BEACH MORPHOLOGY AND SEDIMENTS OF THE CANTERBURY BIGHT

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University of Canterbury
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in Geography.

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Part of the Canterbury Bight showing the mouth of the Rakaia River.

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ABSTRACT

The 84 miles of mixed sand and shingle beach between Banks Peninsula and Dashing Rocks, Timaru, is a high energy shoreline exposed to vigorous wave action emanating from the south Pacific Ocean. Much of the coastline is actively retrograding. However, short term and seasonal variations in beach profiles are small. This is unusual in relation to previous studies of shingle beaches. Analysis of wave processes and of beach slopes and materials indicates that beach morphology is in short term erosional equilibrium with the prevailing south-easterly swell and with southerly storm waves. Long term changes in beach profiles indicate that, over much of the Canterbury Bight, the narrow profile envelopes are retreating landward. There is an excess of wave energy over the supply of materials and so the profiles are becoming wider and flatter. This condition is termed sub-equilibrium.

In plan a similar situation is distinguished, the beach being most stable in the north. Over the last century erosion has been most vigorous in the central section and slower in the south near Timaru. Thus, near equilibrium conditions exist in the north. By comparison with the theoretical stable shape the shoreline curve is too flat in the central area where present erosion is most vigorous.

These results are not consistent with a high order of net longshore transport to the north under present conditions. Previous works have suggested that this has occurred in the past but the

maximum appears to have been reached and passed. Sediment appears to be moved offshore rather than transported along it in large amounts of angular sand to the littoral zone but, surprisingly, there is little indication of a significant supply of pebbles and larger sizes under present conditions.

Because of the intensity of coastal erosion the beach deposit reflects the alluvial origins of much of the material. The deposit is texturally sub-mature. A medium and coarse sand fraction and a pebble fraction are combined by surf action to produce characteristic size-sorting relationships. Erosion of the coast allows little time for the production of changes in grain shape and roundness, so that there are only small differences in these properties between samples taken from the beach and from the coastal cliffs and the present river channels. The shapes of beach pebbles reflect the breakdown of the parent greywackes and sorting for shape and roundness are poorly developed on the beach. There is little abrasion of sand indicated.

A case study of the mixed sand-shingle beach is made using accepted principles of beach study drawn from the literature on both sand and shingle beaches. The study beach has many of the morphological features of the shingle beach but few of the sand beach. This is partly due to the larger grain size of the beach and to the prevailing plunging surf. The sand-shingle profile is almost entirely swash dominated since there is little tidal translation of the breakpoint of the waves. Characteristic sorting processes include the movement of sands in different directions under differing wave conditions. Sand is moved onshore under storm conditions and is winnowed from the gravels and moved alongshore under swell conditions. Pebbles appear to undergo a net offshore motion during storms but are more stable during swell conditions when they characteristically adopt pronounced imbrications. Cobbles are moved to the higher berms by swash since backwash does not usually have the power to move them owing to loss of head by percolation into the beach. These processes result in size-frequency distributions which are characteristically positively skewed-leptokurtic; reflecting a dominance of coarse bed-load material with a significant proportion of infiltrated fines.

Analysis of offshore bottom transport potentials confirms the observed mobility of sands and demonstrates that pebbles moved seaward of the breaker zone are unlikely to be returned to the foreshore. It also indicates that there may be small net movements of fine sands into the area from south of Timaru, and out of the area toward Banks Peninsula in the north.

INTRODUCTION

The "Ninety Miles Beach" that forms the shoreline of the Canterbury Bight is the largest continuous stretch of beach along the east coast of the South Island. It is broken only by the mouths of several major rivers draining from the eroding high country. The coastline forms the actively retrograding margin of two thirds of the Canterbury Plains. Coastal elements comprising the 84.15 miles between Banks Peninsula and Dashing Rocks include the cliffed retreating margin of the combined alluvial fans of the major rivers, the present river mouths and lagoons, and the wave drifted spit, beach ridges and associated dunes that tie the plains to Banks Peninsula in the north and to the Timaru lava flows in the south.

The shoreline is oriented in a NE-SW direction and faces to the SE. As such it is a high energy shoreline exposed to highly variable and often severe wave action emanating from storm centers in the Pacific Ocean. Fetch is unlimited since the largest waves known can be generated in a fetch length of 500 miles. There are thus considerable variations in the sizes of waves received at the shore and rapid changes in wave approach direction.

Very little is known about the movements of beach sediments and the nature of coastal changes along the Canterbury Bight. The coast is potentially well supplied with materials in both the sand and shingle fractions from the rivers and eroding cliffs that form over half of its length. Speight (1930) and Elliott (1958) have suggested that, along the Canterbury Bight, there is a persistent drift of shingle to the north, which has accumulated against Banks Peninsula and formed the 12,000 acres of Kaitorete Spit. More precise information about coastal changes is restricted to the areas immediately adjacent to Timaru Harbour. The construction of harbour works at Timaru has caused progradation of Caroline Bay and erosion near Dashing Rocks over the last century (Hassall 1955). Beyond these few observations there has been no previous study of the movements of beach materials and the nature of coastal erosion along the Canterbury Bight.

Purpose of the Investigation

The primary aim of the investigations of beach morphology and sediments discussed in this report is to describe the types and distributions of sediments and beach forms occurring along the Canterbury Bight. The second aim is to describe variations in these phenomena over short term (*), seasonal (*) and long term (*) periods.

The third objective of the study is to analyse the above features in relation to the marine processes that have given rise to the present beach forms and sediment characteristics.

All symbols and terms marked (*) are defined in the List of Symbols or in the Glossary of Terms.

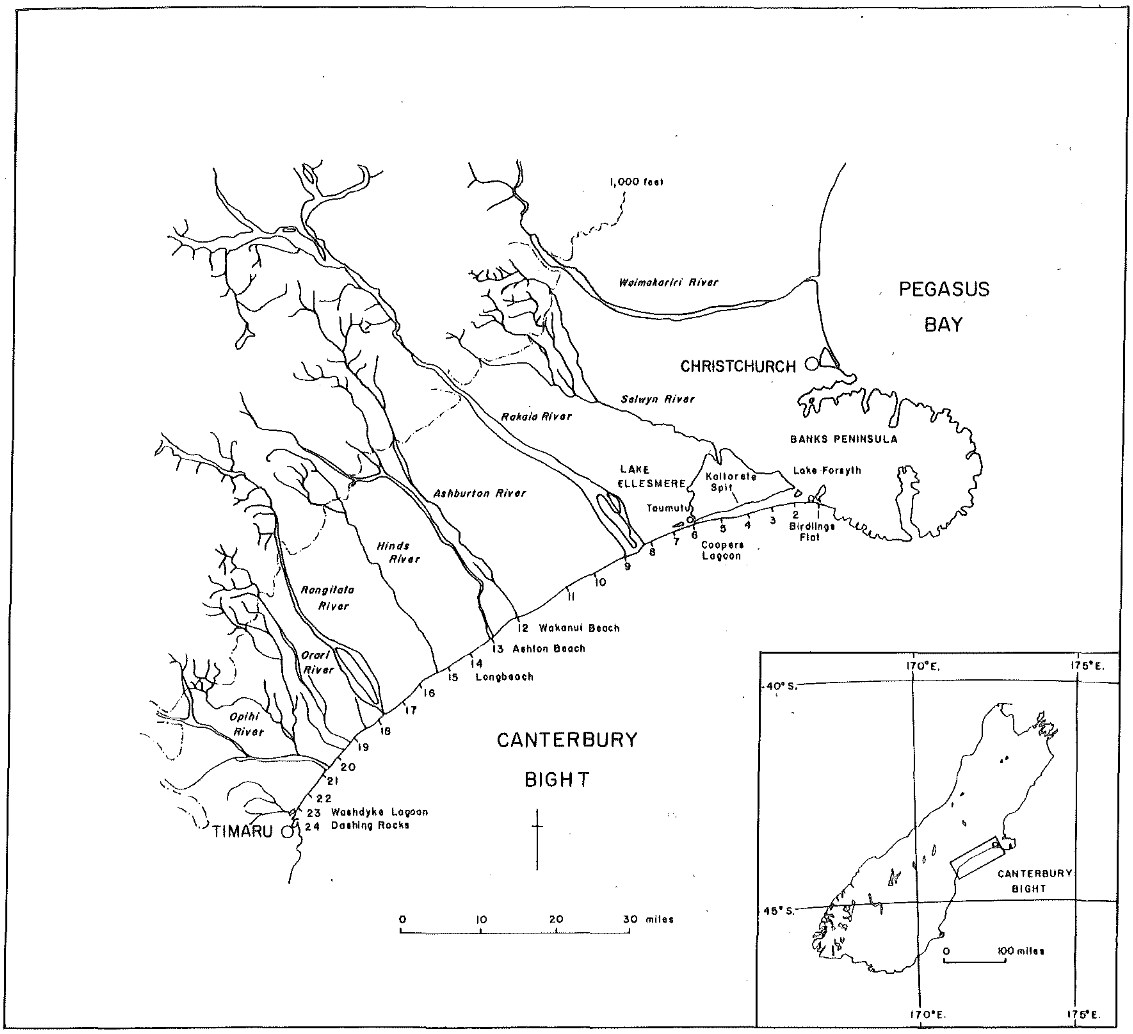


Figure 1. Location of sampling stations and places mentioned in the text.

In view of the lack of detailed information about coastal erosion in the Canterbury Bight the first two objectives have value with respect to the increasing knowledge of New Zealand beaches and to the applied field of coastal protection. The third aim, that of evaluating the causes of coastal erosion, relates to the field of coastal research and to problems of coastal protection. It is thus important to know the processes and rates of coastal erosion in this area. Are beach materials being drifted to the north along the Canterbury Bight?; Is the amount large?; If so, is the material derived from the rivers?, or from the coastal cliffs?, or from both sources? What sizes of materials are being drifted?; Are different sizes moved in different directions?; Where is coastal erosion most vigorous and why?

These problems are approached statistically since the study area is so large. Regression analysis and analysis of variance techniques are widely employed because they make it possible to distinguish "regional" components of beach properties from those that are purely local and random (Krumbein, 1953; 1959). The scope of this study is thus regional rather than local.

Steep shingle beaches and gentler beaches of sand and shingle typify all of the coast (Plate 1; Plate 2). While there is a large amount of literature on pure sand beaches and a lesser, more fragmentary coverage of pure shingle beaches, there are no other studies known to the writer that relate to

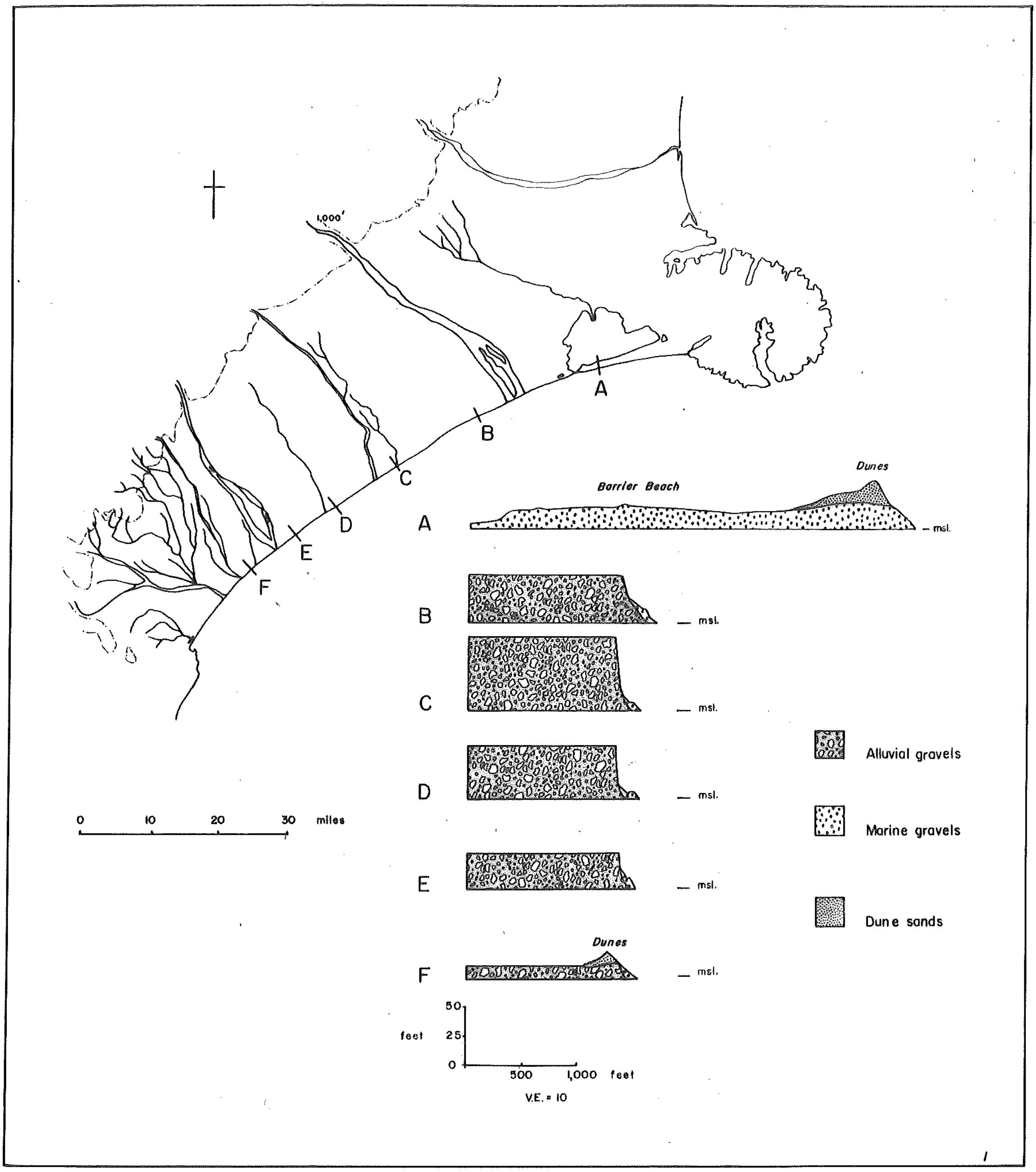


Figure 2. Coastal morphology and sediments.

beaches where sand and shingle are both present in large quantities. Thus a fourth objective of the investigation is a case study of a mixed sand-shingle beach. This is carried out using accepted principles of beach study derived from the literature on both sand and shingle beaches (Krumbein, 1947; 1961; 1963).

Finally, this report adds to the growing knowledge on New Zealand beaches. Most previous studies of New Zealand beaches have involved pure sand beaches but there are many sand-shingle beaches. This is especially true of the east coast of the South Island. Sevon (1966) has described variations in grain size parameters along Farewell Spit and Schofield (1967) has described the effects of dredging and changes of sea level on the size and form of Mangatawhiri Spit on the east coast of the North Island 35 miles north of Auckland. Neither of these beaches is similar in sediment characteristics to that of the Canterbury Bight. The study beach also stands in marked contrast to other New Zealand sand beaches that have been studied, but it will be shown that it may well have many similarities with other sand-shingle beaches not yet studied. The study beach differs markedly from the sandy, accreting beach of Pegasus Bay to the north of Banks Peninsula (Blake, 1964). Dingwall (1966) has studied the sandy bay-head beaches of Banks Peninsula and suggested that sand may be worked along the continental shelf off the Canterbury Bight and into these bays. To the south, the

Plate 1. Broad, planar mixed sand and shingle profile backed by dunes. Characteristic of Kaitorete Spit. Profile 4.

Plate 2. Narrower, steeper shingle beach characteristic of the cliff zone. Profile 14.

sand-spits of the Otago Peninsula also contrast widely with the sand-shingle strands of the Canterbury Bight (Elliott, 1958; Hodgson, 1966).

The report is presented in five parts. The first part of the report deals with the general characteristics of the area, its geomorphology and its history. It also deals with previous investigations and with the methods and materials employed in this study. The second section is concerned with the potential sources of beach sediments in the area, with wave and current conditions in the Canterbury Bight and with a discussion of the effectiveness of these agents in moving sediments and moulding beach morphology. In the third and fourth parts the beach sediments and beach morphology are considered in detail. Finally, the conclusions drawn from the descriptions and analyses of beach processes, sediments and morphology are summarised and suggestions are made for further research.

General Description of the Area

Geomorphology. Topographically, the coastline is composed of four major elements. The locations of these and their characteristics are shown in Figure 1 and Figure 2. Kaitorete Spit is 18 miles long and 2 miles wide at its northern end against Banks Peninsula. The width gradually decreases to about 1 mile 10 miles southwest of Birdlings Flat and to only a few hundred yards at the artificial outlet near Taumutu. The thickness of the marine gravels forming the spit exceeds

20 feet, (the depth of the deepest shingle pits). The altitude is 18-20 feet above sea-level for the most part but the seaward dunes attain 26 feet. Gravels in the pits are moderately to well sorted and of similar mean grain size to materials on the present beach.

Southwest of Taumutu the beach is backed by a line of low dunes and swampy land which merges into the second and largest unit of the coastline. From north of the mouth of the Rakaia River to south of the mouth of the Rangitata River, a distance of more than 48 miles, the coast is formed of the cliffed edge of the combined alluvial fans of the major rivers. (Plate 2) The cliff line is broken only by large gullies and by present river mouths and old mouth positions. It is fronted by steep, narrow beach. The cliff attains a maximum height of 75 feet above sea-level north of the mouth of the Ashburton River near Wakanui, and loses height gradually north and south from this point (Fig. 1).

The third unit extends south from the Orari River. It comprises a low shingle and sand ridge* backed by low dunes and salt meadow. This third unit merges with the fourth and is practically indistinguishable from it. Alluvial deposits give way to swampy mixed estuarine and alluvial deposits. The fourth unit is thus the low, clay-based ridge which encloses the Washdyke Lagoon. The ridge averages 12-14 feet high and is only a few hundred feet wide. At profile 23 (Fig. 1), a pit dug for a settling pond revealed strongly oxidised alluvial gravels and interstitial fines within 300 feet of the mid-tide water line. The long stretch of shingle beach bordering the Canterbury Bight terminates to the south on a flat lava platform below the cliffs at Dashing Rocks, Timaru. Caroline Bay, to the south of Dashing Rocks, is the only pure sand beach along this part of the coast, since shingle extends from south of Timaru down the coast at least as far as the Waitaki River.

There are six main rivers which reach the Canterbury Bight shore. These rivers are all characterised by shifting, braided channels which produce periodic shifts in mouth position during floods. However, while the rivers are similar in this respect there are important differences as far as the beach is concerned. The Opihi River is the only major river in the area that lies beyond the cliffed section of the cliff and has thus flooded its seaward hinterland many times. It is now contained by training works. The Orari River has been similarly entrained to shorten the course in the lower reaches. The Hinds River had no natural outlet to the sea but was artificially opened in the early days of settlement by J. Grieg (T.L. Fancourt, Chief Engineer, South Canterbury Catchment Board. Pers. Comm.). The Rangitata, Ashburton and Rakaia Rivers are the largest in the area and are incised in their beds. The Rakaia was the largest of the Canterbury fan-building rivers and is the widest. It will be shown that these differences are important to the consideration of sediment supply to the beaches.

Geological History. The present coast of the Canterbury Bight is a geologically Recent one composed of cut and built elements developed on vast thicknesses of alluvial gravel, the outwash products of multiple Pleistocene glaciation of the Southern Alps. The gravels are known to be at least 2,000 feet thick (Henderson, 1922). Raeside (1964) noted that a Pleistocene lowering of sea-level of 100 metres, a generally accepted figure, would place the coastline of the Canterbury Bight some 30 miles seaward of its present position. Traces of Pleistocene fluctuations across the bight have been obliterated by the combined action of the post-glacial rise and submergence of the land. The present coast with its extensive cliffs and large depositional features is a product of this and subsequent action.

Old barrier beaches on Kaitorete Spit and near Taumutu suggest that in post-glacial times sea-level may have stood 12-15 feet higher than the present level. Suggate (1958), dates this level to approximately 5,000 years ago in the Christchurch area. This would suggest that much of Kaitorete Spit was formed by that time and that the present river mouth positions are recent. It is not known how much of the remainder of the coast, if any, was formed up to that time. It is possible that the many large gullies along the coast, particularly in the Wakanui area, were formed at this time.

Since the post-glacial high stand of sea-level the

Key to Figure 3A

S	Sand.
fS	Fine sand.
gyS	Grey-yellow sand.
fgyS	Fine grey-yellow sand.
Sh	Shells.
St	Stones.
G	Gravel.
M	Mud.
blM	Black mud.
R	Rock.

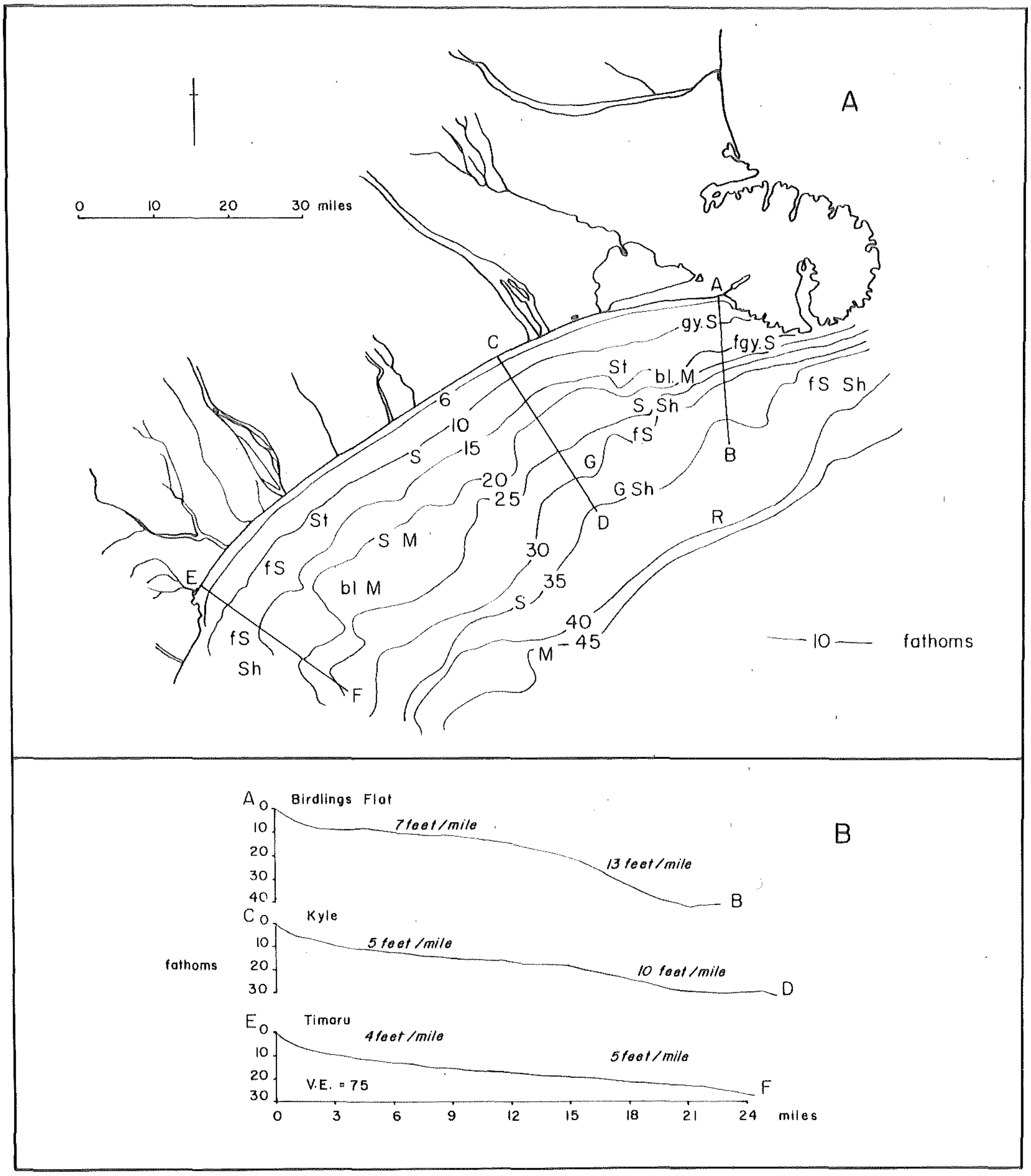


Figure 3A. Bathymetry and offshore sediments.

