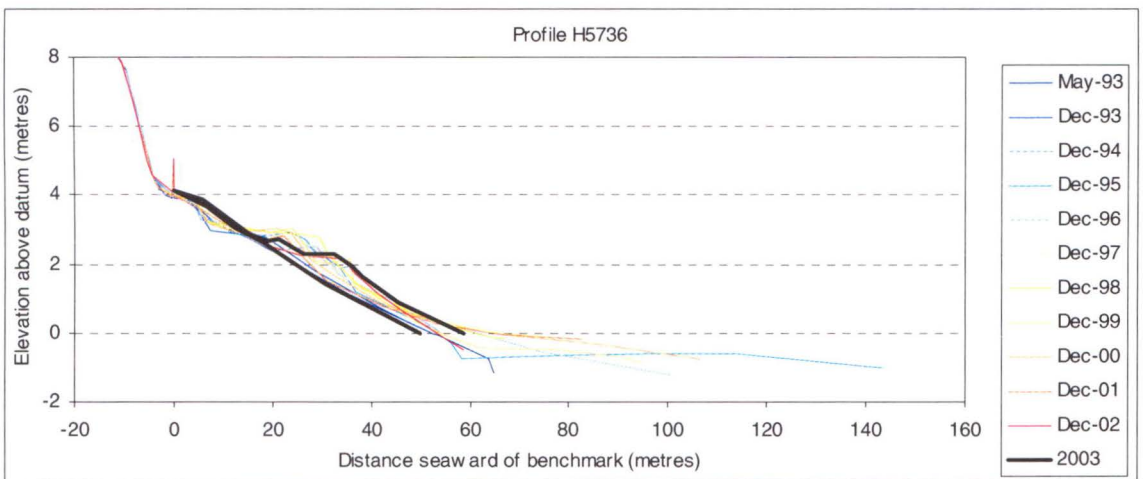
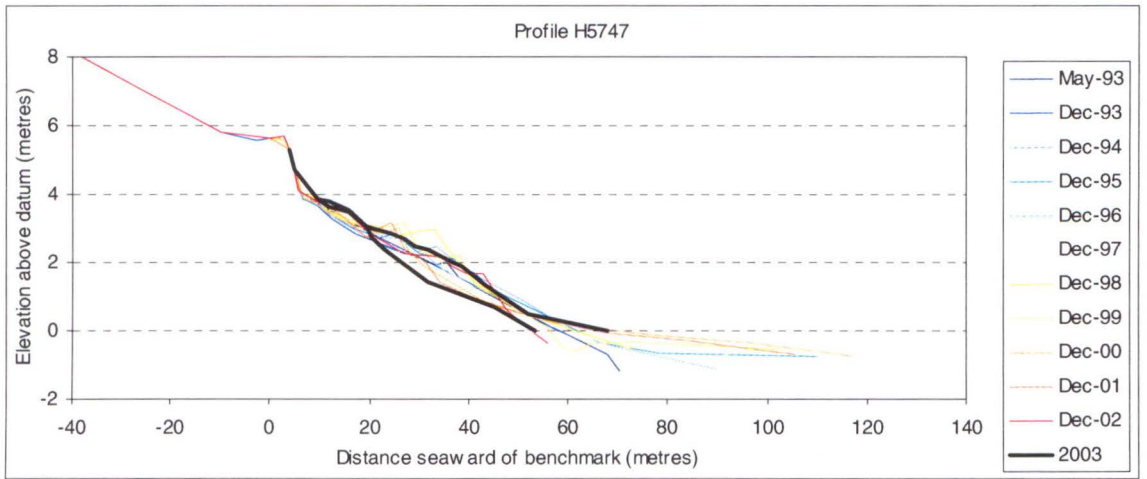