B. Continental shelf profiles.

remainder of Kaitorete Spit, seaward of the barrier beach, and the dune system have been built. This sequence of events has produced the coastal features indicated in Figure 2 and also the submarine features indicated in Figure 3. Alluvial gravels capped by fine sands extend for some distance into the bight, as shown on Figure 3A. These give rise to the remarkably gently slopes of the continental shelf. The offshore profiles shown in Figure 3B demonstrate that the steepest offshore slopes are only 13 feet per mile in depths of 20 to 30 fathoms off Birdlings Flat. Closer inshore nearer the beach, gradients are only 4-7 feet per mile. Figure 3B also indicates that the floor of the bight shallows and flattens south toward Timaru. It will be demonstrated subsequently that these generally uniform offshore features are of great significance in the distribution of wave energy within the Canterbury Bight and thus are an important control on the waves and currents occurring on the beach. There are no canyons or offshore ridges to modify the passage of waves onshore.

Previous Investigations

A great many investigations of the morphology and sediment movement patterns of sand beaches have been carried out in the U.S.A. and Europe. Also many theoretical studies have been performed using scale models in laboratories so that compared to shingle beaches much is known about sand beach forms and processes. Equations for such phenomena as longshore transport and beach equilibrium derived from these studies are couched in dimensionless terms so that they may be applied to all sediment sizes. To date the application of these principles has been mostly oriented toward sand beaches. Some of these considerations are applied in this study, notably those relating to the sorting of sediments by surf action.

Less work has been done on shingle beaches except in Britain. Many authors point to the greater steepness of shingle beaches compared to sand beaches. This is because of the greater permeability of the shingle beach and the consequent reduction in backwash volume (Shepard, 1963, p.170). Thus wave energy is concentrated over a narrower zone of the shingle beach than on the sand beach. However, Lewis (1931) distinguished important differences between the swashes of storm waves and the swashes of swell waves on the shingle beach. He noted that under storm waves the swash is weak relative to the backwash because a greater volume of water is delivered to the foreshore while permeability remains constant. King (1959, p.280) records lateral erosion of up to 5 feet in 3 hours and vertical cut of 2-3 feet of shingle in one hour at Chesil Beach, Dorset, England.

In recent years the development of fluorescent and radioactive tracing techniques has enabled detailed study of the movements of beach pebbles. Kidson, Carr and Smith (1958) using radioactive pebbles demonstrated longshore movement in more than one direction under different wave conditions. Even where tidal current velocities attained 7-8 knots in river mouths, shingle continued to move alongshore. Kidson and Carr (1959) further demonstrated that movement of beach pebbles on the offshore bottom (*) is very limited, even under quite severe wave conditions. All of these observations have direct relevance to the present study since shingle is the dominant constituent of the beach. It will be shown that the study beach has few of the morphological characteristics of the sand beach and many of the shingle beach.

Many New Zealand investigations of Quaternary Geology make brief reference to the Canterbury Bight but there is only one previous study that is directly concerned with the area. This is the investigation by Speight (1930) of the history and development of Kaitorete Spit. Most of this work is given over to the interpretation of past positions of sea-level. He suggested that the bulk of the materials forming the spit had been derived by the erosion and northward transportation of a two mile wide strip of the cliffs to the south, but cites little evidence for this. He concluded that most of the spit was built on a rising sea-level some 8-10,000 years ago. Sea-level ultimately reached the level at which the barrier beach stands (Fig. 2) and then fell to the present level. He also suggested that the major gullying of the cliffed section of the coast occurred at this early time when, "streams probably carried more water than now". Processes operating on the present beach were not studied in detail.

Hassall (1955) records many observations of coastal changes at, and south of Timaru over the last century, but contains little that directly relates to the study area. Hence, most of this study is concerned with data gathered in the field during its preparation, and with evidence derived from laboratory analysis of the beach sediments.

Methods and Materials

The collection of data for this study centered around field surveys of changes in beach morphology at a number of selected stations (Fig. 1), and the collection and analysis of many samples of the beach sediments. Laboratory analysis of sediments was concerned with the determination of mean grain size, sorting, skewness and kurtosis of samples, and with studies of particle shape and roundness.

Analysis of this descriptive data was greatly enhanced by field observations of wave conditions and other beach processes. Study of the "wave climate" of the Canterbury Bight was made possible by daily wave observations made at Timaru from February to May 1967. For the study of long term aspects of coastal processes extensive use of old surveys, aerial photographs and other records was made. A full summary of the sediment and wave data is given in the Appendices.

Transverse Profiles. Owing to problems of access only 24 transverse profile and sediment sampling stations were established in December 1966. The locations of these stations and of river bed and cliff sampling stations are given in Appendix IB. The major river mouths are adequately represented

(Fig. 1). The maximum distance between stations is 10 miles and the minimum is 1.75 miles. Most are 3-4 miles apart.

Profiles were surveyed at four intervals between December 1966 and June 1967. Profile pegs were located on the backshore (*) and traverses were run seaward to the breaker zone. Survey equipment comprised a compass, tape, ranging rods and an Abney Level. Because of the prevailing plunging surf (*) it was not possible to extend the surveys seaward of the surf zone (*), as is frequently done in studies of sand beaches. Transverse profiles of the alluvial cliffs and of the dunes were surveyed in February 1967, and re-surveyed in June 1967 in order to record changes due to storms and cliff-fall.

<u>Sediment Samples</u>. Two sediment samples were collected from each of the profile stations during three of the surveys. The first sample was taken from the "reference point" (*) i.e.: the zone of swash (*) at mid-tide level (Bascom, 1951). The second sample was taken from the backshore, the zone affected by wind action and by the long swashes of storm waves. Additional samples were taken from a number of profiles to establish profile distributions of sediment characteristics for stations located on the open beach, off the river mouths and in front of the cliffs. Also a number of samples were taken from the river beds and alluvial cliffs.

A total of 178 samples were collected and analysed. Samples of sand were 100 to 200 grams, dry weight in accordance with standard practice. However, it is important to collect larger samples of mixed sand and shingle because "Little is known of the reliabilities of samples for different ratios of particle size to sample size", (Krumbein, 1953). For this reason mixed sand-shingle samples and shingle samples were two to three Kilograms in weight. Folk (1965) noted that faulty sampling particularly affects values of skewness. Thus where pebbles and sand are mixed there is a tendency, if sampling on a weight-frequency basis (as in this investigation), to overestimate the sand fraction; and if on a number-frequency basis, to overestimate the pebble fraction. Attempts to deal with this problem have been made by Marschner (1953), Emery (1955), Wolman (1954) and Krumbein and Lieblein (1956).

Laboratory Analysis of Samples. Samples were washed to remove salt and oven-dried. Materials coarser than ⅛" diameter were sieved by hand and the remainder was sieved for 15 minutes in an Endecott, "Endrock" sieve machine in the Physical Laboratory, Geography Department, University of Canterbury.

The weights of material retained on each sieve were converted to percentages of total sample weight and plotted cumulatively on log.-normal graph paper. Grain size was plotted on the abscissa and frequency on the ordinate. The sieves used, conform to the British Standard Code of Practice No.410 and are graduated according to the Wentworth scale of particle sizes. This was converted to the phi (Ø) scale (*) (Krumbein and Pettijohn, 1938, p.84), to facilitate the computation of statistical parameters. Percentile values

(ϕ) from the size-frequency distributions were transferred to IBM data cards and the Graphic Mean Diameter (Mz) (*); Inclusive Graphic Standard Deviation (σ_I) (*); Skewness (Sk_G) (*) and Kurtosis (K_G) (*) coefficients (Folk, 1965), of each distribution were calculated on the University of Canterbury's IBM 1620 Computer. Subsequent analysis of grain-size data was performed on the computer and on a desk calculator. Before sieving for size several samples from the beaches, rivers and cliffs were analysed for shape (*) and roundness (*) properties.

Measurement of Shape. Shape was determined by measuring the three major axes of pebbles with vernier calipers. Measurements were accurate to within 0.1 mm. The longest axes were designated 'A', the intermediate 'B', and the shortest 'C' in accordance with Folk (1965). Effective Settling Sphericity (Ψ)*, flatness index ($\frac{C}{A}$) and other measures were calculated for each sample of 25 pebbles. Ψ was obtained for each pebble by locating $\frac{C}{A}$ and $\frac{A-B}{A-C}$ on the "Form triangle" in Folk (1965). Histograms of Ψ were plotted to enable the calculation of mean effective settling sphericity and the standard deviations (σ_Ψ) of the distributions. The latter measure is employed as an index of shape sorting.

Determination of Particle Roundness. Roundness analysis was performed on 50 grains of both pebble and sand fractions for 29 samples taken during the second (B), and third (C) surveys. The method used was the photographic comparison chart (Powers, 1963). Each of the 50 grains in a sample was assigned to a roundness class. The total number of grains in each class was multiplied by the geometric mean for that class and the totals of the products divided by 50, the total number of grains counted. The resultant Powers roundness number was then converted to the logarithmic scale of roundness (ρ) (Folk, 1965, p.11). This was done to facilitate computation of roundness standard deviation (σ_ρ), a measure of roundness sorting. Some variation in the data results from counting in more than one size grade because no representative single size class was continuous throughout the samples.

Wave Observations. Wave observations during field surveys were made to determine variations in wave energy along the shore. Records of wave period, wave height and direction were taken during each of the four surveys and at other times. Wave period was measured as the time interval between breakers at each station. Wave height was determined by estimating the height of the highest one third of the waves at each station, to the nearest foot. Wave direction was determined by compass measurement of the angle of approach of the waves relative to the shoreline at each station. At each station the direction of the prevailing longshore current was obtained by observing the direction of travel of driftwood floats thrown into the surf. No records of drift velocity were attempted because of the inertial properties of these floats (Norrman, 1964, p.82), but relative strength of flow was noted.

Since wave conditions vary continually, the records of wave conditions obtained during surveys are of limited value unless they can be related to waves occurring before and after the observations. For this reason synoptic records are vital to this study.

From February 1st 1967 Captain A. Grieve, Timaru Harbourmaster, was responsible for keeping daily wave records and local wind records at the entrance to Timaru Harbour. In order to make results from both sets of observations comparable the methods employed were the same as those of the field surveys. In addition wind speed at Timaru was estimated according to the Beaufort Scale. These records facilitated analysis of the "wave climate" of the area and, more importantly, they made it possible to relate beach conditions at the time of survey to changes in wave conditions over the interval since the previous survey. Furthermore, greater relevance was imparted to studies of wave refraction in the Canterbury Bight.

Study of Long Term Changes in Coastal Morphology. Recent map coverage of the Canterbury Bight area was provided by Topographic Maps at a scale of 1:63,360. Though this was sufficient for most purposes it was inadequate for accurate determination of coastal change. Maps of the "Black Map Survey" of Canterbury on a scale of ten chains to the inch date back to the 1860's. These are housed in New Zealand Lands and Survey Department, Christchurch. They provided much data on past positions of the coast, particularly sheets BM 115, BM 71, BM 43 and Timaru 1 and Timaru 2.

Profiles surveyed across the beach at four culverts between Taumutu and the Rakaia River provided valuable information on changes in profiles since 1930. This data was obtained from the records of the North Canterbury Catchment Board, Kaianga.

Further evidence of coastal change was obtained from residents along the coast. Their local knowledge and experience proved helpful.

New Zealand Hydrographic Charts No. 2532 "Banks Peninsula to Otago Peninsula", and No. 6442 "Approaches to Timaru", provided data on bottom sediments and bathymetry of the Canterbury Bight.

It can be seen from the above discussion that much of the data collected for this study relates to the responses of the beach and its sediments to variations in wave energy both over short periods and longer periods. Analysis of these changes requires detailed consideration of the sources of the beach sediments and of the beach process factors.

SOURCES OF MATERIALS

Consideration of the sources of beach sediments is important because they provide the inputs to the beach. The sizes and shapes of particles in the beach deposit may be conditioned by the source rocks from which they were derived. Also, over a long period, the rate of supply of sediments to the littoral zone has important effects on the form of the beach deposit. If there is a large supply relative to wave energy the coast may prograde. If there is only a small supply, erosion of the coast may occur.

Bowen and Inman (1966, p.6) list six potential sources of littoral sediments. They are:- Longshore transport into an area, Onshore transport, Wind transport into an area, River transport, Biogenous deposition, and Hydrogenous deposition. Of these only two may be considered as potential primary sources of beach materials in the Canterbury Bight. These are firstly, the rivers; and secondly, the alluvial coastal cliffs (longshore transport). A potential secondary source is the offshore zone (onshore transport). Inman (1960) indicates that in most cases the rivers can be shown to be the major sources of beach sediments, but it will be shown that, in the case of the Canterbury Bight this may only apply to the sand sizes. In general hardrock cliffs probably provide less than 5% of coastal sediments and unconsolidated deposits such as the alluvial cliffs of the study area may provide amounts comparable to those derived from rivers. Biogenous deposition in the form of shell materials is common on sand beaches but is minor on the study beach where the mobility and mechanical rigours of shingle largely prevent occupation by shellfish. Wind transport of sand into dunes represents a loss of beach sediments in the Canterbury Bight, rather than a gain. Hydrogenous deposition of inorganic precipitates is not important in the study area.

The Rivers

Due to the shifting, braided nature of the river channels most guaging is done at the rock gorges where the rivers enter the Canterbury Plains. Hence, little is known of bed and flow characteristics between these points and the coast. Flood discharges are generally high (Table 1), but in most of the rivers the peaks are of short duration. With the exceptions of the Rakaia and Rangitata Rivers, all of the rivers rise in the foothills and flow in broad anastomosing channels across the plains to the sea. Floods are generally produced by easterly storms, the bulk of the rain falling within 48 hours and often within 24 hours or less (Chandler, 1967), so that even though suspended sediment concentrations are high these rivers may not deliver large amounts of material to the coast.

The two largest rivers in the area, the Rakaia and the Rangitata, drain from the main divide and are affected by different conditions. Northwest conditions may prevail for a week or more in the upper catchments, giving very heavy rain.

Table 1

Flow Data for rivers along the Canterbury Bight

Catchment	Terminus	Area sq. miles	Minimum Flows cusecs.	Flood Discharge. cusecs.	& year.
Selwyn	Main Sth. Road Bridge	262	---	22,000	19/7/61
Rakaia	Gorge Bridge	1,000	3,740 11/9/58	41,000	13/9/63
Ashburton	State Highway Bridge	590	---	12,100	12/5/61
Hinds	Black Bridge	110	---	5,970	20/4/63
Rangitata	Arundel Bridge	623	---	---	
Orari	Rolleston Bridge	273	69.6 (Gorge) 12/3/56	5,400	11/12/60
Opihi	State Highway Bridge Arowhenua	682	408 6/4/61	71,200	20/7/61

- Source. Hydrology Annual Nos. 7,8,9,10,11. 1959-1963.

Thus protracted high flows in these rivers are not unusual (Chandler, 1967). Suspended sediment concentrations are very high at such times, (B.R. Palmer. N.Z. M.O.W. Soil Con. Div. Kaianga. Pers. Comm.), and with flow durations of about a week these rivers probably deliver large amounts of suspended fines to the coast. Surprisingly, the Rakaia delivers relatively high concentrations of fine materials even at low flows.

Because the beds are unstable and shift continually measurement of bed-load movement has been impossible. Oram (1941) noted a tendency for the texture of bed-load to fine downstream. Sediment samples taken during the present study from the beds of the Rakaia and Ashburton Rivers at positions near the mouths were made up of dominantly bladed pebbles averaging -3.50 to -3.70ø in mean diameter. Sorting ranged from good to very poor, and all samples were fine skewed (Appendix ID). It will be shown that this material is little different from that on the beach.

Studies carried out by the South Canterbury Catchment Board over the last 20 years indicate that the beds of the Ashburton, Hinds, Orari and Opihi Rivers are all degrading at rates ranging from -0.02 feet per year to -0.158 feet per year (T.L. Fancourt, Chief Engineer, Pers. Comm.). This is thought to be due to channel shortening for flood control. Channel degradation has been most marked in the lower reaches of the rivers. No data was obtained for the Rakaia and

Rangitata Rivers. It is felt that little significance can be attached to this data insofar as sediment supply to the coast is concerned, firstly because the observed changes are so small, secondly because the period covered by the records is so short and thirdly, because of the partial nature of the data. Gross channel change is a poor indicator of sediment movement.

Significantly, it appears that along the Canterbury Bight, as elsewhere in New Zealand, the behaviour of river sediments is the single largest unknown factor. Both rates and modes of bed-load movement are unknown. The rivers undoubtedly contribute large quantities of fine material to the coastal zone, the sand fraction of which appears to be the source of the extensive dune, beach and offshore sands of the Canterbury Bight. It will be shown that this material is highly mobile within the littoral zone and Dingwall (1966) has indicated that some of it may find its way onto the bay-head beaches of Banks Peninsula. Similar river borne fines are responsible for extensive progradation in Pegasus Bay (Blake, 1964).

However, in the light of the known rates of retrogression along the Canterbury Bight it would appear that the rivers supply relatively little coarse bed-load material to the littoral zone. Either it is moved offshore in flood conditions, to depths where waves are unable to return it to the beach, or it is deposited in the river channels inland from the coast.

Possibly both processes are operative. Whatever, the case it will be shown that a large supply to the littoral zone under present conditions is inconsistent with observed distributions of beach materials and with observed changes in beach morphology both over short and long periods. Changes in the broad berms (*) and lagoons at the river mouths relate more to flood induced changes in channel position than to the accumulation of river gravels and sands. For these reasons the alluvial cliffs must be considered as the largest source of beach gravels under present conditions.

The Coastal Cliffs

Since the eroding cliff line is composed of unconsolidated, partly oxidised alluvial gravels rising to a maximum height of 75 feet above sea-level, they are potentially the major source of beach gravels. It has been indicated above that Speight (1930) considered them to be the principal source of the materials in Kaitorete Spit. A general view of part of the cliffs is shown in Plate 3. They comprise crudely interbedded gravels, sands and silts which, apart from oxidation effects, differ insignificantly from the materials in the present river channels. This makes it difficult to determine the directions and magnitudes of longshore drift in this region, but other considerations suggest that it is of a small order.

Erosion of the cliff is performed mainly by sub-aerial processes, marine processes serving to remove accumulated

Plate 3. Prominent cliff-falls at Profile 12. Failure of the cliff-face occurs along clearly defined shear planes and leads to parallel retreat of the face and the maintenance of steep slopes.

debris from the cliff-base and thus prepare the face for the next fall. Retrogression of the cliff line by approximately three feet per year occurs everywhere save for the northern and southern termini where the cliffs are lower and are fronted by shingle ridges up to 18 feet high.

Hence there is a continuing supply of gravels and sands to the beach from the cliffs. Cliff falls occur at all times of the year and the materials are removed by the swash of southerly storms so that there is rapid movement of sediments from this source across the beach. Sands from this source are widely transported as are river sands. Both may be involved in similar movements in the offshore zone. Cliff gravels moved seaward of the breakers to the nearshore bottom are virtually permanently lost to the beach.

The Offshore Zone

It was demonstrated in Figure 3 that much of the offshore bottom of the Canterbury Bight has very gentle slopes mantled with fine sands. The lack of canyons in the offshore zone means that sediment movement, if begun by waves or currents, is unimpeded by bottom relief. It will be shown subsequently that storm waves produce onshore transport velocities near the bed that are more than sufficient to move sand onshore. However, because of the turbulence of the swash-backwash zone (*) only a small part of this material remains on the beach. It is trapped by percolation through the beach shingle. Medium and coarse river sand fed into the nearshore current system may be recycled between the beach foreshore (*) and the nearshore bottom (*) by storm wave deposition on the beach and subsequent winnowing by swell waves. Analysis of the distributions of beach sediments suggests that this is an important process contributing to the sorting of beach materials. Sands undergo complex movements resulting from changing wave conditions, thus producing changing admixtures of sand and pebbles. During storms large "suspension clouds" and turbid water were observed outside the breaker zone.

There is also evidence to suggest that a small amount of material is supplied to the beach from south of the Timaru breakwater. The infilling of Caroline Bay with sand and the removal of a small shingle bar near Dashing Rocks were direct results of the construction of the breakwater (Hassall, 1955). In 1895 the annual drift accumulation against the south side of the breakwater was estimated at 112,000 cubic yards. In 1896 30,000 tons of shingle were thrown over the breakwater into the harbour (Hassall, 1955, p.123). By 1926 shingle drift had stabilised and only sand and finer materials now move north past the breakwater. Dredging of the harbour entrance is undertaken regularly. This sequence of events has resulted in increased erosion of the southern portion of the study beach. Sandy foreshores south of the Opihi River undoubtedly result from the transport of small amounts of sand across the shallow shelf zone, from south of Timaru.

The above discussion has indicated that the rivers of the Canterbury Bight contribute much fine sediment to the beach and that this undergoes complex movements both along and across the shore. Probably the bulk of the beach shingle and much of the sand is derived from this source. An analysis of the ways in which these materials are transported can now be presented.

BEACH TRANSPORTATION PROCESSES

This section of the report is concerned with the description of beach processes, the winds, waves and currents that are involved in the transport of sediments on the beach. It is these processes that govern the day to day variations in sediment distribution and morphology on the beach. Following the description of the processes a detailed analysis of the transport potentials of waves is made, firstly for waves in deepwater, secondly for breaking waves and longshore currents, and thirdly for the swash-backwash zone.

Winds

The significance of wind as a shore process in the Canterbury Bight is in the modification of ocean waves and in aeolian processes. Figure 4 shows the annual wind distributions for Christchurch, Ashburton and Timaru. The frequency distributions of wind velocity are approximately normal. Mean wind speeds are 9.2, 9.6, and 6.18 miles per hour respectively. All of the distributions show a tendency to be positively skewed.

The recording stations are all inland so that the distributions do not reflect the large number of land and sea breezes occurring at the coast. Also, the instrument used to make the recordings, Dines Anemometer, records only those velocities that are in excess of 3 miles per hour so that calms appear to be more frequent than is actually the

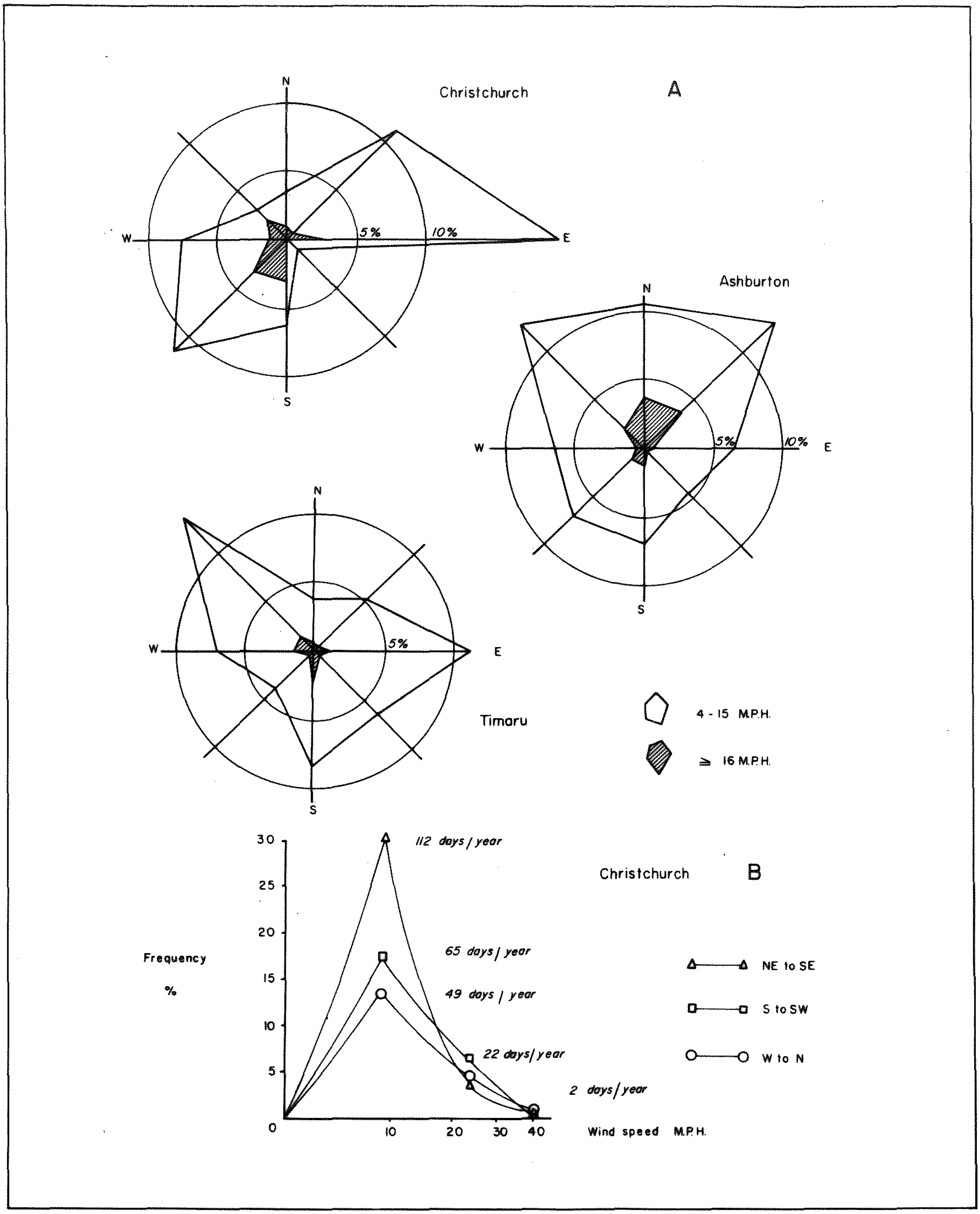


Figure 4. Wind distributions. Christchurch: N = 26,240 (1942-50), Calms = 23.8%, 14.3% ≥ 16 mph; Ashburton: N = 26,240 (1943-51), Calms = 17.6%, 13.2% ≥ 16 mph; Timaru: N = 32,120 (1948-58), Calms = 35.6%, 5% ≥ 16 mph.

Source: N.Z. Meteorological Service.

case.

Notable features of the distributions are the prevalence of north-east winds at both Christchurch and Ashburton, and of southerly winds at Timaru. All of these winds blow sub-parallel to the shore and are thus potentially significant in the longshore transport of sand grains. Winds which blow along the shore can also have marked effects on the directions and magnitudes of littoral currents and on the location and formation of rip currents. The wind distribution for Christchurch differs from those for Ashburton and Timaru in that the percentage of south-east winds is much lower. This is because Christchurch is situated on the northern side of Banks Peninsula and winds originating in the south-east are re-directed by flow around and over the peninsula.

More significant than winds which blow along the shore are those that track across it. King (1953) and many others have demonstrated that shore-normal wind components play a large part in the movement of beach sand. Onshore winds tend to produce net offshore movements of water near the bed and hence erosion of sand from the foreshore. Sand which has accumulated above the reach of the waves is blown toward the dunes. Offshore winds result in buildup of sand on the lower foreshore. Figure 4B is a graph of the average occurrence of winds of given magnitudes for sectors relative to the orientation of the shoreline of the Canterbury Bight. Clearly, onshore winds predominate over winds blowing offshore and alongshore, but it can be noted that winds from the southerly sector attain higher velocities more frequently than winds from other directions. Frequent onshore winds contribute both to rapid passage of sand toward the dunes and to winnowing of sand from the foreshore by wave action.

The most frequent velocity attained by winds from all sectors is sufficient to transport the medium and coarse sand (in the range 2.0 to 0.0ϕ), of the Canterbury Bight beaches. Bagnold (1941, p.6) gives the velocity requirements for different sand sizes and notes that where the beach is wet the velocity requirements to initiate motion are higher. However, the permeable shingle foreshore of the study beach dries rapidly beyond the zone of wave action. Wind transport of sand appears to be most active in spring and summer but seasonal differences are not pronounced.

Extensive lenses of medium and coarse sand were deposited across the profiles during storm conditions. Subsequent wave action and wind action reworked this material into sporadic stringers and bands along the backshore zones of many profile stations. Bagnold (1941, p.69), suggested that "... a pebble surface can be regarded as a resevoir in which sand is stored during periods of gentle wind, and from which it is removed by a sudden storm". On the study beaches this phenomenon appears to be initiated by deposition of sand in the interstices by swash action. These processes are responsible for the extensive dune ridges along the Kaitorete Spit and south of the Orari River. Blowouts in the dunes of the spit are oriented to the more powerful, less frequent southerly winds.

Wind distribution patterns also have significance with regard to wave modification. Table 2 is an analysis of the relation between wind and wave directions at Timaru. The wind pattern is similar to that shown in Figure 4. Though the data are limited it is apparent that the lower easterly waves were most frequently accompanied by a following (onshore) wind. Swell from the south-east was nearly equally opposed and followed by local winds. Thus almost half of the waves received in the period February to May 1967 were accompanied by onshore winds, a condition that made for rapid winnowing of sands from the shingle foreshore. Sand landward of the swash berm persisted longer but was ultimately removed to the dunes or cliff-base, or carried alongshore. Southerly storm waves were always accompanied by strong following winds and frequently by stormy weather. These waves were responsible for the deposition of much of the subsequently reworked sand.

There is thus a relationship between local wind conditions and wave approach direction, but this is an indirect one resulting at most in modification, albeit important, of existing wave trains. Frequently waves of considerable magnitude reach the coast under very light wind or calm conditions.

However, strong following winds, as during southerly storms have the important effects of inhibiting the increase

Table 2

Percent Occurrence of Winds Following and Opposing Wave Trains at Timaru

Wave Direction	Direction of Wind	February	March	April
North-east	Opposing	3.84	--	5.0
	Following	--	--	10.0
	Calm	--	--	--
East	Opposing	15.36	6.66	--
	Following	38.46	23.31	--
	Calm	11.52	3.33	--
South-east	Opposing	--	26.64	25.0
	Following	15.36	9.99	35.0
	Calm	3.84	26.64	5.0
South	Opposing	--	--	--
	Following	11.52	3.30	20.0
	Calm	--	--	--
		N=26	N=30	N=20

- *Source.* Wave records made at the entrance to Timaru Harbour. February 1st to May 8th, 1967.

Plate 4. Spilling storm breaker. H_b = 12 feet approximately.

Plate 5. Typical plunging breaker. Note that the backwash of the previous wave had not completely drained from the foreshore.

of wave height onshore, and of causing spilling of the wave crest. Thus storm waves tracking from the south into the Canterbury Bight produce irregular plunging breakers (*) and spilling breakers (*) (Plate 4). Plunging breakers characterise lower wave heights and are especially pronounced under strong opposing winds, such as north-weat winds (Plate 5).

The above discussion has indicated that waves in the Canterbury Bight are modified swell that have travelled along distances from storm centers in the South Pacific Ocean. This means that the wave trains arriving at the coast are frequently composite in nature, containing elements of two or more originally distinct trains. Further, strong local winds having significant durations can superimpose very short period "choppy" waves, on longer, more regular ocean swell. This makes for complexity of wave pattern which means that for detailed study synoptic observations of wave parameters are vital. Hindcast techniques for predicting wave patterns from wind data cannot be employed, even where recording stations are close to the coast.

Waves in Deepwater

The characteristics of waves reaching Timaru are shown in Figure 5 and Table 3. There are three major approach directions, the most frequent being the south-east and the dominant being the south. In summer waves of low amplitudes approach mostly from the east and north-east, whilst in autumn and early winter there is a change in prevailing direction to

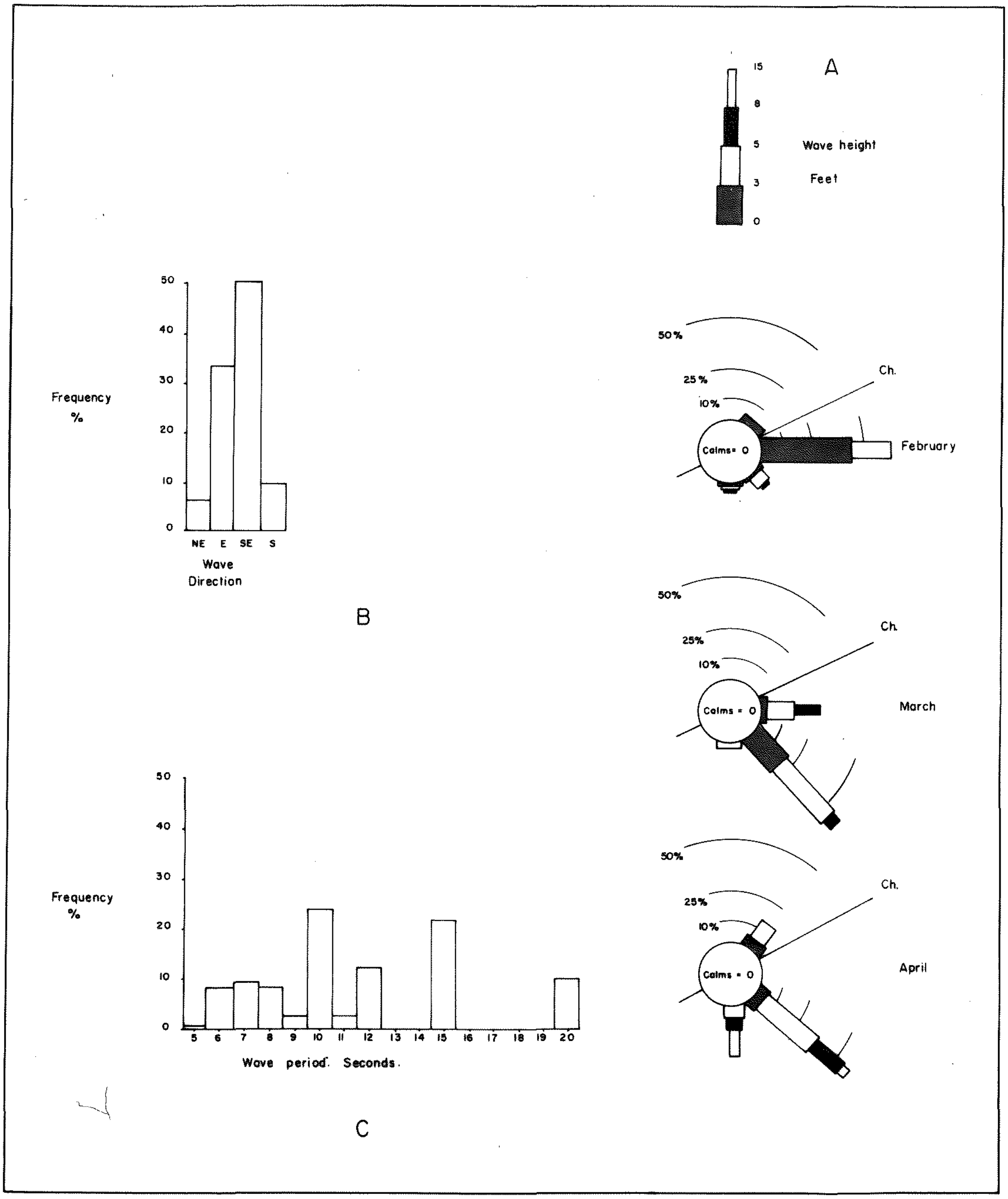


Figure 5. Distributions of wave height, period and direction. Ch = Chord of the beach, headland to headland. Ch = N64°E.
Source: Timaru wave records. February - May 1967.

the south-east. Southerly storms are not infrequent in summer, but increase markedly in autumn and winter. The highest wave recorded at Timaru was 12.0 feet and the lowest 1.5 feet. The histogram of wave periods in Figure 5C reveals a strong observer preference for waves of 10.0 and 15.0 seconds. However, both the range of periods (5 to 20 seconds) and the computed average periods shown in Table 3 agree well with observations by other workers (Dingwall, 1966; Elliott, 1958; Hodgson, 1966). An average period in the range 10 to 12 seconds is reported by these workers. Hodgson (1966) notes that 81% of his observations lie between 6 and 12 seconds. This compares with 61.56% in this investigation, a feature probably due in large measure to the lack of records covering a full year.

Wave energy levels show a wide range and increase markedly toward winter. Figure 5 and Table 3 make it clear that the fundamental wave type received in the Canterbury Bight is a typically long period ocean swell. Both wave height (Fig. 5A) and wave period (Fig. 5C) increase toward winter but since the waves are predominantly ocean swell, steepnesses remain low. Table 3 shows that wave steepness ranged from 0.0012 up to 0.03. It is interesting to note that only the steepest storm waves reached values of 0.025 to 0.03, the theoretical laboratory boundary between beach erosion and deposition (Ippen and Eagleson, 1955; Saville, 1950). Mean steepnesses in the

Table 3

Summary of Wave Records at Timaru

Month	*	Wave H (feet)	Wave T (seconds)	Wave $\frac{H}{L}$	Wave E $\text{Ft.lbs.ft.}^{-1} \times 10^{4}$
February	L	7.0	20.0	0.032	9.45
	M	3.46	11.27	0.0044	7.81
	S	1.5	5.0	0.0013	0.59
March	L	7.0	20.0	0.028	28.93
	M	4.34	11.81	0.005	11.012
	S	2.50	6.0	0.0012	3.69
April	L	12.0	20.0	0.030	59.04
	M	5.175	12.29	0.01053	20.424
	S	1.50	7.0	0.00152	3.2114

* L = Largest; M = Mean; S = Smallest value.

\- Source. Wave Records taken at the entrance to Timaru Harbour. February 1st to May 8th, 1967. (See Appendix IVA).

range 0.0044 to 0.0105 indicate a theoretical potential for much beach accretion. However, since these waves are confined to less than one third of the available profile lengths above low water level, and since the higher storm waves cover and erode the whole length of the profiles, the forms resulting from low steepness waves are small and short lived. Short term erosion or accretion of the profile depends upon whether the profile resulting from the preceding period of wave action is too steep or too flat relative to the next period of wave action. Beach profiles along most of the Canterbury Bight appear to be very closely adjusted to the distribution of wave energy in profile as evidenced by the small amplitude of most envelope curves and by the rapid recovery of slope and form after cliff falls.

Transportation of Materials in the Offshore Zone. Shepard and Inman (1950) divide nearshore circulation patterns into coastal currents and nearshore circulation proper. Coastal currents constitute relatively uniform current flows and occur in deeper water. It will be shown that they are of little significance as a transporting agent in the study area. On the other hand the nearshore circulation is of prime significance in the movement of beach sediments. It is determined by waves and wave motion in and near the breaker zone and is comprised of (1): The mass transport of water shoreward; (2): Transport along the coast of these shoreward moving water masses (Littoral current); and (3): A return flow to deeper water as a compensation of the mass transport and the raising of sea-level against the shore. The return flow may be restricted to narrow streams (rip currents) and/or is uniformly distributed over the breaker zone ("undertow"). Rip current patterns were not studied in this investigation. Thus, the following discussion is confined to onshore transport potentials and to longshore currents generated in the direction of wave motion by waves approaching the shore at an angle.

The shallow floor and gentle slopes of the Canterbury Bight mean that waves "feel bottom" at considerable distances from the shore. Dingwall (1966) demonstrated a significant concentration of greywacke derived sands in some bay-head beaches of Banks Peninsula and the extensive mantle of fine sands of similar type on the floor of the Canterbury Bight has been noted (Fig. 3A). For these reasons an analysis of bottom transport conditions in the bight is warranted. Dingwall suggested tidal currents, accentuated by their attenuation around the peninsula as the possible mechanism of sediment transport, but this does not apply within the bight itself. It has been noted that southerly storm wave action results in the deposition of medium and coarse sands on the beaches. On three such occasions it was observed that the water was turbid for considerable distances offshore.

The offshore sand deposits are finer than the beach sands, but it is not known what sizes prevail inshore near the breaker zone. Fine sands and even silts occurred in small amounts in many beach samples, where they had been trapped by percolation, but generally turbulence in the surf zone and in the swash-backwash would keep these sizes in permanent suspension. However, medium and coarse sands are abundantly supplied by the rivers and by erosion of the coastal cliffs as has been demonstrated. Erosion of sand from the foreshore has already been noted and river discharge is such that fines in suspension would be carried beyond the breaker zone.

Bruun (1954) and many others have noted that there are two types of littoral drift: swash and backwash driven bed-load transport (beach drift); and suspended transport in the surf zone due to the turbulence of breaking waves and the resulting longshore currents. It is the latter type of motion both in and near the breaker zone that is under consideration here. Figure 6A shows the onshore maximum horizontal components of wave orbital velocity, ($U_{max.}$) (*) for typical swell and storm waves received in the Canterbury Bight. Zeigler (1964) indicates that the limits of application of the wave theories used are given by: $\frac{H}{d} \leq \frac{1}{50}$ (Where 'H' is wave height and 'd' is the depth of water). The limiting depth for the highest waves considered is thus 200 feet. Formulae used in computation of the diagrams are given on the diagrams and were derived from Shepard (1963,pp. 61-65) and Norrman (1964,pp.72-75, 89). It will be noted that different formulae have been employed. This is because, "as far as short, steep waves are concerned, the motion off the breaker zone should be looked upon as

Figure 6A.1. Maximum onshore oscillatory velocities near the bottom for swell waves with a steepness in deepwater of 0.005.
L_o = 184.32 to 737.28 feet,
T = 6 to 12 seconds.

6A.2. Maximum onshore oscillatory velocities near the bottom for storm waves with a steepness in deepwater of 0.03.
L_o = 32.92 to 329.2 feet.
Modified from Norrman (1964, Fig.37, p.75).

6B.1. Depth of initiation of bed-load transportation in relation to wave height for swell waves with a steepness of 0.005.

6B.2. Depth of initiation of bed-load transportation in relation to wave height for storm waves with a steepness of 0.03. Modified from Norrman (1964, Fig.42B, p.89).

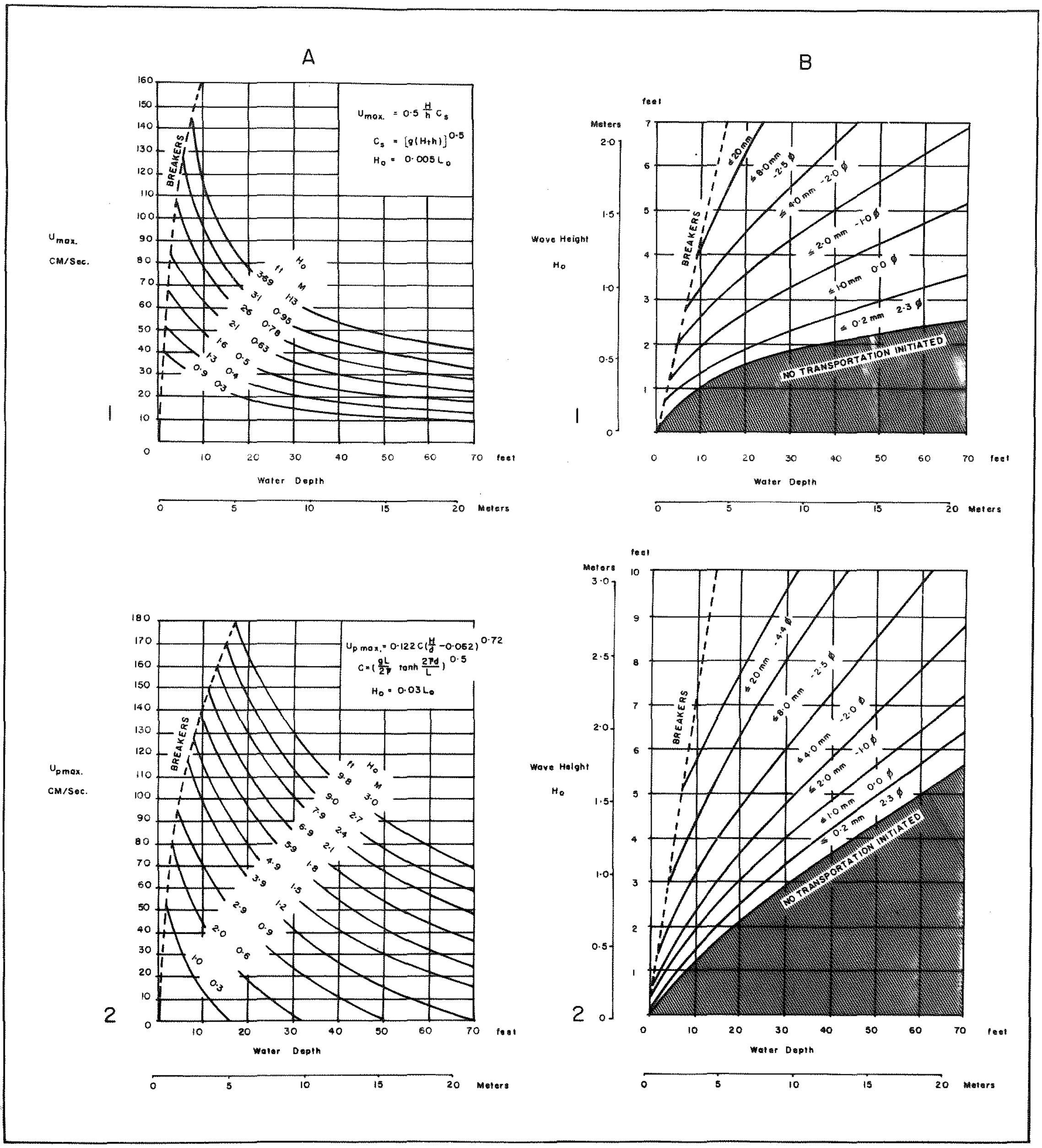


Figure 6A. Bottom transport velocities under storm and swell waves.

B. Limits of bottom transport for different grain sizes under storm and swell waves.

following the theory of oscillatory waves, whereas long, low waves may be better treated according to solitary wave theory when they have become steep before the breaking point" (Norrman 1964, p.75). Cherry (1965, p.53) shows that the distribution of $U_{max.}$ is also an approximation to the general distribution of mass transport velocity (U_b) (*) near the bed. This velocity occurs in the same direction as wave propagation. In such considerations it is important to note that the velocity requirements for the initiation of motion in sediments are higher than those required to perpetuate it. Figure 6A indicates that transport velocities near the bed increase rapidly toward the breaker zone, as well as with increasing wave height. Low swell waves of the type shown "feel bottom" at 92 feet but it can be seen that velocities are very low below 70 feet. The fine sand mantling the floor of the Canterbury Bight is undisturbed by swell waves. Shepard (1963, p.128) notes that sediments finer than approximately 0.18 mm.(the "bed-load limit") require much higher velocities to initiate motion than many sizes larger than this. This is because below a diameter of 0.18 mm. individual grains cease to produce turbulence in the flow. The surface of the bed becomes hydraulically smooth so that transport is more difficult to initiate. This process results in the deposition of fine sands on the floor of the bight.