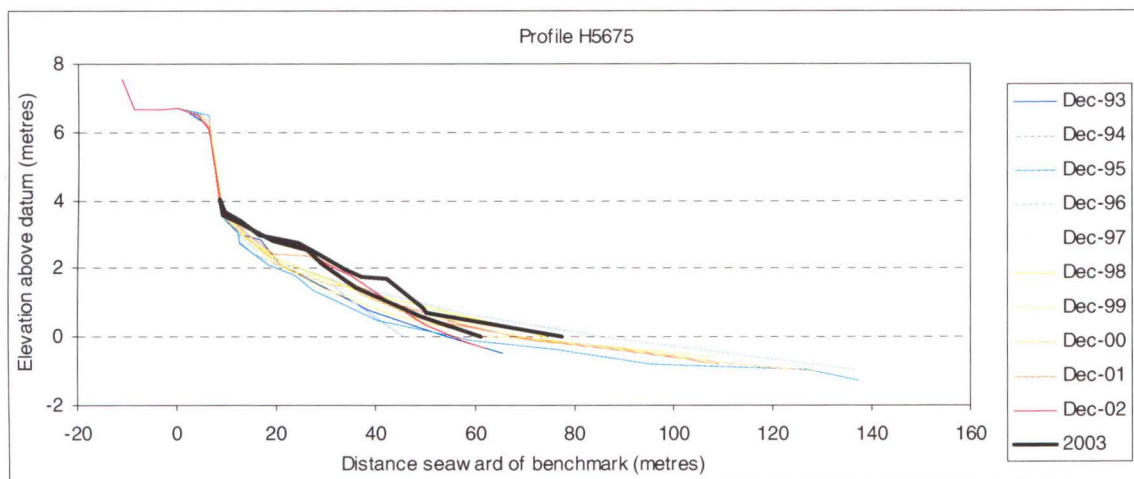
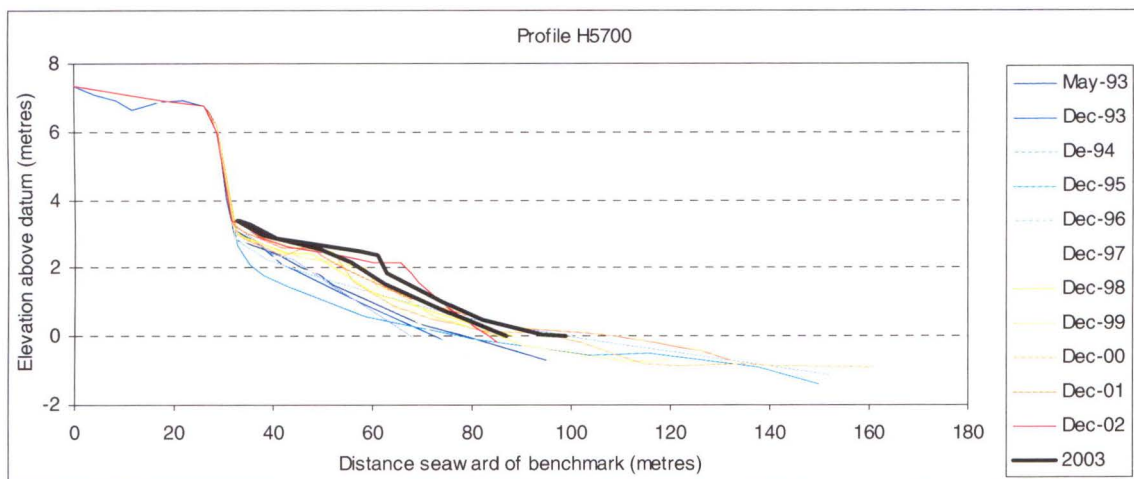
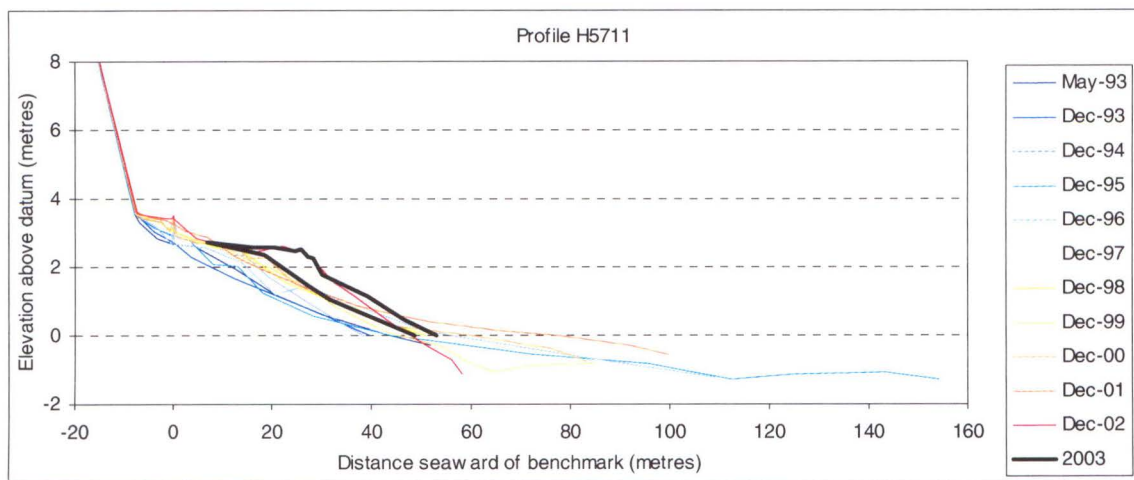