Table 4 shows that velocities sufficient to entrain medium and coarse sand lie between 28 and 40 cm/second. Under swell

Table 4

Critical Erosion Velocities for Different Particle Sizes

Source	Particle Size mm.	Particle Size ∅	$V_{crit.}$ cm/sec.
X	30.0	-4.9	150.0
S	20.0	-4.3	130.0
S	8.0	-3.0	100.0
S	4.0	-2.0	75.0
S	2.0	-1.0	55.0
S	1.0	0.00	40.0
S	0.2	2.3	28.0

- Sources. S. Sundborg in Norrman (1964, p.88).
X. Krumbein and Leiblein (1965).

waves these conditions obtain only in water shallower than 50 feet for long period low swells. Movement under such conditions would be confined to the nearshore zone where other currents operate. However, in storm conditions transport is indicated at depths of up to 70 feet, a distance of 6 miles offshore over most of the Canterbury Bight. The potential for transport then increases steadily onshore. At such times the transport of sand and even small pebbles in the nearshore zone is clearly indicated. The directions of transport are, in part, a function of wave refraction (*). Thus Figure 6A clearly indicates the potential for transport of sand along the coast from south of Timaru during southerly storms.

Figure 6B was compiled from Figure 6A by interpolating known critical erosion velocities ($V_{crit.}$) (*), for different particle sizes on the velocity distributions (Table 4). As expected,the potential size of transported materials increases toward the breaker zone where turbulence is at a maximum. Even under swell conditions the diagram indicates at least intermittent suspension of pebbles up to 8 mm. diameter (-3.0ϕ) for waves 4 feet high. However, since the beach deposit slopes steeply into water up to 30 feet deep (Fig. 3B), and since shape effects are important in transportation of pebbles it is thought that little, if any, onshore transport of particles coarser than 4 mm. (-2.0ϕ) takes place except under the largest storm waves. It is therefore concluded that pebbles carried beyond the breaker zone represent a sub-permanent loss of material to the beach.

The above analysis of wave potential for transport near the bed agrees well with the findings of Trask (1955) and Inman (1957). That is, that disturbance of the bed is continual at depths less than 30 feet, and that between 30 and 60 feet strong disturbance of the bed only occurs under vigorous storm wave action.

Because swell waves arrive from several different directions and storm waves arrive from the south, it is apparent that sediments of different sizes will be transported in different directions under different conditions. Also different sizes may move in divergent ways under the same wave conditions.

<u>The Plan Distribution of Wave Energy</u>. The distribution of wave energy in plan is strongly controlled by offshore relief. As previously indicated the offshore bottom of the Canterbury Bight has very gentle slopes. There are no submarine canyons or ridges to impede or localise wave activity or sediment motion. Bottom contours parallel the shore and depths are shallow. Figures 7, 8 and 9 illustrate wave refraction patterns for the prevailing swells and storm waves. Because of the nature of the offshore relief there is very little concentration of energy at any point along the shore. Since all of the waves approach at an angle to the shore and first reach shallow water at the ends of the bight, there is divergence of the wave

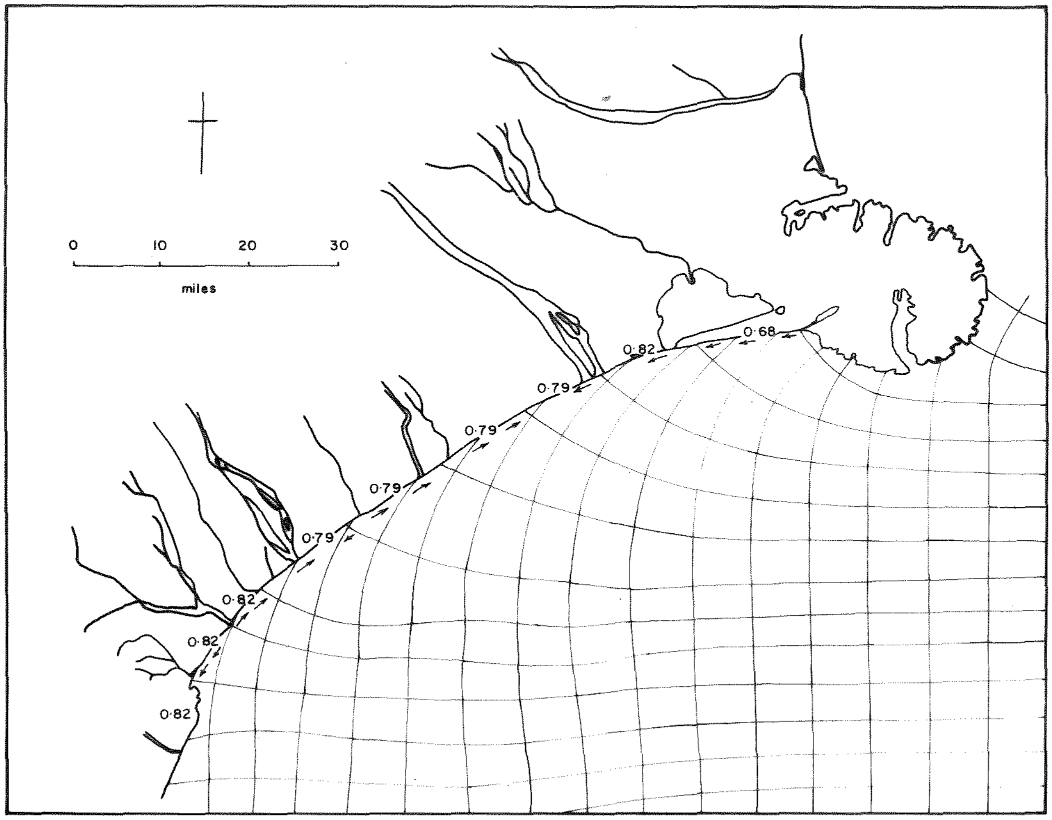
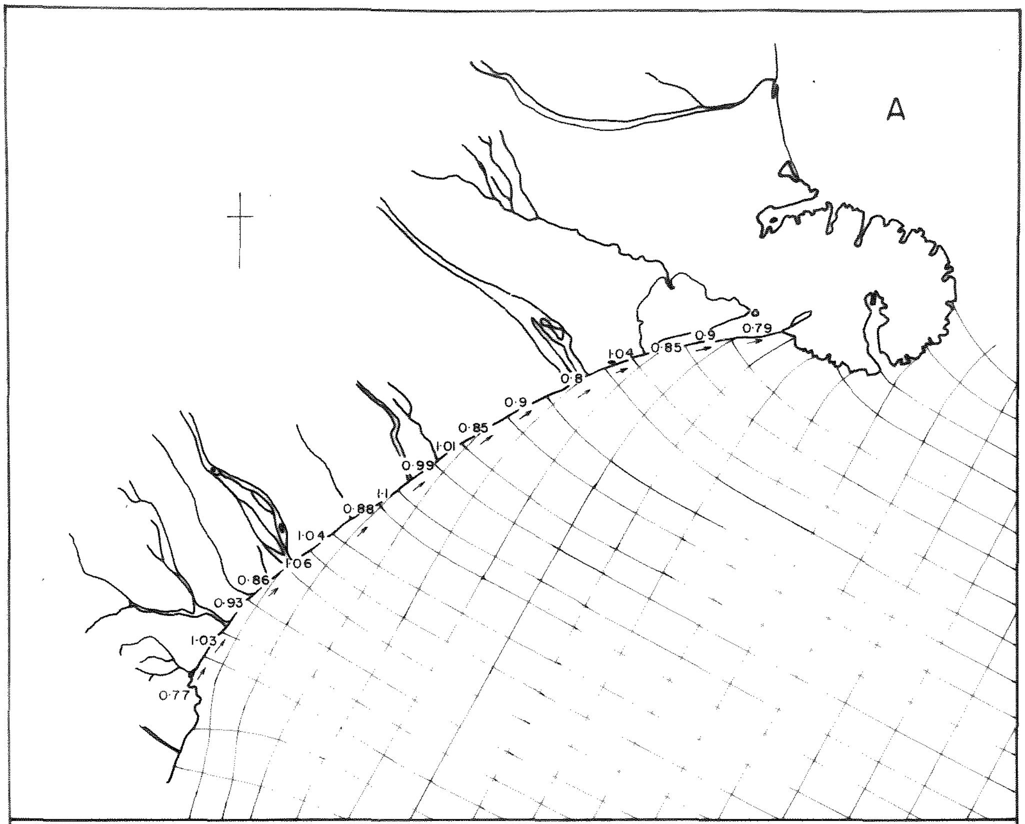


Figure 7. Wave refraction. T = 11.0 seconds. From the East. Every 67th wave crest. The numbers are shallow water wave refraction coefficients (K_b). Arrows indicate observed directions of longshore drift during field surveys.

Figure 8A. The numbers are shallow water wave refraction coefficients (K_b). Arrows indicate observed directions of longshore drift during field surveys.



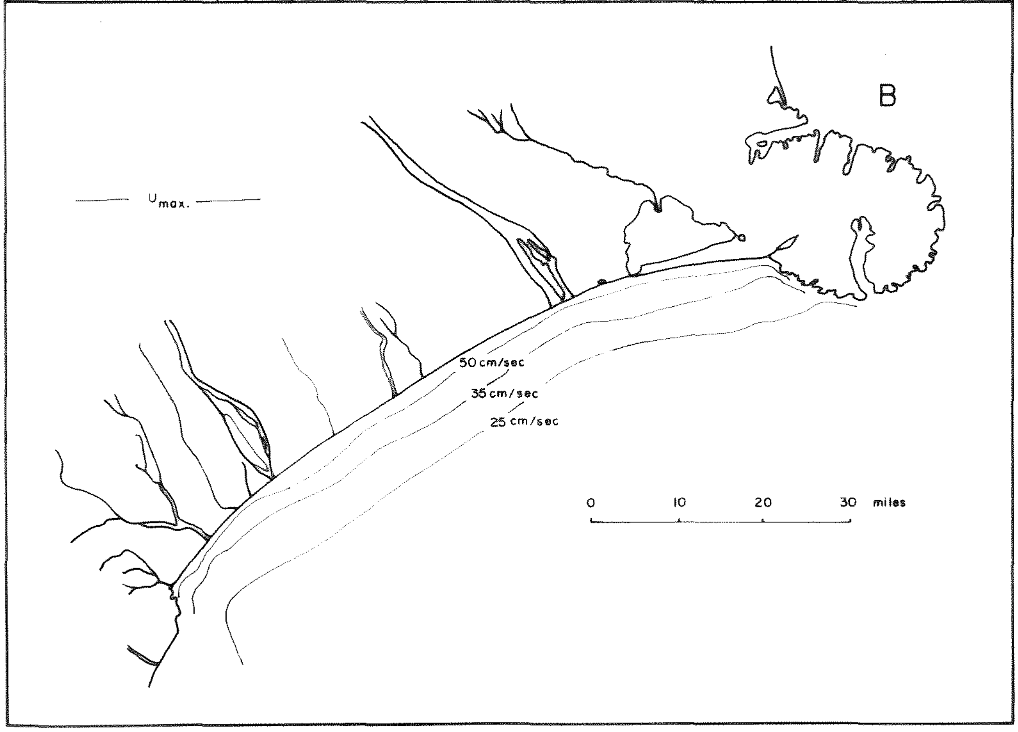


Figure 8A. Wave refraction. T = 11.0 seconds. From the South-east. Every 67th wave crest.

B. Distribution of bottom transport velocities for south-easterly swell waves.

Figure 9A. The numbers are shallow water wave refraction coefficients (K_b). Arrows indicate observed directions of longshore drift during field surveys.

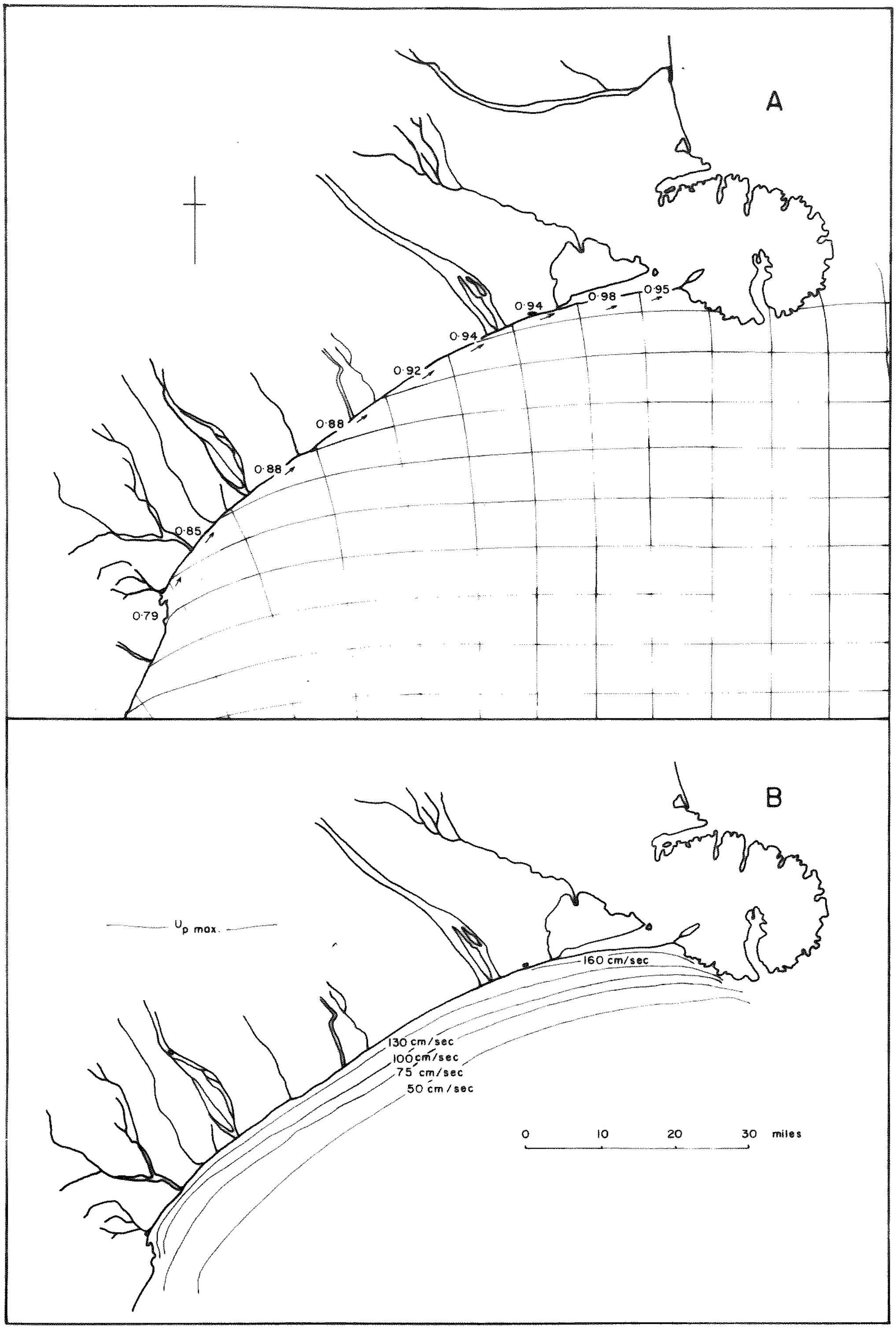


Figure 9A. Wave refraction. T = 11.0 seconds. From the South. Every 67th wave crest.

B. Distribution of bottom transport velocities for southerly storm waves.

crests. Wave crests in the center of the bight are in deeper water than those at the ends and so travel faster.

The shallow water wave refraction coefficients, K_b, (*) given on the diagrams are a measure of this divergence. They are a measure of the ratio of a unit length of wave crest in deep water to its shallow water resultant due to wave refraction. Where no refraction takes place the value of K_b is 1.00, where the crests converge values are higher than 1.00, and, as in the Canterbury Bight, where the crests diverge the ratio has values less than 1.00. It can be seen from Figures 7, 8 and 9 that values of K_b range from 1.09 (very weak convergence) to 0.365 (strong divergence). Appreciable refraction occurs only close to the shore. The higher energy sections of the shore are thus those where crests do not diverge greatly so that much of the initial deepwater wave energy is retained. Figure 7 indicates that the easterly waves of summer are strongly divergent at the shore resulting in low breaker heights and variable littoral currents. This is particularly true of the less refracted shorter period waves. Northeast waves reaching the Canterbury Bight coast are even more refracted (K_b = 0.3 to 0.5). Southeast waves retain much more of their initial energy levels and produce a more persistent drift to the north. These are the conditions responsible for the varied movements of foreshore sands discussed above. Figure 9 demonstrates the powerful longshore component (from south to north), of the southerly storm waves. Figures 8B and 9B show the plan distributions of mass transport velocities under the prevailing south-easterly swell and the southerly storm waves respectively. It is apparent that velocities are uniform and low along the shore under south-easterly wave action. A similar situation would occur during easterly and north-easterly waves. However, under southerly storm conditions the northern section along Kaitorete Spit emerges distinctly as the high energy zone of the beach. It is therefore apparent that significant variations in wave energy occur along the Canterbury Bight. It has been shown that this is due to refraction of waves approaching from different directions over the shallow floor of the bight. These differences result in marked variations in the types and intensities of surf action on the beach.

The Surf Zone. The types of surf occurring on the beach have been discussed in connection with wind effects on waves. Plates 4 and 5 show typical spilling and plunging types. As mentioned above it is those breakers that spill that deliver the longest, most powerfull swashes to the beach foreshore.

The most important feature of the surf zone is its narrow width. At no time is the zone of breaking waves more than a few yards wide and much of the time it is only a few feet. There is little, if any translation of the breakers shoreward and seaward with the rise and fall of the tides. Hence energy dissipation is confined to a very narrow band and the lower foreshore area is continually subject to high turbulence. In this respect the study beach is similar to shingle beaches previously investigated by other workers, (e.g. Lewis, 1931; King, 1959, p.138).

The longshore distribution of breaker heights for the different wave approach directions has been computed and the results are shown in Figure 10. This diagram was compiled by considering the effects of both shoaling transformations and wave refraction on the advancing wave. Hence, following Shepard (1963, p.73), breaker height H_b (*), is given by:

$$\frac{Hb}{Ho} = 0.3 \left(\frac{Lo}{Ho}\right)^{\frac{1}{3}} . Kb$$

Where: H_o is the deepwater wave height.
L_o is the deepwater wave length.
K_b is the shallow water wave refraction coefficient.

Field observations of breaker height plotted on Figure 10 show that except for the terminal ends of the beach agreement of the predictions with the observed is within 15%.

Under easterly and north-easterly conditions breaker heights are greatly diminished. For other wave approaches the position of the highest breakers reverses. Under south-east waves there is a general current flow away from the region of high breakers. Shepard and Inman (1950) observed similar flows on some Californian sand beaches. By contrast under southerly wave conditions the refraction pattern is such that a strong flow occurs toward the high energy (north) end of the Canterbury Bight. Significantly, littoral drift directions under easterly wave conditions are variable in both magnitude and

Figure 10. Arrows indicate directions of longshore drift during field surveys. Length of arrow is proportional to strength of flow at each station. Open circles, triangles and squares represent observed breaker heights during surveys.

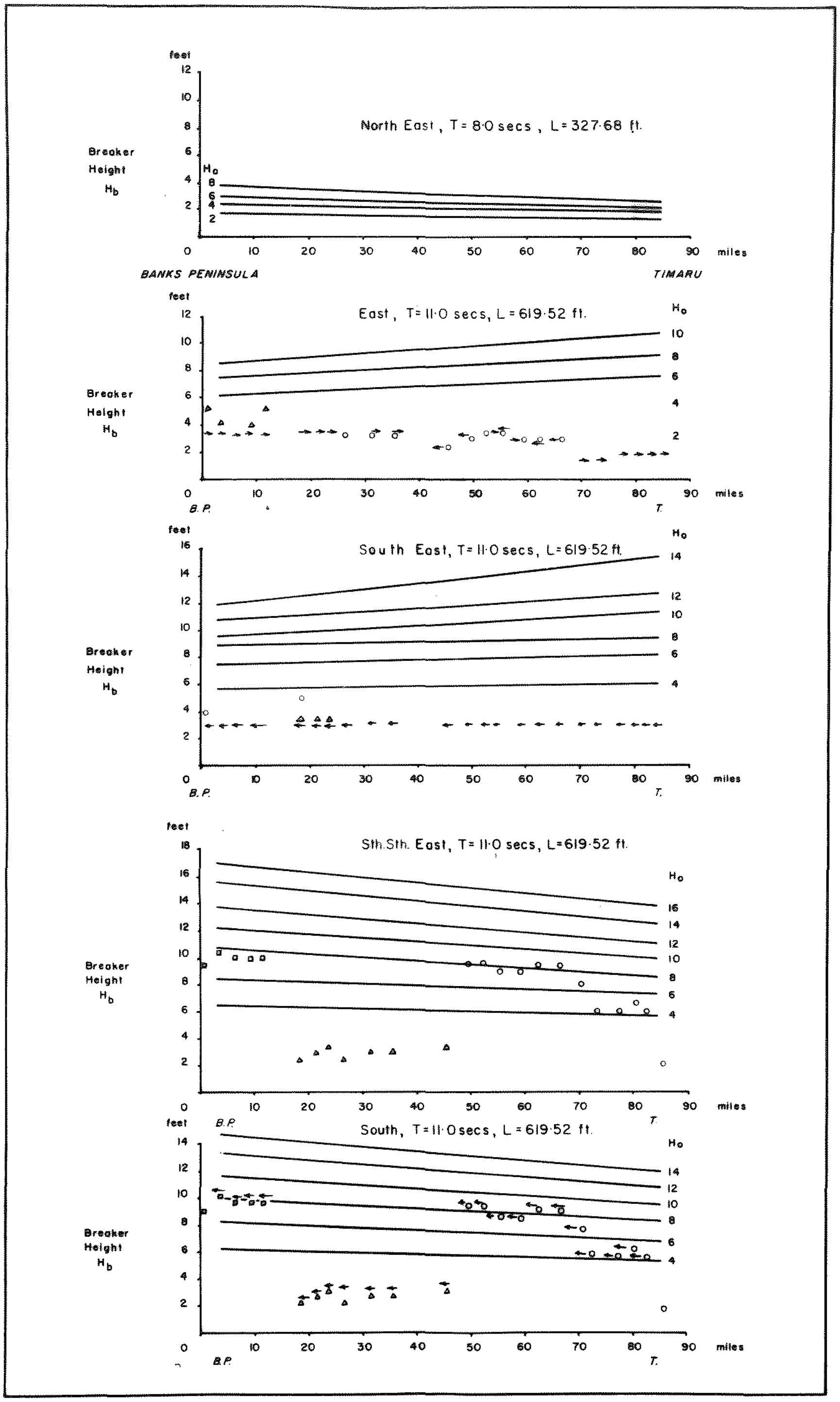


Figure 10. Longshore distributions of breaker heights.

direction. Figure 10 shows that both the south-east swells and the southerly storm waves increase greatly in height toward the breaker zone. This is typical of long period waves (Davidsson, 1963, pp.13-14).

Discussion of Wave Potentials for the Transport of Sand and Shingle. It is clear that considerable potential exists for complex movements of medium and coarse sand. However, there is probably only one major direction of transport for pebble and cobble sizes (from south to north). Owens (1966) noted variations in grain size, sorting and skewness along the northern 2 miles of the Canterbury Bight near Birdlings Flat and suggested that storm waves transported all sizes to the north and that subsequent swell action returned the fines toward the south. Similar variations along the whole of Kaitorete Spit were found during this investigation. It is therefore concluded that considerable counterdrifting of sand and granule sizes takes place along the Canterbury Bight shoreline. Shingle sizes covering most of the beaches between the swash berm and the backshore dunes or cliff are affected by littoral drift of sufficient velocity from one direction only. Thus movement is restricted to across the shore or along it from south to north. Other considerations indicate that shore-normal movement of pebbles is probably greater than net longshore transport. Shingle moved offshore is lost sub-permanently to the beach. The sand sizes undergo even more complex movements than mere counterdrifting along the shore. It has been shown that sand commonly moves onshore under storm wave conditions and offshore and into the dunes during subsequent conditions. There is also the probability of the transport of sand from outside the study area, around the Timaru breakwater on the shallow, flat nearshore edge of the continental shelf.

The Swash-Backwash Zone. Swash is a complex function of the manner of breaking of the parent wave, of the foreshore slope (*) and roughness, and of other variables. The swash zone is the area of beach drifting and is regarded as the zone of maximum bed-load transport. Because there is little translation of the breakers on the study beach the swash-backwash processes dominate the beach profile. Almost all of the changes in morphology and sediment distribution observed were produced by the action of swash and backwash. This is true of other shingle beaches but because of the difficulties in measuring flows of short duration which vary continuously in depth and velocity, very little is known about the processes operating. Some general considerations have already been mentioned. Shingle beaches stand at steeper angles than sand because of the greater permeability of shingle. Percolation into the beach reduces the backwash volume so that the forces acting down the beach face (*) are not so strong as on sand for waves of the same size. Shepard (1963, p.114) demonstrates that permeability of the beach increases with the square of the grain diameter and decreases exponentially with increasingly poor sorting of the sediments. For a given grain size a poorly sorted deposit is thus less permeable than a well sorted one. The effect of increasing wave height on the relative volumes of the swash and backwash can be seen from these considerations. For low waves on a moderately sorted shingle beach the effects of permeability are relatively high. Very little of the small volume of swash will remain to return to the surf zone as backwash. The effects of increasing wave height is to deliver larger volumes of swash to the foreshore. If permeability remains constant then the volume of the backwash relative to the swash is greatly increased. Erosion and "downcombing" of the profile occurs, resulting in flatter slopes. This explains the observation of Lewis (1931) that under storm waves the backwash is relatively more powerful than the swash.

Figure 11 shows the relation between swash length and breaker height, as well as the frequency of occurrence of swash lengths on the study beach. The diagram was compiled from 101 observations made during surveys under all the wave conditions shown. For the broad, planar profiles characteristic of Kaitorete Spit and the beaches near Timaru there is an almost linear relationship between increasing wave height and increasing swash length. For the steeper cliff front profiles the swash of waves lower than 4 feet is confined to a level a little

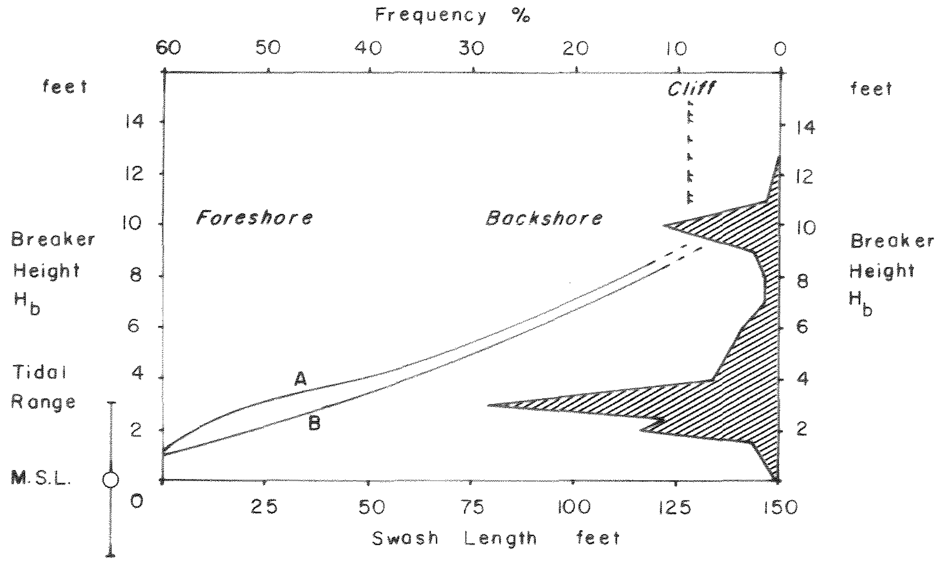


Figure 11. Frequencies and distances attained by swash. A - from profile 14 (cliff zone). Maximum slope on swash berm = 13°. B - from profile 3 (Kaitorete Spit). Maximum slope throughout = 7°.

above the high water mark. This is the level at which swash berms (*) are built in summer and during moderate wave conditions, on all profiles. Most beach cusps (*) are formed at this level. The histogram of the frequency of occurrence of swash lengths on the diagram indicates that this is the level at which most swash terminates.

Though deepwater wave heights in excess of 4 feet are frequent, as was shown in Figure 5, long swash is not common except during storms. This is primarily because of the prevailing plunging surf associated with most waves (Plate 5). Storm waves spill and deliver larger volumes of water so that the frequency distribution of swash lengths is strongly bimodal. Most waves deliver short swashes, whilst the largest storm waves give less frequent, very long swashes.

The pattern of swash is clearly one of prolonged concentrated activity up to and a little beyond high tide level; and of less frequent but very powerful activity which covers the whole profile. There are very few waves that deliver swash to the central parts of the profiles. This helps to explain the vigorous erosion of accumulated materials on the backshore of cliff profiles (Plate 6), the trimming of dunes during storms (Plate 7), and the exposure of the beach basement beneath the dunes near Timaru (Plate 8).

This pattern of swash distribution explains much of the morphology of the beach profiles. Minor changes in form with tidal and low wave variations are confined to the zone seaward

Plate 6. Erosion of the cliff base by storm swash at profile 14. The cliff base is 11.0 feet above mean sea level.

of high tide level. The rare incidence of swashes having intermediate lengths accounts for the lack of berms developed between high water mark and the berms built high on the profiles by storm swashes. It will be shown that this intermediate zone is a near equilibrium form related to the erosional activity of storm wave backwash.

Under southerly storm conditions swash is directed, in the main, perpendicular to the shoreline (Plate 9), so that while strong littoral drift has been demonstrated in and near the breakers there is only a very small longshore component of wave energy available for beach drifting. Most-bed-load transport on the backshore is directed offshore. Thus, significant longshore transport of pebbles and cobbles is more probable in the nearshore and surf zones than on the beach. Moreover, it has already been shown that this transport is confined to a narrow zone. The known rates of coastal retrogression suggest that much material is permanently lost to the beach by storm wave backwash transport into the surf zone.

Therefore it appears that net transport alongshore by the swash-backwash of storm waves is very small, involving relatively small quantities of coarse materials and sand, (the latter moving to and fro in response to changes in wave energy and direction). Bruun (1954) uses the term "undernourished" for beach profiles which are retrograding in this manner. Relative to wave energy there is an insufficient supply of sediments and so erosion of the shore occurs.

Plate 7. Storm swash trimming of sand dunes at profile 6, Taumutu. The staff is graduated in 6 inch intervals.

Plate 8. Exposure of the beach basement by erosion of the beach at profile 20. Alluvial clays and gravels have been exposed below sand dunes. The staff is graduated in 6 inch intervals.

High, spilling storm waves deliver a large volume of turbulent water to the topmost berm or to the cliff-base. Though much of this volume is lost by percolation into the beach, sufficient head of water remains to move material down-slope on the backwash. The presence of sand between the pebbles greatly inhibits percolation. Swash-backwash period is usually longer than wave period so that water may still be moving down the foreshore as the next wave breaks. Plates 5 and 9 illustrate this. Both show the last of the backwash on the foreshore as the succeeding wave breaks. The exit of ground water and percolating seawater onto the foreshore have been shown to be important controls on beach erosion and deposition (Grant, 1948; Duncan, 1964; Emery and Foster, 1948). Plate 10 shows rilling of the lower foreshore produced in this way. Entrainment of sand and even small pebbles was observed on several occasions.

Only swash has the power to move cobble sizes landward of the surf zone so that they tend to migrate to the higher berm levels. Frequently when berms are overtopped coarse materials are thrown over onto the landward face. Plate 11 shows very large swash overspills near the mouth of the Rangitata River. Driftwood has been piled high in many gullies along the cliffs.

<u>Summary of Swash-Backwash Processes</u>. It is apparent that the manner of profile retreat along the Canterbury Bight is closely related to swash-backwash processes. Of principal importance

Plate 9. Storm swash directed perpendicular to the shoreline and channeled in cusps. Profile 2, Birdlings Flat.

Plate 10. Strong rilling of the lower foreshore produced by the emergence of percolating swash.

amongst these are the erosion of pebbles from the seaward faces of profiles, complex wind and wave working of the sand fraction, and the hurling of pebbles and cobbles landward over the topmost berm into gullies, swamps and river flats. Along the cliffs sub-aerial processes bring about the destruction of the cliff face whilst swash and backwash maintain an equilibrium profile of erosion at the base. The long turbulent swashes of southerly storm waves are the principal erosive agents. The shorter swashes of the prevailing south-easterly swells are confined to the zone below high tide mark and thus produce only minor variations in beach morphology. The backwash of these waves is weak because of percolation and can therefore only effect movement of the smaller sizes, the sands and granules. These then are the major processes acting on the beach face. Currents other than those generated by waves are relatively insignificant in terms of sediment transport on the beach face.

Currents

There are three types of currents distinguished in this investigation. They are:- (1): Coastal currents; (2): Wind generated currents; and (3): Tidal currents.

Coastal Currents (*). The Canterbury Current is a major cold water current which flows north off the Canterbury Bight coast. Brodie (1960) states that at certain times of the year it is deflected from its path by the sub-tropical East Cape Current (which flows south), and sets up eddies in the Canterbury Bight.

No observations of current velocity at depth are known to the author but it is probable that the velocities attained are several times less than those of wave generated currents nearer the shore. It is unlikely that the coastal current effects sediment transport.

Wind Generated Currents. These are surface streams set up by the prevailing winds and hence they track with the winds. Commonly there is a strong inset toward the shore after strong south-east winds. The only significance of these currents with regard to the beach is in the drifting of flotsam, mostly Gorse and Lupin from the river beds to the south. This material is common at all points along the coast between Birdlings Flat and Timaru, indicating that surface drift is very variable. Speight (1930) reported a current running south 3 miles offshore from Birdlings Flat. The current "is intensified in north-east gales until reaching approximately 4 knots. Between this current and the north-running nearshore current is an eddy where flotsam accumulates".

Tidal Currents (*). Tides in the Canterbury Bight are semi-diurnal, with high water occurring twice a day at intervals averaging 12.3 hours (N.Z. Tide Tables, 1967). Thus the tidal streams change direction four times daily. The tidal range at Lyttelton is 6.3 feet on springs and 5.4 feet on neaps. Observations during profile surveys confirmed that the tidal ranges in the Canterbury Bight are of a similar order so that on the steep-to shingle beach, having a predominantly plunging

Plate 11. Storm swash overspill channels near the mouth of the Rangitata River. Note the flotsam bordering the channels.

surf, there is very little tidal translation of the breaker zone. The most noticeable effect of the tides is that swash length increases by a few feet at high tide.

Flood streams (*) set to the north and ebbs (*) to the south but variation in direction and intensity is common, depending upon local water and weather conditions. Dingwall (1966) notes that during southerly weather the flood stream may prevail all day and with the return to calmer weather the south-going ebb tends to predominate. Occasionally streams set normal to the shore rather than north around Banks Peninsula. The maximum flow near Banks Peninsula occurs when the spring tide flood current is reinforced by southerly winds. This results in extremely turbulent flows of 4 to 5 knots. Dingwall suggested that this and the velocity increase due to constriction of the tidal streams near Banks Peninsula may be responsible for transport of fine sands to the north. In the Canterbury Bight where bottom contours are regular and there are no constrictions to flow this does not apply. However, tidal currents are responsible for the dispersal of sediment-charged river flood waters. Rangitata, Orari and Opihi flood waters commonly reach Timaru and suspension clouds from the Rakaia River have been frequently observed near Birdlings Flat. It seems at least probable that fine sediments thrown into suspension by waves are moved north by tidal currents toward Banks Peninsula. Bed velocity conditions in the Canterbury

Bight have been shown to be sufficient for this at depths up to 70 feet, especially when the combination of southerly storm waves and the flood tide current is considered. Hence, just as it is probable that there is sediment movement into the study area from the south, so there may be movement of fines from the study area to the north around Banks Peninsula.

In the above discussion the distributions of beach processes in both plan and profile have been described and examined. The emphasis given to wave processes serves to highlight their importance in the movements of beach sediments. This is particularly true of swash-backwash and surf zone processes. The ways in which sediments on the beach respond to these variations in process will next be examined.

BEACH MATERIALS

Study of beach materials is closely related to study of beach process factors because, as has been indicated, the sizes of particles have important effects on beach morphology. A shingle beach is usually steeper than one of sand. More importantly, the distributions of material sizes both along and across the beach, yield much information relating to the effectiveness of the process factors in moving materials.

In this section of the report the types and distributions of beach materials will be described and analysed in relation to the beach processes discussed previously. Attributes of the size distributions of the beach materials are considered first and then effects of particle form on the movements of different sizes are considered.

The materials forming the Canterbury Bight beach are all alluvial in origin, save for a small quantity of volcanic rocks from Banks Peninsula in the beach deposit at Birdlings Flat. It will be shown that there is little primary difference between particles in the alluvial cliffs, in the present river channels and on the beach.

The dominant mineralogy of the beach sediments is greywacke. Small percentages of amygdaloidal quartz, agate and Cretaceous lavas are also found along most of the Canterbury Bight, but notably at Birdlings Flat. These materials may be found in the present cliffs as well as in the present river channels.

They appear to originate in the marginal volcanics along the inner edge of the Canterbury Plains in the Malvern Hills and near Mount Somers. Shell materials (mostly Mussels), are common in the beach near Dashing Rocks. Pebbles released from the alluvial cliffs are generally oxidised. This gives a blocky texture to cliff-fall materials that is rapidly removed. Oxidation produces coating and pitting of pebble surfaces. The alteration of this type of surface texture is rapid under wave action. Few pebbles on the foreshore zone of any profile displayed oxidation discolouration though many retained surface pits.

Grain Size of the Beach Sediments

The most striking feature of the beach sediments is the wide range of sizes present, from medium sand (Mz = 1.860) up to large pebbles and cobbles (Mz = -5.180). All combinations from pure sand, to mixed sand and gravel, to pure gravel were found. Consequently, sorting, skewness and kurtosis values varied widely. As previously indicated the wide range of sizes made for difficulties in sampling and preparation of size-frequency distribution curves.

Table 5 contains the results of analyses of variance performed on the mean sizes of samples from the beach. The method employed was that of Blalock (1960, pp.242-253). The table clarifies several important points about the distribution of materials on the beach.

Table 5

Analyses of Variance Performed on Distributions of Mean Grain Size of Beach Samples

Source of Variation of Distribution	Variance	N	Degrees of Freedom	'F' at p = 0.001	Remarks
Along the beach. Between sectors of 6 stations.					
A November 1966	14.03	24	20; 3	8.1	S
B February 1967	21.72	24	20; 3	8.1	S
C May 1967	27.61	24	20; 3	8.1	S
Across the beach.					
A November 1966	44.64	48	46; 1	11.97	S
B February 1967	82.48	48	46; 1	11.97	S
C May 1967	64.69	48	46; 1	11.97	S
Between times.	54.35	72	69; 2	7.76	S

* S = Significant at $p=0.001$.

Firstly, analysis of the variation in mean grain size within and between groups of six sampling stations shows that even though stations averaged 3 to 4 miles apart, there is no single sector of the beach that has a variation in mean grain size that is significantly greater than that along the total length of the beach. This was true for all three surveys. This suggests that it is meaningful to treat the whole of the Canterbury Bight as one unit, though it has been shown that because of offshore transport conditions the region cannot be thought of as a closed system cut off from the areas adjacent to it. In common with the findings of Kidson, Carr and Smith (1958) at Orfordness, England, it would appear that none of the river mouths of the Canterbury Bight is a significant barrier to longshore transport of materials, but the similarity of sizes released by the cliffs and rivers makes it difficult to test this generalisation. Though there is no zone of marked change in mean grain size it must be noted that at almost any point along the beach it is possible to find a range of sizes at least as great as that along the whole beach. This is apparent from Table 5. The low values of variance shown in row one demonstrate that there is no marked tendency for sand to be concentrated at the ends of the beach. Mixtures of sand and gravel occur throughout with only a slight increase in the sand fraction at the beach termini.

Secondly, and more importantly, the variation in mean grain size is significantly greater across the shore than along it, even for 90 miles of coastline. This corresponds with the observed distributions of wave energy and is a fact noted by many investigators on both sand and shingle beaches. Sorting takes place in lanes that roughly parallel the shore. Wave energy generated hundreds of miles out to sea is dissipated in only a few yards onshore. Hence variation across the shore is consistently greater than that along it. The lower order of observed variation along the shore is that produced by longshore currents and by beach drifting. This difference is most pronounced at the end of summer (February survey, Table 5), when few storms have modified the backshore and summer low wave modification of the foreshore is advanced.

Thirdly, the last row of Table 5 demonstrates that the observed seasonal variation in wave activity produces a series of significant changes in the distribution of mean grain sizes alongshore. It will be shown that the sorting processes responsible for these changes are closely controlled by the sizes of the beach sediments.

The Relationship between Mean Grain Size and Sorting

Sorting of sediments depends on at least three major factors, (Folk, 1965, p.4): (1) size range of sediments supplied; (2) type of deposition; and, (3) current characteristics. The first of these three factors will be considered in relation to the other two since current characteristics have already been considered in detail. Many investigators have noted that beach sediments tend to be the best sorted of any natural deposits. Folk (1965, p.4) suggests that this is due to the "bean spreading" action of waves on sediment grains as opposed to dumping of grains under river and other types of flow.

Figure 12 shows the relationship between mean grain size and sorting of the beach sediments. It is apparent that the relationship takes the form of a distorted sine curve of two cycles. Folk (1965, p.6) suggests that this relationship holds for all sediments but that curves derived from different environments adopt different positions on the graph. The curve shown in Figure 12 is only an approximate fit to the center of gravity of each segment of the scatter-graph. Better fit could have been achieved by fitting a power function of the fourth order to the data, or by harmonic analysis, but this was not attempted.

The curve suggests that there are two populations of particle sizes involved in the beach deposit; a sand and a pebble population. The pebble population has its modal contribution in the region -2.5 to -3.50 and the sand peaks at 1.0 to 2.00. Folk (1965, p.6) indicates a coarser mode for the pebble fraction and does not show the decrease in sorting for pebbles coarser than -4.00. However, increasingly poor degrees of sorting with passage to the cobble and block sizes is to be expected. The wide scatter of values from 1.0 to -2.00 mean size is indicative of the highly variable degrees

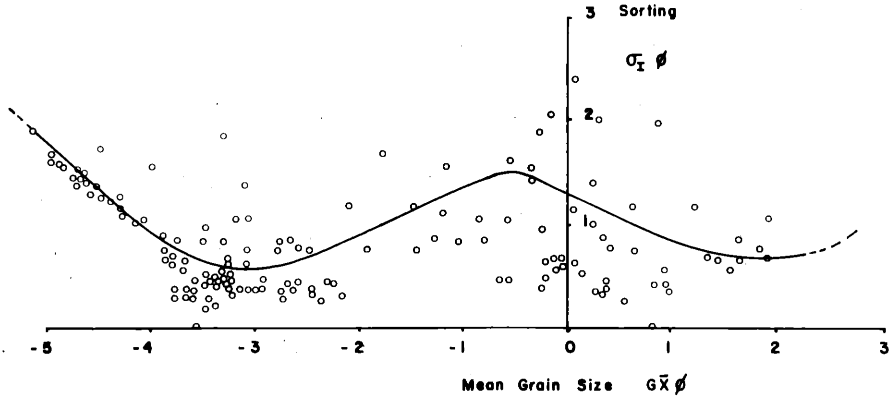


Figure 12. The relationship between mean grain size and sorting.

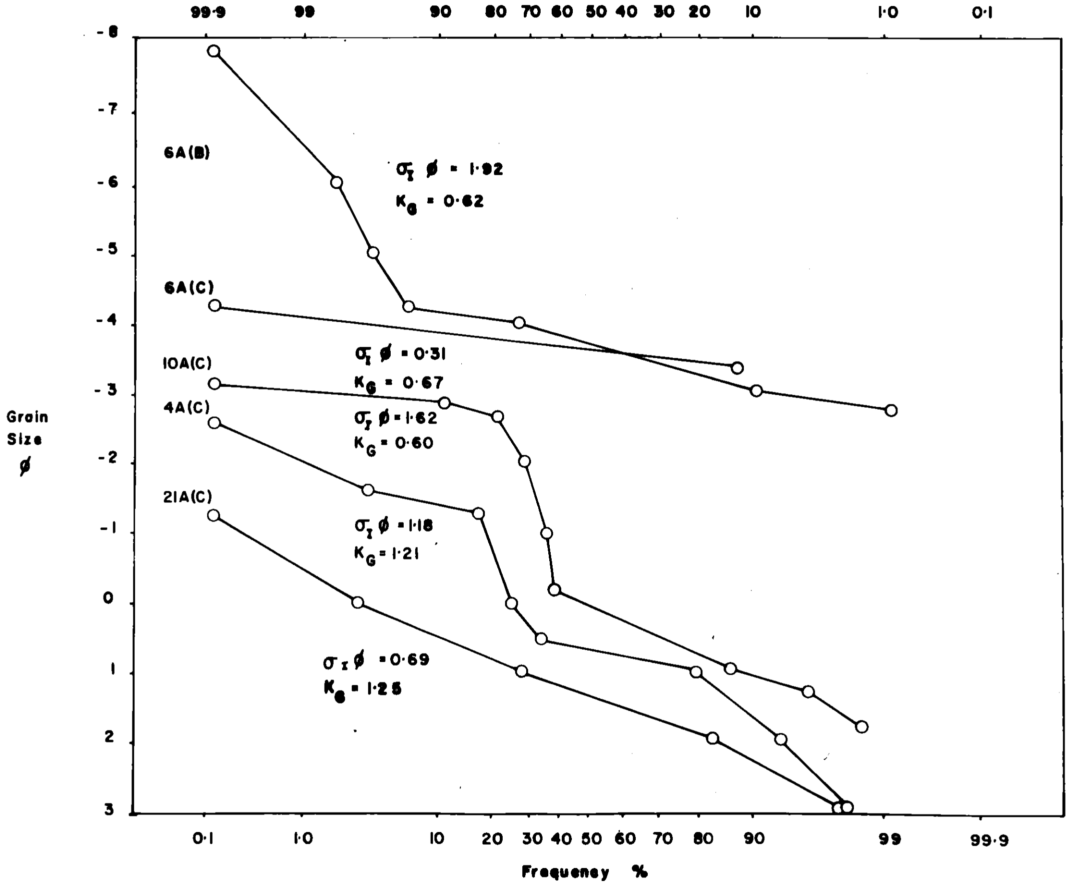


Figure 13. Representative grain size-frequency curves.

of mixing that take place between the two "end member populations" (Folk, 1965, p.5). Owing to the prevailing high energy levels on the beach and the dominant sifting action of swash-backwash in the sampled environments, quite high degrees of sorting were attained in some of the "mixed" samples, especially for smaller grain sizes.

Some of the processes giving rise to this relationship can be demonstrated by analysis of individual grain size-frequency distributions. The curves shown in Figure 13 cover the range found in the study area. The notation for the samples cited is such that, for example, 4A(C) refers to the foreshore sample from profile 4 taken during survey C. The sample notation and the dates of the surveys are given in Appendices IC and ID along with percentile values from the grain size-frequency curves and the grain size parameters calculated. Two features of the distributions shown in Figure 13 may be noted here. Firstly, there is the source population effect discussed above and secondly, there are effects related to wave action.