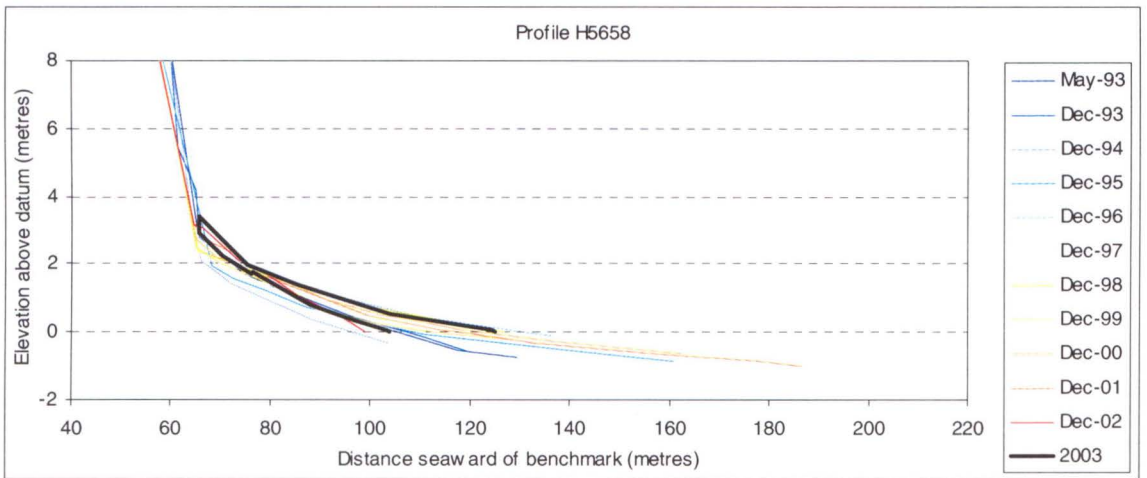
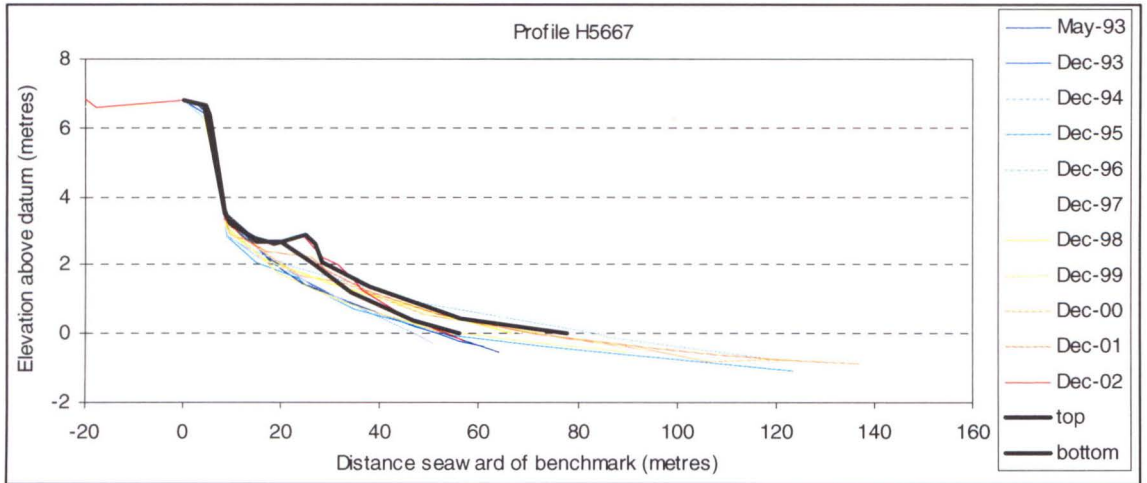
Appendix G

Annual profile variation at Gore Bay – May 1993 to December 2002









Appendix H

Beach profiles at Gore Bay in 1934, 1936 and 1948

Key:

1934 – dash-dot line

1936 – dashed line

1948 – thick solid line

1993-2002 – thin solid lines