Sorting is the process whereby particles of different sizes attempt to reach equilibrium with a given hydrodynamic environment. Thus, given the population characteristics discussed above selection, winnowing and mixing of different grain sizes occurs under varying wave conditions. This has been termed a "statistical filtering process", by Tanner (1966). He showed that under low energy wave conditions a break (termed

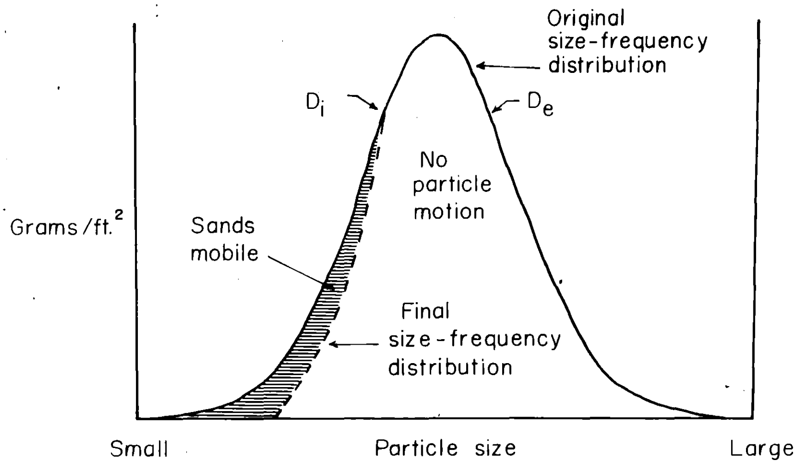
Plate 12. Small pebbles and granules saltating up the foreshore in the swash.

"surf break") occurs in sand size-frequency distributions. Materials finer than 1.50 tend to be filtered out. Tanner suggested that under high energy wave conditions the break passes out of the sand sizes and into the pebble sizes. Figure 13 appears to verify that this occurs in samples taken from the high energy beach of the Canterbury Bight. The sand sample shown, (21A(C)) exhibits no pronounced break, but mixed sand and pebble samples, (4A(C) and 10A(C)) show marked breaks from -1.5 to -3.00. Samples coarser than -3.00 either have no break (are well sorted), or have a sufficiency of pebbles in the range -4.0 to -5.00. The latter is especially true of samples from the storm swash dominated backshore zones. The small "tail" of well sorted fines in the coarser samples is not affected by the process of filtering since velocities in the swash-backwash zone are at all times sufficient for its movement on, off, and alongshore. Hence sand and even granules are moved with equal ease by the prevailing swell waves and turbulent swash (Plate 12).

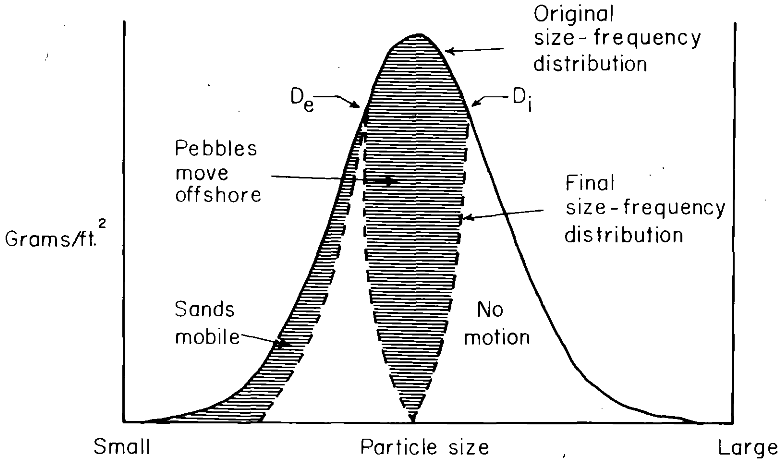
Johnson and Eagleson (in Ippen, 1966, pp.449-62), have shown theoretically that the breaks occur at or near the incipient diameter for particle motion (D_i) (*) under low wave energy conditions. The equilibrium motion diameter (D_e) (*) is greater than this size and a unimodal distribution deficient in fines results since particles coarser than the incipient diameter cannot be moved. This situation is shown in Figure 14A. Figure 14B shows that under storm conditions the incipient motion diameter becomes much larger than the equilibrium motion size and particles in the pebble sizes would be eroded, leaving a bimodal distribution of sizes with one mode in the larger pebble and cobble sizes (which tend to move onshore), and another in the finer sizes (which are completely mobile in the swash and backwash). In this way the mixing of the sand and pebble population end-members and the deposition of the observed sand lenses occur under storm wave conditions. Subsequent wind and wave action results in the filtering out of the finer particles.

It has been shown that sand movement both across and alongshore is complex and that energy levels sufficient to move large pebbles are infrequent and tend to be directed onshore. Hence, the larger pebble and cobble sizes move onshore, whilst the smaller pebbles (-3.0 to -4.0Ø) move offshore. Sand is mobile in all directions. Under given wave conditions different particles move in different directions.

There is thus a close relationship between particle size and sorting. This phenomenon is also closely related to coastal erosion since particles in the range -3.0 to -4.0Ø predominate in the materials supplied from the sources previously discussed. The apparent net offshore motion of the modal class of the beach sediments will be shown to relate closely to the morphological characteristics of the beach.



A. $\frac{D_e}{D_i} > 1$. As for low swell waves.



B. $\frac{D_e}{D_i} < 1$. As for storm waves.

(Modified from Ippen
1966 Pp. 449-62.)

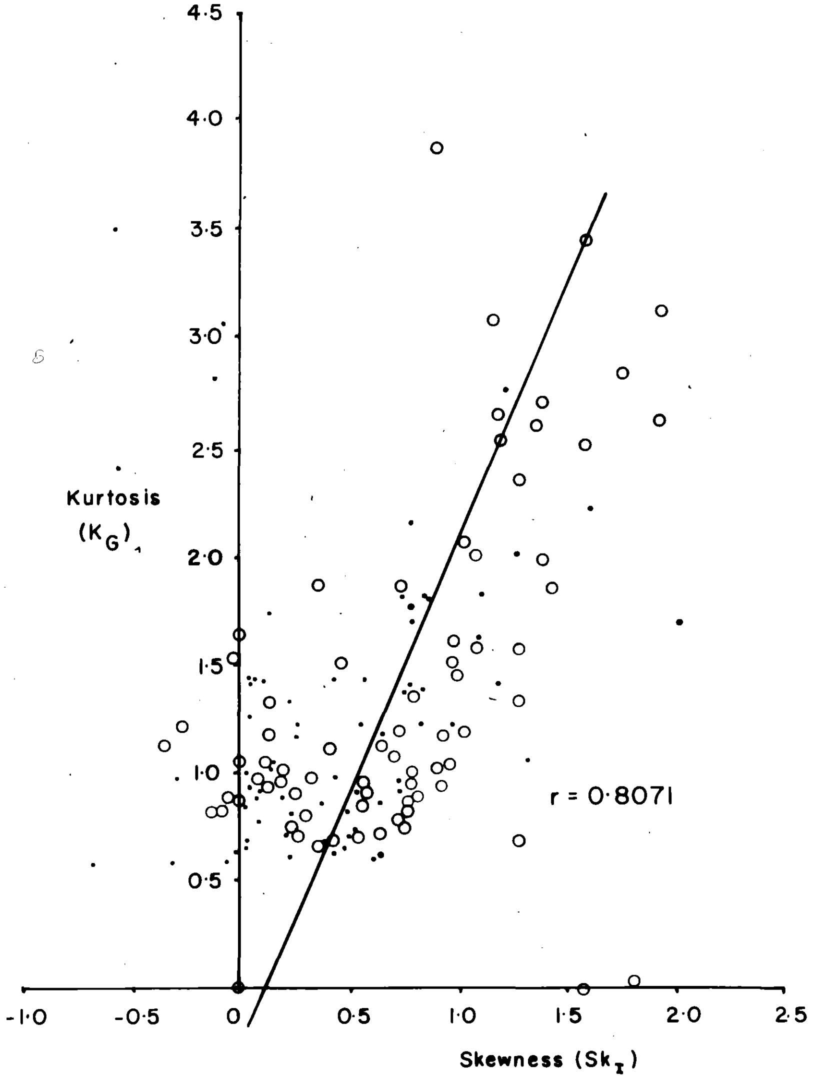
Figure 14. Theoretical sorting of beach sediments under swell waves and storm waves.

The swash-backwash processes discussed also have important effects on skewness and kurtosis values.

Skewness and Kurtosis

The mixing of two particle size populations together with their differing responses to wave energy are responsible for the very wide range of skewness and kurtosis values amongst the samples (Fig. 15). In common with Folk and Ward (in Folk, 1965, p.7), it was found that pebble samples with only a little sand, and conversely sand with only a few pebbles, exhibited pronounced skewness and kurtosis. Such samples were poorly sorted, very leptokurtic and fine skewed and coarse skewed respectively. These sample types were common near dunes and at the base of the coastal cliff. Elsewhere on the profiles skewness varied considerably and samples were mesokurtic or platykurtic, since sub-equal amounts of both end-member populations were present. For the samples shown in Figure 13 kurtosis ranges from 0.67 to 1.25. Coarse pebble samples such as 6A(B) and 6A(C) were very platykurtic while the finer mixed sand-pebble samples were leptokurtic.

Figure 15 shows the characteristic relationship between skewness and kurtosis. The majority of the samples were fine skewed. On the diagram increasing fine skewness is associated with more pronounced lepto-kurtosis ($r=0.807144$). This is common for environments consisting chiefly of traction load (coarse) with some infiltrated suspension load (fine) (Folk, 1965, p.7). The coefficient of Determination (R^2) for the



Regression Equation $Y = -0{\cdot}4 + 2{\cdot}2X$

Figure 15. Skewness and Kurtosis of the beach sediments. Dots represent foreshore samples. Open circles represent backshore samples.

regression equation is 0.651481 which indicates that the relationship plotted explains 65.1481% of the variation in the data. Hence, typically the beach sediments of the Canterbury Bight may be said to be positive skewed - leptokurtic. This is consistent with the sorting processes and movements of sediments discussed above.

The Relationship Between Mean Grain Size and Foreshore Slope

Many observers have reported a close relationship between mean grain size and beach face slope. Bascom (1951) showed that finer grains are associated with lower slope angles and that erosion produces lower slopes than deposition. Shepard (1963, p.171) gives the average relation between slope and grain size. This relation has been plotted on Figure 16 for comparison with beach face slopes along the Canterbury Bight. Slopes were measured perpendicular to the water line at the reference point of all profile stations. The wide scatter of data around the average trend falls into two loose groups. This is a consequence of the mixed nature of the grain-size populations.

Sands and granules produce slopes that are optimum for their size groups whilst the pebble fraction produces a wider variety of slopes that are consistently below optimum gradient. This is closely related to the size-sorting processes discussed above. Sand is highly mobile so that it readily adopts a slope which is in equilibrium with the prevailing hydrodynamic conditions. The low slopes adopted by the pebble fraction on

Figure 16. A.R. = The average relationship of Shepard (1963, p.171). Dots indicate samples taken during this investigation.

r for samples = 0.487.

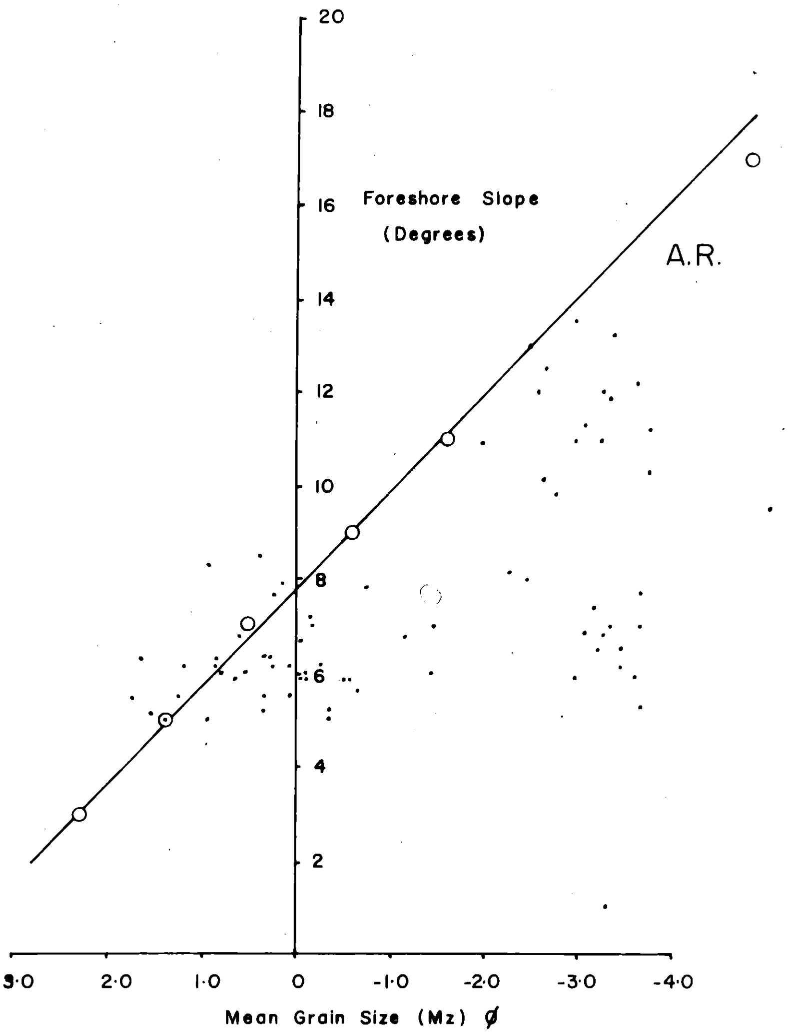


Figure 16. The relationship between mean grain size and foreshore slope.

the foreshore suggest that it is not in a stable equilibrium with respect to wave conditions. The slopes adopted by the pebbles suggest a response to erosional conditions; "combing down" of the profile by storm swash-backwash. This is consistent with the sorting and transportation properties of pebbles as demonstrated above. The highest slope angles observed on pebble foreshores were 20 to 25° near storm berm crests (*) and at the beach termini.

Thus it is probable that pebble sizes pass across the shore more abundantly than along it; for if beach drifting of the pebble fraction was pronounced foreshore slopes would tend to be optimised. Low planar slopes such as those of the Canterbury Bight beach indicate a shore-normal movement of materials in the pebble sizes by storm swash-backwash. Low foreshore slope angles are consistent with wave energy levels that are excessive in relation to the quantity of materials supplied for transport. These conclusions are supported by analysis of the distributions of grain size parameters in both plan and profile.

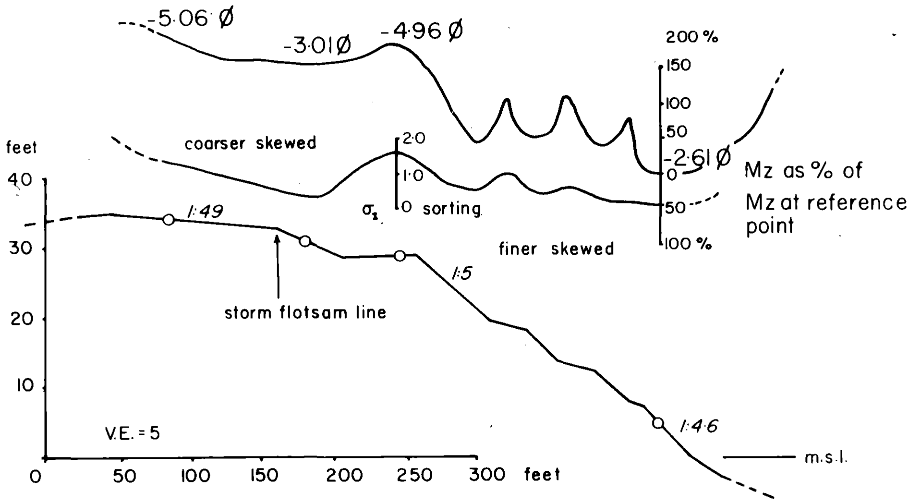
Distribution of Grain Size Parameters in Profile

It has already been demonstrated that grain-size trends are more pronounced across the shore than along it. Also close relationships between grain-size, sorting, foreshore slope and coastal erosion have been demonstrated. The relationships between grain-size parameters, beach morphology and wave conditions will now be examined in more detail.

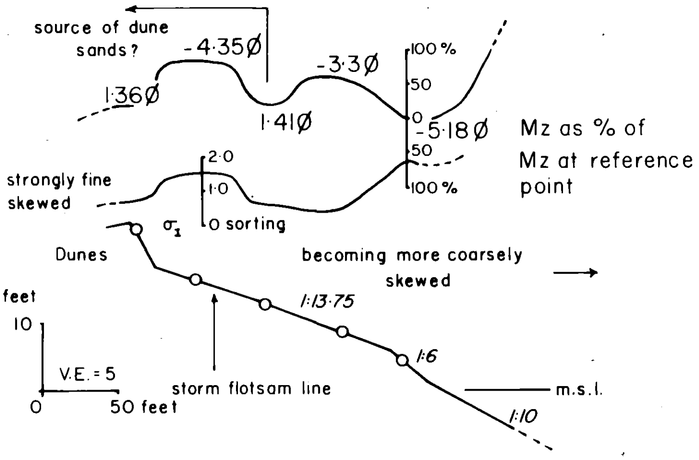
Typical distributions of grain-size parameters are shown for four representative profiles in Figure 17. The most important feature is the general increase of mean grain size both onshore and offshore of the reference point. The associated variations in sorting and skewness demonstrate well the selections for grain-size discussed previously. Grain sizes are finer and sorting better on the steeper seaward faces of berms than on the flatter treads (*). Tread materials are a product of erosion from higher up the profile together with sporadic swash emplacement from below and thus are more poorly sorted. It can be seen that gradients vary greatly over short distances on beach ridge profiles from horizontal to 1 in 4.6.

Profile 6 (Fig. 17B) shows the typical pattern for beaches north and south of the cliff zone. The top of the foreshore is coarse gravel which grades landward into alternate stringers and bands of sand and gravel, and seaward into mixed sands and gravels. Mean sizes of dune sands may be seen to be little different from those of beach sands.

It can be seen from Figure 17C that beach profiles at the river mouths are low, wide and flat with a steadily increasing mean grain size onshore. Landward of the topmost berm, size becomes variable and sorting poorer owing to sporadic overspill of storm swash (Plate 11). River bed materials, as previously indicated, are more poorly sorted but of similar grain size to

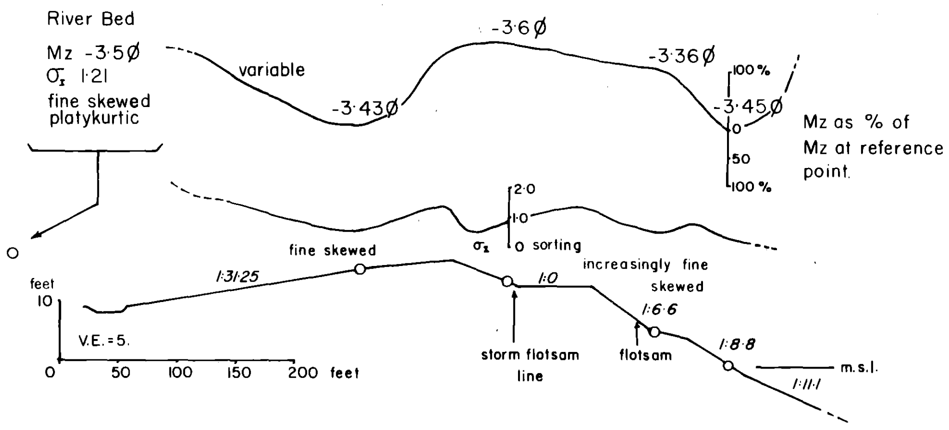


Profile 1. Birdlings Flat.

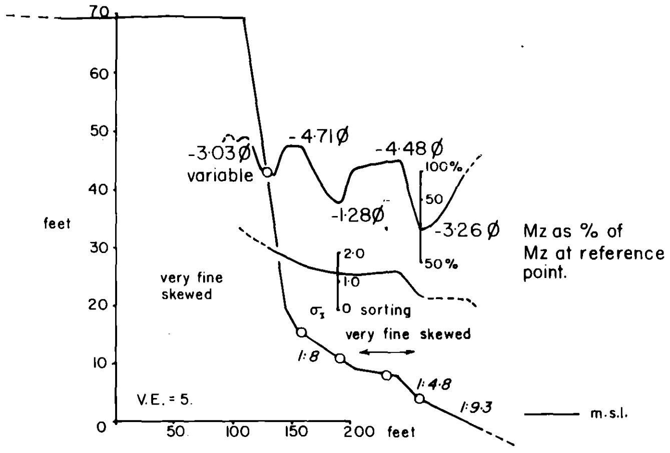


Profile 6. Taumutu.

Figure 17. Profile distributions of mean grain size and sorting. Open circles indicate sampling points on the profiles.



Profile 9. Rakaia River Mouth.



Profile 12. Wakanui Beach.

Figure 17. (continued) Profile distributions of mean grain size and sorting. Open circles indicate sampling points on the profiles.

those of the beaches.

Figure 17D shows a typical cliff-front profile. These characteristically exhibit wide ranges of grain size, as does the cliff itself, so that sorting decreases markedly onshore from the reference point. Cliff materials are poorly sorted and very fine skewed owing to the abundance of interstitial sand, silt and secondary oxidation products. The position of the flotsam line on all profiles marks the levels commonly attained by storm swash. Grain size increases seaward of the reference point on all profiles because of the greater turbulence of the surf zone.

Skewness varies widely among the samples taken from the profiles. The high, steep beach near Birdlings Flat has a fine skewed foreshore owing to infiltration of sand during periods of low waves, and coarse skewed backshore samples resulting from concentration of larger particles under storm swash action. Though this trend is repeated elsewhere it is often masked where sand lenses are deposited over the pebbles by storm swash (Plate 13). Thus, near dunes and cliffs fine skewing prevails while foreshore samples may be more coarsely skewed because of subsequent winnowing of fines.

Profile stations passed through several cycles of mixing and winnowing of grains due to changing wave conditions. Storm-derived lenses of sand and granules were worked by wind and waves to produce a diminution of sand and a resorting of the beach face into bands of sand and pebbles and mixtures of the

Plate 13. Storm swash deposited layer of sand over pebbles. Much sand has been trapped in the interstices between the pebbles and the more mobile small pebbles have remained on the surface. The lense-cap is 2 inches in diameter.

two, as indicated in Figure 17. Though this sequence of events has a seasonal period related to the observed seasonal variation in wave conditions, it must be noted that it also occurred in summer, (February-March 1967) following the incidence of southerly storms.

Distribution of Grain Size Parameters in Plan

Because of the complex movements of sand demonstrated above the distribution of grain size parameters in plan is largely stochastic. Attempts to trace longshore movements of materials by grain size modes, sorting trends etc. were unsuccessful. This is a surprising result in the light of other studies. Bascom (1951) demonstrated strong longshore trends in sand size along Half Moon Bay in California, and King (1959, p.169) records similar trends in pebbles on Chesil Beach, Dorset, England. In both cases the observed trends were related to the angle of approach of the prevailing swells and storm waves. Bascom concluded that the largest particles came to rest in the areas of most intense wave action. In the Canterbury Bight both the prevailing swell and the southerly storm waves approach the shore at an angle so that a similar result was expected.

However, two features previously discussed probably account for the lack of trend. Firstly, it has been noted that the prevailing surf on the study beach is of the plunging type. Such surf tends to direct most of the swash transverse to the shoreline rather than obliquely across it. It was also noted that the swash of the southerly storm waves was directed across the shore. Hence, there is little of the classical "zig-zag" motion imparted to particles on the foreshore by swash and backwash. Secondly, the mixing of sand and shingle was shown to be a continual process and one that easily obscures movements of pebbles. It was demonstrated that sand and pebbles move in different directions under given wave conditions, so that clear trends in longshore movement of materials are unlikely to be developed. Figure 18 shows that the foreshore zone becomes better sorted and coarser in autumn and winter but, as previously indicated this can result from storms at any time of the year.

Significantly, the widest ranges of grain size and sorting occur in the central and southern sections of the Canterbury Bight. These are the locations where sand is most mobile and supply from the cliffs is most variable. Beach profiles are narrower and berms and cliff bases lower so that swash working of the beach is more vigorous. Kaitorete Spit undergoes much less variation in mean size and sorting. This is suggestive of near equilibrium conditions.

Backshore samples follow a similar pattern of mean size but sorting is much more variable owing to the storm swash processes discussed previously. In this zone short term gains and losses of sand have the most conspicuous effects. Correlation coefficients (r) for the plan distributions of mean size and sorting range from 0.2323 to 0.0965. An analysis for trend using Spearman's Rank Correlation Coefficient (Miller and Kahn,

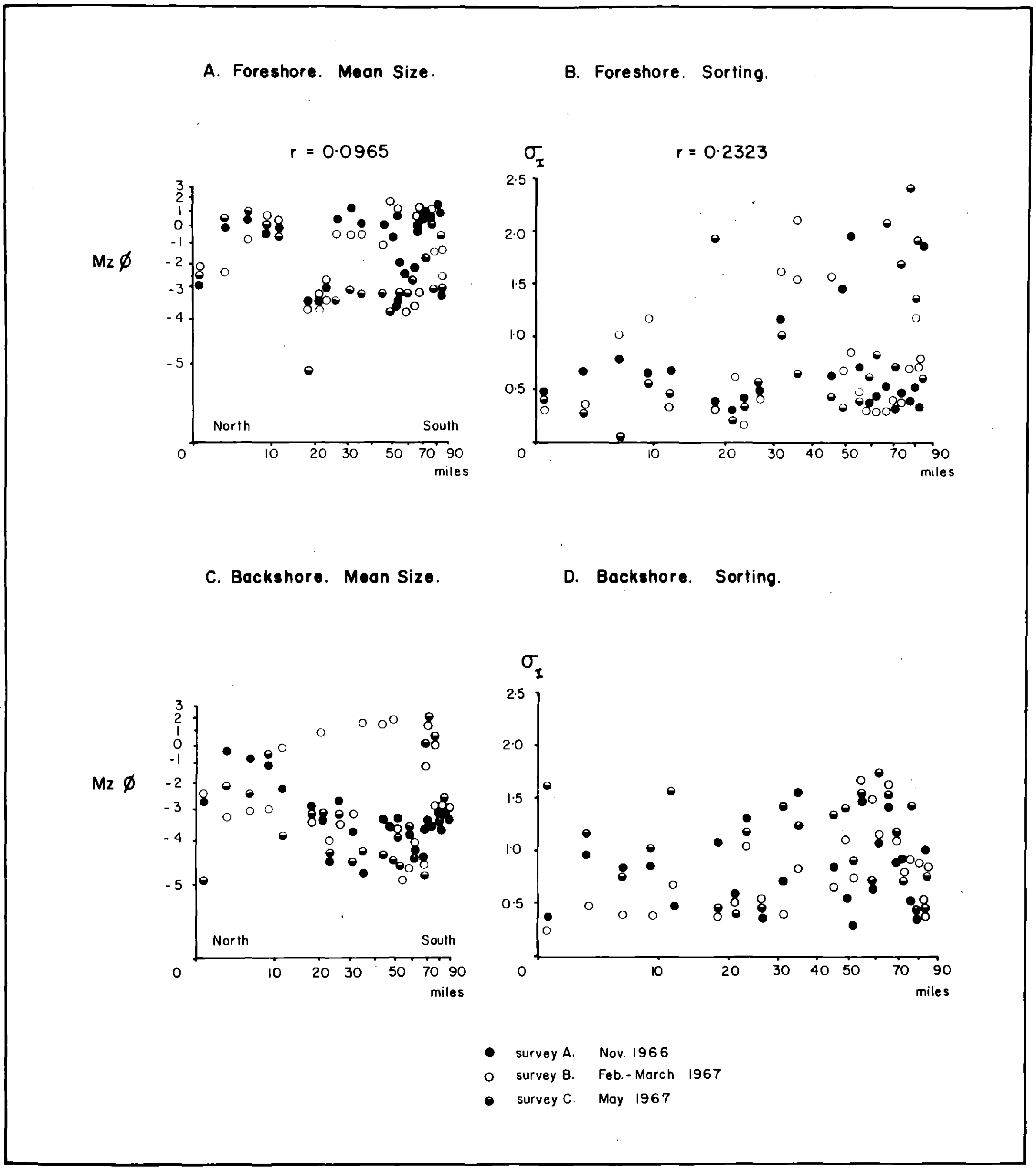


Figure 18. Longshore variations in mean grain size and sorting.

1962, pp. 335-36), appears in Table 6. No trend that was significant at the 99.9% confidence level was found. However, very weak trends are indicated. The foreshore fines generally to the south and sorting improves in this direction during the summer. Considering the mixed sand and pebble nature of the beach deposit this is probably most simply explained by the fact that samples finer than 0.0Ø mean size tend to be better sorted.

For the backshore the distribution of sample sizes suggests transport from the south with mean size coarsening in that direction. Sorting however, exhibits very little trend. The lack of even marginal significance in these results highlights two points made previously. Firstly, movements of sands are complex and even where small amounts are involved are sufficient to obscure movements of the pebble fraction. Secondly, northward longshore movement of the pebble fraction is not pronounced. It has been demonstrated that the relationship between grain size, sorting, foreshore slope and wave energy suggests a more important shore-normal movement.

Owens (1966) showed that for a 2 mile strip of Kaitorete Spit it is probable that southerly storm waves move wide ranges of sizes to the north and that subsequent south-easterly swell moves the finer winnowed fraction south again. It has already been shown that distribution of breaker heights and directions over the whole length of the Canterbury Bight is sufficient to produce longshore currents in opposite directions at different

Table 6

Analysis for Trend in the Longshore Distributions of Mean Grain Size and Sorting

Foreshore

Season	Spearman's r_s on mean size $Mz\phi$	Z	Spearman's r_s on sorting $\sigma_I\phi$	Z	Remarks
A Summer	0.334	0.068	-0.128	-0.026	N.S.
B Autumn	0.003	0.002	0.59	0.102	N.S.
C Winter	0.078	0.015	0.099	0.02	N.S.

Backshore

Season	Spearman's r_s on mean size $Mz\phi$	Z	Spearman's r_s on sorting $\sigma_I\phi$	Z	Remarks
A Summer	-0.524	-0.106	-0.019	-0.003	N.S.
B Autumn	0.118	0.024	-0.113	-0.023	N.S.
C Winter	-0.049	-0.01	0.611	0.124	N.S.

* N.S. = Not significant at p=0.01.

times. The currents observed during south-east wave conditions flowed to the north rather than to the south in the manner suggested by Owens. Figure 11 shows that easterly waves produce a southerly drift which may have local reversals of direction and considerable variation in strength along the bight. Therefore the indicated foreshore grain size-sorting sequences are a complex product of both the southerly storms and south-east swells on the one hand, and of the easterly and north-easterly swells on the other. Though there is a considerable component of littoral drift under each of these different conditions it has been shown that the beach drift imparted by oblique run-up of the swash is small. Most storm swash-backwash runs transverse to the shore rather than obliquely.

Both the distributions of grain-size properties and of breakers and swash conditions show that similar mechanisms operate along the remainder of the Canterbury Bight. However, on the steep, eroding cliff-front profiles and the narrow beach deposits to the south changes are more pronounced since supply and loss of materials to the beach are more rapid.

It has been noted that the sorting of sediment grains depends upon the type of deposition as well as on the size range of the available materials and the current characteristics. One of the strongest controls on the type of deposition, and thus on the movement of sediments, is particle shape. Hence important variations in beach materials result from selection for shape amongst sediment grains.

The Shapes of Beach Pebbles

Study of particle form involves measurement of particle shape, roundness and surface texture. Form attributes of particles give much information on origin, abrasion and physical conditions in the sampled environment of sedimentation. Thus, form analysis is the complement of grain size analysis. "Surface features and roundness are important clues to the latest environment...; sphericity and form are the clues to the earliest environment in which the particles were formed, namely the source rock." (Folk, 1965, p.15).

Table 7 indicates that pebbles from the beaches, rivers and cliffs are dominantly bladed in shape. Discs and rod shaped pebbles (platy and elongate respectively), make up smaller, subequal amounts of the samples. Compact or spheroidal particles make up only very small percentages of the samples. The table also shows that the amgdaloidal quartz found mostly at Birdlings Flat is very similar in shape to the greywackes so that its concentration at that point is more probably a result of resistance to abrasion than of selection for shape during transportation.

Form ratios shown in the table confirm that the dominant shape is bladed. Positive values of the ratio indicate a prevalence of disc-shaped or platy pebbles; negative values a dominance of rod-like or elongated pebbles. Values near zero reflect a dominance of bladed pebbles or subequal amounts of

Table 7

Percent Pebble Shapes in Samples

Form Class	Beach				River	Cliff			Quart
	1	2	3	4	1	1	2	3	1
Compact	8	-	-	-	4	8	-	-	4
Compact-Platy	12	12	-	-	8	4	12	16	16
Compact-Bladed	-	4	4	-	20	40	12	8	12
Compact-Elongate	16	4	-	-	24	8	8	20	8
Platy	8	20	12	12	4	12	16	12	8
Bladed	36	20	56	24	24	16	32	20	32
Elongate	8	20	4	4	4	8	16	20	20
Very Platy	-	8	8	16	4	-	-	-	-
Very Bladed	12	8	12	32	4	4	4	4	-
Very Elongate	-	-	4	12	4	-	-	-	-
Form Ratios.	-0.04	0.8	0.64	0.64	-0.32	0.0	0.08	-0.4	-0.32

platy and elongate pebbles (Sneed and Folk 1958, p.141).

Smalley (1966) has demonstrated that the result of disaggregation of rocks in a random fashion is the distribution of particle shapes shown in the first row of Table 8. The second row shows that by comparison, the greywackes of the Canterbury Bight have more tetragonal shapes than if they were derived by random breakdown. (Tetragonal shapes include plates, rods and their extremes and intermediate shapes.) The similarity of shapes in the three sample environments indicates that the distribution of shapes shown in Table 8 is a function of the breakdown of the alpine greywackes rather than of selection for shape during transport. Greywacke exhibits a strong preference for disaggregation along this bedding planes, (C-axis). The lengths of the other axes appear to vary randomly thus producing subequal amounts of blades and discs. Kuenen (1964) suggested that flat particles are more prevalent on beaches and more spherical particles are dominant in river deposits. This cannot be argued in the case of the Canterbury Bight. Though selection for shape between the two environments will be shown to occur it should be realised that the scope for this on any beach is controlled closely by rock breakdown characteristics.

Selection for Pebble Shapes. Selection for shape along the Canterbury Bight is demonstrated in Table 9. Pebbles at the updrift (south end of the beach are flatter ($\frac{C}{A}$=0.282),than at the downdrift end (north, $\frac{C}{A}$=0.42). The flatter particles lag behind the more mobile

Table 8

Percent Composition of Samples in Relation to Random Breakdown of Rocks

Source	Equiaxed	Shape Bladed	Tetragonal
Random breakdown (Smalley, 1966)	1.0%	72%	27%
Canterbury Bight Greywackes. (THIS STUDY)	2.5%	53%	44.5%

Table 9

Variation in shapes of beach materials along the foreshore of the Canterbury Bight

Location (PROFILE NO.)	Mean $\frac{C}{A}$	Mean $\frac{A-B}{A-C}$	Mean Ψ	Shape Sorting
Updrift (south)				
end (18)	0.282	0.474	0.45	0.134
(15)	0.344	0.456	0.475	0.089
Middle (8)	0.392	0.469	0.469	0.123
Downdrift				
(north) end				
(2)	0.42	0.499	0.58	0.13

Table 10

Shape Characteristics of river and cliff materials

Environment	No. of Samples	Mean Shape	Mean $\frac{C}{A}$	Mean $\frac{A-B}{A-C}$	Mean Ψ	Shape Sorting
River beds	2	Bladed	0.484	0.541	0.58	0.127
Coastal Cliffs	3	Bladed	0.495	0.502	0.58	0.144
		Bladed	0.481	0.523	0.59	0.088
		Bladed	0.491	0.516	0.59	0.099
Beach Quartz	1	Bladed	0.464	0.489	0.55	0.075

thicker ones. Consequent on the narrow range of shapes supplied the selection process is not pronounced. Hence, mean effective settling sphericities (mean Ψ) differ little along the beaches. This is consistent with a low order of net bed-load transport to the north as indicated by grain-size analysis.

Tables 9 and 10 demonstrate the similarities of pebble shapes in the rivers, cliffs and on the beach. Because of the uniform lithological type giving rise to the pebbles and the similar alluvial derivation at the coast the shape distributions have very low standard deviations. "Sorting" for shape is well developed before the particles reach the coast. There is thus no wide range of abundant shapes upon which the waves can exert selective influences.

However, given the range of shapes and their relative abundances on the beach it is possible to distinguish a relationship between shape and the size-sorting of pebbles. Table 11 indicates that the larger pebbles have lower mean effective settling sphericities. Therefore they have larger lifting surfaces in relation to their weight than do rod-shaped and spheroidal particles, (which are usually smaller). Thus, the larger particles are more easily carried up the foreshore by the turbulent lift of swash. Downslope motion in the backwash can only occur by sliding and is therefore restricted since the flow is greatly depleted by percolation into the beach.

Significantly, the more spherical particles roll more easily downslope as well as upslope so that they are more

Table 11

Pebble Sphericity as a Function of Pebble Size

Size range	Beach Mean Ψ	 No.	River Mean Ψ	 No.	Cliff Mean Ψ	 No.	Quartz Mean Ψ	 No
4-16mm -2.0 to -4.0Ø	0.613	40	0.65	1	0.712	19	0.644	10
16-32mm -4.0 to 5.0Ø	0.532	55	0.668	13	0.678	42	0.697	13
32-64mm -5.0 to -6.0Ø	0.454	5	0.689	11	0.642	14	0.51	2

Σ = 225 pebbles. Sample No. = 25 pebbles.

easily eroded from the profile. From Table 11 it may be seen that most of the pebbles measured had intermediate axes (corresponding to sieve size), in the range -4.0 to -5.00. Since the dominant shape is bladed mean effective settling sphericities lie in the range 0.5 to 0.6. These particles are most stable under swash-backwash flows since they are not readily moved seaward. In discussing size-sorting processes it was demonstrated that gravels in the range -2.5 to -3.50 are the best sorted. (Table 11 shows that these are also bladed particles, but they are more readily moved). It would thus appear that the coarse, bladed particles (-4.0 to -5.00), represent a lag deposit on the beach face (*). Finer pebbles of the same shape are filtered out and eroded from the profile. For this additional reason the backshore segments of the beach profiles can be said to be well adjusted to storm wave swash-backwash. Slopes stand at low levels where erosion of the pebbles is minimised. Higher slopes incurred as a result of cliff-fall are rapidly removed down to the former level. This relationship is further clarified by analysis of the orientation and inclination of pebble axes in the beach deposit.

Orientation and Inclination of Beach Pebbles

It has been shown that pebbles of different shapes are transported in different ways. Johansson (1965, pp.19-23) in summarising the literature on littoral imbrication patterns concludes that roller shaped pebbles (rods) tend to align

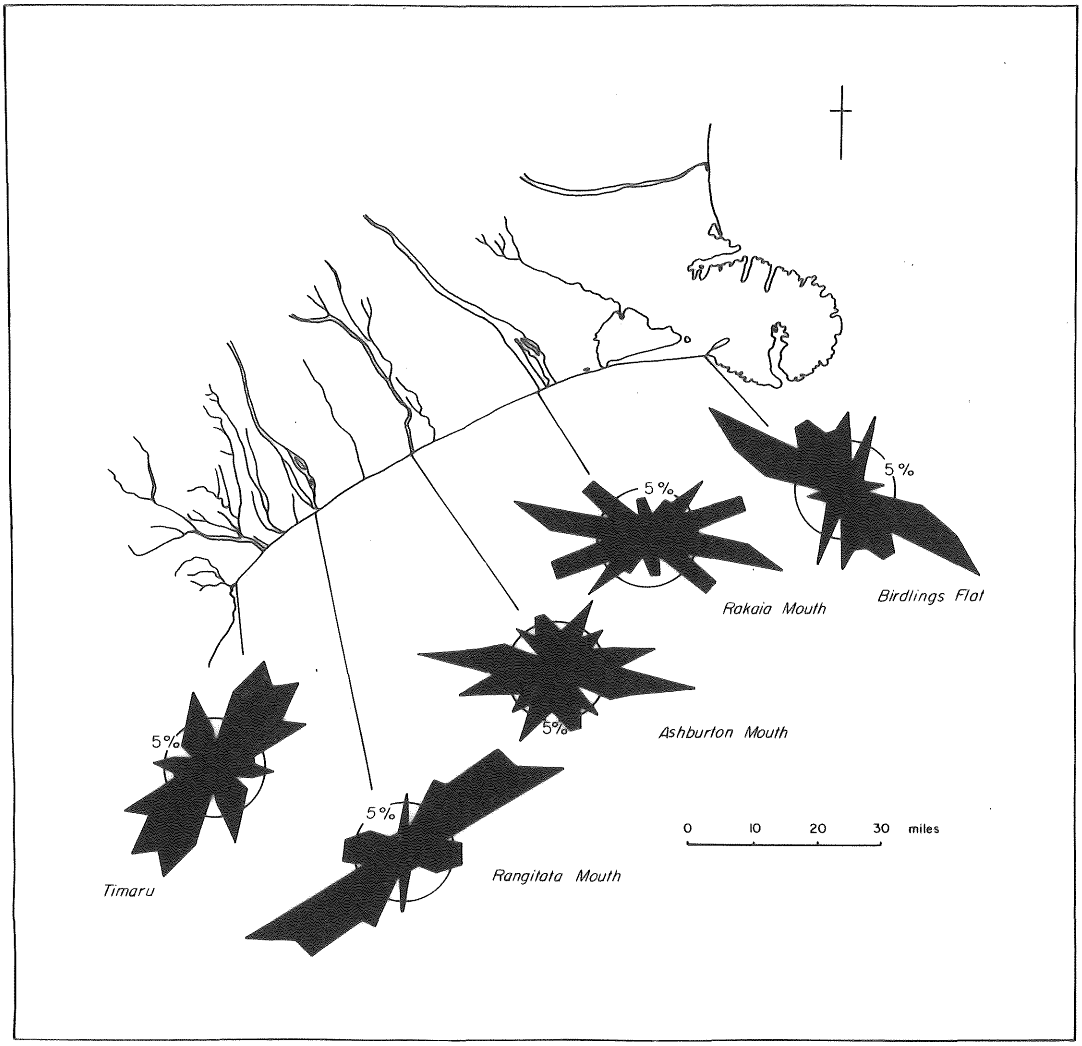


Figure 19. Long axis orientation of beach pebbles.
Sample number at each station = 25 pebbles.

themselves parallel to the direction of the backwash, discs and blades transported across the bed align themselves transverse to the swash direction. In the case of rods orientation results from transport in the swash-backwash, the pebble coming to rest after rolling on its shortest (C) axis. Blades and discs are most usually oriented by reaction to the swash without the occurrence of significant transport (Norrman, 1964, pp.109-110).

The horizontal orientations of the long axes of beach pebbles from five sites around the Canterbury Bight are shown in Figure 19. The Samples were of 50 pebbles each, measured with a compass and Abney Level at the upper foreshore at each location. Orientation of sand grains was not measured. Several maxima are apparent. At all five stations distinct maxima are aligned transverse to the most frequent south-easterly swell waves. For the southerly stations orientation parallel to the shore reflects rolling of small pebbles on low, sandy foreshores. In the central and northern areas where beaches are coarser and steeper, orientation is more complex, though the major alignments relate to the oblique swashes of easterly swell, south-easterly swell, and to the shore-normal swashes of southerly storm waves. Minor orientation maxima at other angles relate to rod shapes that are backwash aligned.

Most of the pebbles forming the transverse swash orientations were inclined landward at between 20 and 30 degrees (A-axis), and were imbricated one-on-the-next to form a pattern "like an inverted tile roof" (Johansson, 1965, p.21). This is an erosional pattern in that the most stable form is presented to the backwash, rather than to the swash. The incomplete nature of the imbrication at many places is largely due to the saltation up the foreshore of small roller shaped pebbles in the swash. Under storm wave conditions the backwash is competent to move most pebble sizes so that the imbrication presented to south-easterly swells is rapidly destroyed. Erosion of the profile occurs and slopes are combed down to lower angles, the larger pebbles adopting a more stable backwash equilibrium in the manner discussed above.

Lower on the foreshore low angle seaward imbrications occur. These result from pebble adjustment to the greater turbulence of the swash near the breaker zone. Landward of the swash berm (*) landward inclinations give way to seaward imbrications, which are found mostly in cobble sized materials that can only be transported by the swash of storm waves. Imbrications on the landward sides of storm berms are not well developed because of the nature of emplacement. Particles are thrown into this zone or moved by sporadic swash that overtops the berm and so orientation and inclination angles are very variable.

The effects of shape on size-sorting and transportation of pebbles have been examined in the above discussion. It was noted at the beginning of the discussion that shape properties are largely inherited from the breakdown of the parent rock.

Changes in shape characteristics are slow and are effected mainly by the transportation processes previously discussed. These modifications are most apparent in the surface texture and the roundness of the particle.

Roundness of the Beach Sediments

Mean roundness ranges from 5.70 (well rounded) to 2.90 (subangular) for the samples (see Appendix III). Variation in roundness relates mainly to particle size, the sands being less well rounded than the pebbles. All samples show high standard deviations (1.42 to 5.36), that is, they possess very poor roundness sorting. Folk (1965, p.11) gives the average roundness sorting value for Recent sands as 0.90. Freshly broken quartz sand had a roundness sorting value of 1.30. River materials from the Canterbury Bight are less rounded and are also poorly sorted for roundness (Table 12).

The content of angular pebbles in river and cliff samples ranges from 10% to 26% but only two beach samples had more than 15% of angular constituents. Most had none and a few had 2%. This suggests that preliminary rounding of greywacke pebbles is rapid under surf action; but the poor values of roundness sorting indicate that this is only true of the larger sizes.

There is no longshore trend in pebble roundness. This is consistent with a low order of net longshore transport to the north since large movements would be accompanied by changes in size and roundness, while changes in shape would be of a

Table 12

Mean Roundness of Beach, River and Cliff Materials

Environment	Mean Roundness ρ	Mean Roundness Sorting $\sigma\rho$
Beaches	4.57 Rounded	2.82 Extremely poor
Rivers	3.85 Subrounded	2.69 Extremely poor
Cliffs	3.48 Subrounded	1.96 Very poor

low order. Changes in size and shape are brought about by abrasional alterations in particle roundness.

Sands in the Canterbury Bight are mainly composed of quartz grains, but a few heavy minerals are present. Angular content of the sands ranges from 14% to 52%. Sands in the south are better rounded than in the north, a fact which is consistent with movement into the area from south of Timaru. Sands from the north appear fresh and polished under the microscope, but a significant proportion is rounded and frosted. Fresh, angular grains are undoubtedly from the rivers while the more rounded sands are more probably derived from the offshore zone, and may possibly have been recycled between the beach and the offshore zone a number of times. Folk (1965, p. 14) suggests that more than 16% of angular sand indicates a lack of significant abrasion in the sampled environment. This is to be expected where supply, movement and loss of sand to the beaches is rapid. There is insufficient time for river-derived sands to become well rounded along the Canterbury Bight, unless they are recycled through the beach several times. Pebbles on the other hand tend to achieve high roundness rapidly and thereafter to round more slowly. Continual erosion of the beach means that particle sorting and roundness do not develop to optimum levels because the beach deposit is arrested at a "young" stage. There is insufficient time for continued development of particle morphometry.

Discussion of Grain Properties

Several important transportation and sorting processes occurring on the mixed sand-shingle beach of the Canterbury Bight have been described and explained. It has been demonstrated that these processes are close controls of beach morphology along this retrograding coast. It is probable that many of these sorting, transport, and beach morphology interrelationships apply to other sand-shingle beaches.

The beach materials of the Canterbury Bight are clearly derived from a medium-coarse sand and a pebble population. Good sorting is found in the pure end-members of the spectrum but wide ranges of sorting, skewness and kurtosis result from the differing responses to wave energy occurring in admixtures of the two populations. Dominantly, the beach deposit reflects the combination of suspended and bed-load transport of the fines and bed-load traction transport of the coarse materials. Because sand is moved under a wide range of conditions its movements along and across the shore are complex. Pebbles undergo a net northward movement only under southerly storm swash conditions. However, the volume of transport is small since the swash is directed more across the shore than obliquely along it, and the velocity of the backwash is sufficient to move most pebble sizes offshore. It was previously demonstrated that the supply of materials to the littoral zone from rivers and cliffs is of a small order. Pebbles moved seaward of the surf zone are unlikely to be returned to the beach. A significant process on the beach face is the deposition of sand lenses while pebbles are being eroded from the beach face during southerly storms. Sand is trapped in the interstices between pebbles by percolation of the swash and backwash. Large pebbles and cobbles form lag deposits since they move onshore to the higher berms.

Comparison of Particle Properties. The origin of all the materials is alluvial, whether from the present river channels, or reworked from the cliffs, or derived from relict deposits offshore. There is only one dominant mineralogy; greywacke. Because of the rapid losses of materials the beaches of the Canterbury Bight are notable for the reflection of the alluvial origins of their materials in all properties (Table 13). There is therefore little modification of alluvial materials in both the sand and shingle fractions in the present environment. The distributions of grain-size, sorting and beach face slope suggest an adjustment to erosional conditions under southerly storm waves. The plan distribution of grain-size is largely random relative to the distribution of wave energy. Size-sorting relationships tend to be better and more stable in the north where some influx of materials offsets erosion. Grain-size is coarsest near the sources of sediments, but sorting is most variable. South of the cliff zone grain sizes are finer, more variable and sorting ranges widely. This is controlled by

Table 13

Comparison of Particle Properties

Distribution tested	Environment	't'	Df	Probability	Remarks
Grain-Size	River vs. Beach	1.757	24	0.1	S*
	Cliff vs. Beach	2.185	26	0.05, 0.01	S*
	Cliff vs. River	0.009	4	0.80	NS*
Grain Roundness	River vs. Beach	0.227	22	0.80	NS*
	Cliff vs. Beach	0.586	21	0.50, 0.80	NS*
	Cliff vs. River	0.104	2	0.80	NS*
	Quartz vs. Beach	0.132	22	0.80	NS*
Pebble Sphericity	River vs. Beach	0.239	3	0.80	NS*
	Cliff vs. Beach	0.88	5	0.80	NS*
	Cliff vs. River	0.038	3	0.80	NS*
	Quartz vs. Beach	0.321	3	0.50, 0.80	NS*

* S = Significant. NS = Not significant.

the influx and removal of sand, some possibly from south of Timaru, and by erosion of the pebble fraction of the beach so that the fluvial basement is exposed and eroded.

Analysis of shape and roundness of the beach materials reveals that the beach deposit is texturally "submature", (Folk, 1965, pp.104-05). It is moderately to well sorted in the sand sizes but the grains are mixed angular and rounded in character. By contrast the pebble population may be said to be more "mature", since the modal size classes are well sorted and well rounded. The pebble fraction reflects well developed size-sorting in better developed grain roundness values than the sand fraction. The texture of the beach deposit is thus used as a measure of the ability of the environment to winnow, sort and abrade the materials furnished to it. Excess of wave energy over the supply of materials in the Canterbury Bight means that this ability is not great, notably because of insufficient time for these processes to operate on particles. On sand-shingle beaches where erosion of the shore was not occurring a different degree of textural "maturity" would be expected.

Under swell conditions swash movement of particles up to -3.0Ø is indicated Particles greater than this size, even under storm conditions are oriented and imbricated according to their shapes. Under storm conditions erosion of all except the larger pebbles and cobbles is possible. The swash-backwash velocities are sufficient to move pebbles and are greater than the velocities required for particle equilibrium and thus net movement offshore occurs. Swell sorting of the finer sizes produces a high energy "surf break", in the pebble fraction.

Speight (1930) suggested that the materials forming Kaitorete Spit were derived from the cliffs to the south, and Elliott (1958) stated that there is a general drift of materials from south to north in the Canterbury Bight. While this has been shown to exist it appears to be of very small magnitude. Considerable evidence for this conclusion has already been presented. The analysis of the potential for beach drifting, the principal form of longshore transport of bed-load materials, revealed a stronger offshore motion during southerly storm waves. Analysis of sorting processes, size distributions, shape and roundness characteristics and particularly of the relationship between mean grain size and foreshore slope further suggested a low order of net northward transport. The beach slopes of the Canterbury Bight are consistently lower, for a given grain size, than the average relationship. This suggests a short term erosional equilibrium rather than optimum or even significant transport to the north. Bruun (1954) notes that on beaches where there are large volumes of longshore transport beach face slopes are at a maximum (consistent with grain size). It will next be shown that analysis of the changes in beach profile morphology over short term, seasonal and long term periods confirms the suggestions made above. Further, comparison of the rates of erosion along the shore with theoretical plan morphology reveals a striking correspondence of the wave energy patterns and sediment distributions previously discussed with beach morphology.

CHANGES IN BEACH MORPHOLOGY

Changes in beach morphology are produced by daily, seasonal and longer term variations in hydrodynamic conditions. A distinction must be made between short term variations in beach morphology (which are a function of the incidence and distribution of wave energy), and the longer term variations in size, shape and position of the beach deposit relative to a fixed set of co-ordinates. These longer term changes are a function of the type and rate of supply and loss of materials to the littoral zone.

It has been shown by many workers that low swell waves move materials onshore and thus build profiles up and out. Longshore transport is at a maximum under these conditions. Conversely, high, steep storm waves erode beach profiles. Sediment moves offshore, and larger sizes are thrown high up the profile to build beach ridges. The typical shingle beach profile is thus comprised of steep foreshore, a series of berms which may be either erosional or depositional or composite in origin, and one or more storm berms at the limit of storm wave action.

If, over a period of decades, more material is supplied to profiles than can be adequately disposed of by storm wave erosion and longshore drift, the profiles will prograde relative to a fixed set of co-ordinates. Bruun (1954) terms this condition "overnourished". Such profiles have maximum steepness (consistent with grain size), and longshore transport is maximised. Where wave energy is more than equal to the supply of materials, in Bruun's terminology the profile is "undernourished", and retrogradation of a flatter profile occurs. Longshore transport is of a lower order. It is this latter situation that exists along much of the Canterbury Bight.

Between these two extremes of retogradation and progradation is a long term equilibrium configuration in which supply is balanced against loss. The equilibrium beach profile (*) may therefore be defined as a "statistical average about which rapid short term fluctuations take place" (Tanner, 1958).

The beach profiles of the Canterbury Bight have more affinities with the shingle beach type than with typical sand beach profiles. No foreshore troughs, ridges or runnels of the type frequently observed on sand beaches are present. Some profiles along the study beach exhibit pronounced tiers of berms related to erosion and deposition by waves of different magnitudes. It has been shown that the highest waves have the longest swash and thus produce the highest berms. High waves also remove and modify berms built at lower levels by lower waves.

Typically the foreshore has a low-tide step at its seaward extremity upon which waves break at all stages of the tide. During periods of low waves small swash berms are built a little above the mean high water level. As indicated these are removed or substantially modified by storm wave action. As far as can be ascertained from bathymetric charts the beach drops steeply outside the breaker zone to depths of up to 30 feet. As previously demonstrated pebble sized materials lost down this face would not be easily returned to the foreshore.

Where intermediate berms are not present between swash berms and storm berms the profiles are concave upwards, or planar in the section from the swash berm to the storm berm, cliff-base or foredune. Profiles that have been recently supplied with cliff debris are convex upwards. Such profiles become concave upwards following storms. Beach cusps (*) are common in the swash berms and in storm berms. Cusps found in the higher berms are characteristically larger and more widely spaced than those in the lower berms.

Short Term Changes in Beach Morphology

Sedimentation cycles of foreshore cut and fill occurring on single tidal periods have been observed by Otvos (1965), King (1951) and Strahler (1966). Strahler noted that under equilibrium conditions cycles of scour and fill introduced and removed a wedge of sand and gravel so that at the end of a tidal cycle the beach was restored to "its original elevation, slope and composition". Where other than equilibrium conditions obtain either net erosion or net fill results from each tidal cycle. Otvos and King noted that the depths to which sand was disturbed by waves varied with the height of the waves and with the grain-size. Higher waves and larger

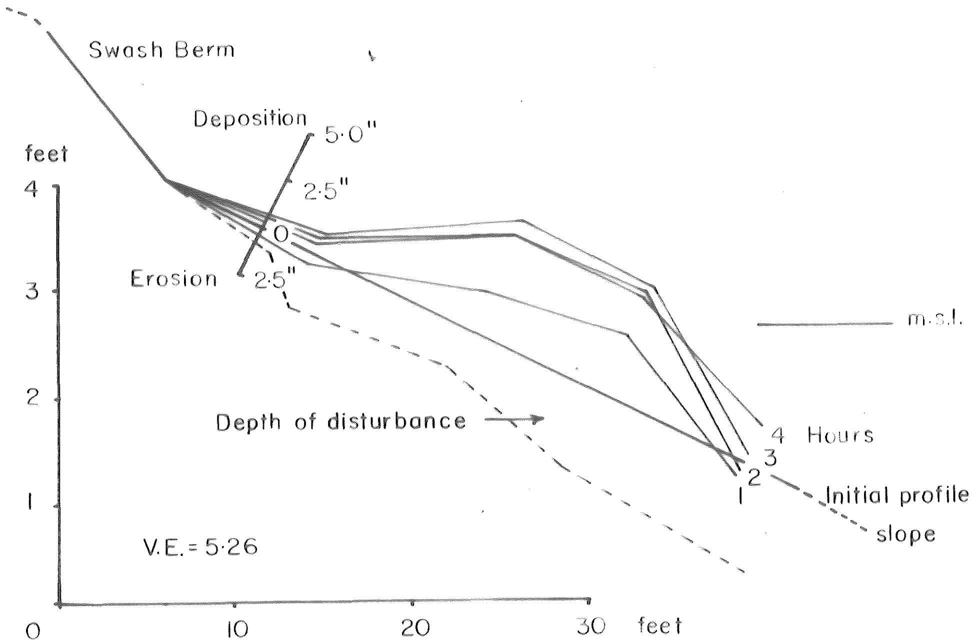


Figure 20. Short term changes in foreshore level.

particle sizes are associated with greater depths of disturbance. Experiments similar to those of Otvos and King were carried out at Birdlings Flat in the winter of 1966 using painted pebbles (Fig. 20) (Kirk, 1966). On a pebble slope (M_z = -3.080) of 4° depth of disturbance for a breaker height of 4 feet ranged from 0.75-4.0". The disturbance was greatest on the lower foreshore and diminished landward to the top of the swash. Table 14 shows that smaller disturbance values were obtained for a breaker height of 3 feet. It is significant that the two experiments were performed under conditions of both net foreshore fill and net erosion, so that it is evident that the foreshore is continually disturbed whether it is eroding, in equilibrium, or building up. The disturbance values indicated lie between those obtained by King for fine sand and those by Otvos for medium and coarse sand. This result is consistent with the differing responses of pebbles and sand to wave energy previously demonstrated.

Figure 20 shows a typical pattern of foreshore fill. It may be seen that as the tide rose the upper and lower foreshore areas were scoured. Following this, deposition of granules began on the middle foreshore. With passage toward high tide the grain size became coarser and the lense of gravel moved up the foreshore. Disturbance of the bed was maximised at high tide and some erosion of the gravel lense occurred on the ebb tide. The net result was a berm-shaped body of gravel at the

Table 14

Depth of Disturbance and Sedimentation Cycles Over Single Tidal Periods

Depth of Disturbance inches	Wave Height feet	Sedimentation cycle Maximum amplitude inches
3.75	3.0	Net foreshore
2.0	2.0	Erosion
1.0	3.0	9.90
4.0	4.0	Net foreshore
2.0	4.0	Fill
0.75	4.0	6.0

-Source. Kirk (1966).

mid-tide swash level. It is this sequence of events, multiplied over many tidal cycles in low wave conditions, that gives rise to the swash berms found on many profiles. Individual prisms of gravel are moved progressively onshore to the limit of the swash at high tide.

The effect of storm swash on foreshore morphology is the reverse. Net erosion of the profile over much greater lengths than swash deposition is characteristic. Commonly the amount of cut during one storm equals or exceeds the accumulated deposition of long periods of low waves. Erosion in one storm can be as much as the total seasonal amplitude of the profile. Recovery of swash berms is rapid after storms. Also, storm waves which occur at spring tides result in more erosion of the profiles than those arriving on lesser surges. This is of great significance with regard to the erosion of some cliff-front profiles, as will be demonstrated.

Seasonal Changes in Beach Morphology

Significantly, despite the large variations in wave energy occurring along the Canterbury Bight, seasonal changes in beach morphology are generally small. The largest changes recorded were on river mouth profiles and at the termini of the beach. At all stations the beach profile envelope curve is characteristically wedge-shaped, diminishing in amplitude landward of the low water mark.

Figure 21 indicates that there is a strong relationship between berm height and breaker heights of the southerly storm

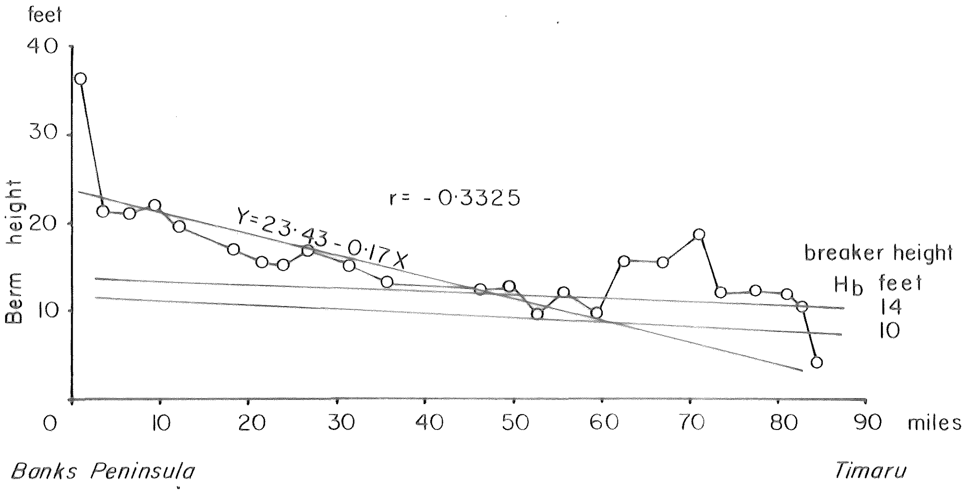


Figure 21. The relationship between berm heights and storm breaker heights. Waves from the south; $T = 11.0$ seconds; $L_o = 619.52$ feet.

waves. With progress toward the high energy terminus berm height increases to a maximum of 35 feet at Birdlings Flat, where sediments have accumulated against Banks Peninsula. This berm is overtopped by storm swash an average of two to three times per year. Local increases in berm height occur off the mouths of the Rakaia and Rangitata rivers where floods and waves are continually reworking materials. Most of the retrograding cliffed section of the shoreline may be seen to stand very close to storm breaker height, thus facilitating removal of accumulated materials. Berms south of the Rangitata River are similarly situated and are frequently overtopped by storm swash. Under the lee of Dashing Rocks berm height decreases rapidly to the point where the beach terminates as a low shingle ridge lying on a rock platform.

Figure 22 shows beach profile envelope curves for the 24 stations along the Canterbury Bight. The wedge-shaped nature of the profile changes and the generally small order of the changes are apparent. Characteristic swash and storm berms occur on many of the profiles. Of particular importance is the relation between cliff erosion and changes in beach profiles. This is shown for profiles 12 and 15 in Figure 23. The rate of cliff recession is approximately 3 feet per year everywhere, save for the northern and southern termini where the cliff is lower and is fronted by shingle ridges up to 18 feet high.

Erosion of the cliff is performed mainly by sub-aerial processes, marine processes serving to remove accumulated debris

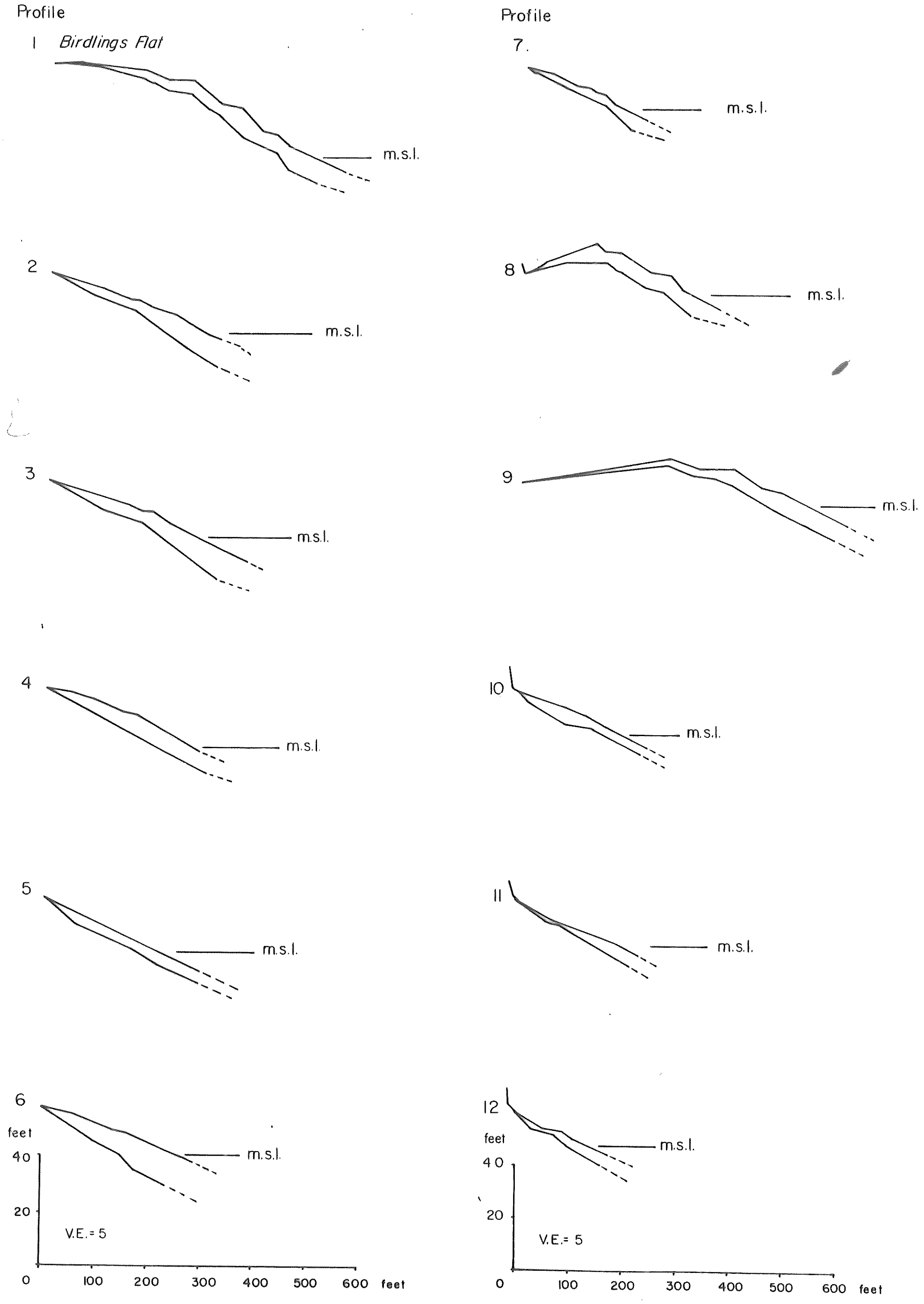


Figure 22. Beach profile envelope curves.

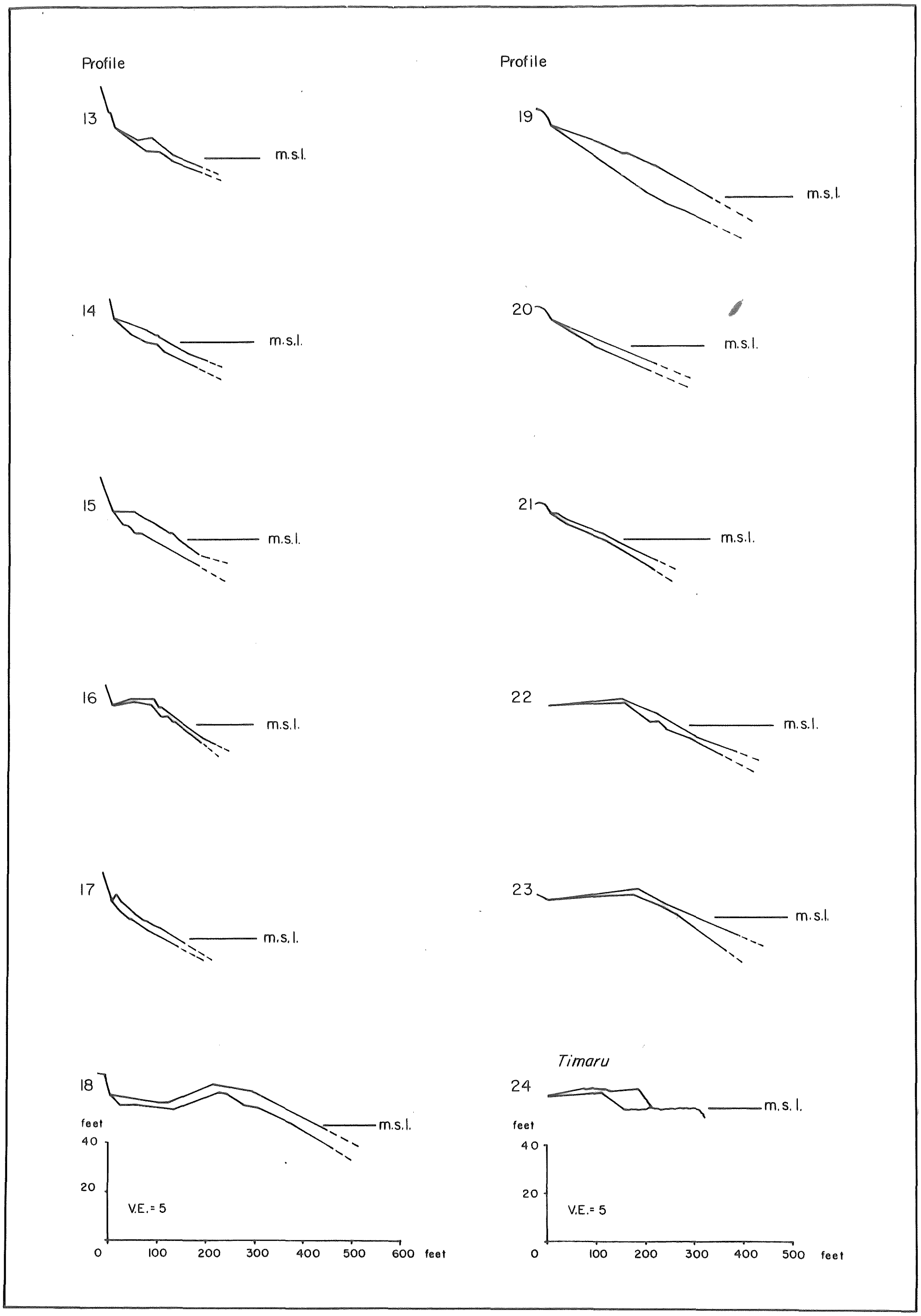


Figure 22. Beach profile envelope curves.
(continued)

from the cliff-base and thus prepare the face for the next fall. Figure 23A shows the typical pattern of cliff erosion at Wakanui near the highest part of the cliff. A small amount of accumulated debris was swept from the cliff-base by the first storm of winter. The face at this time was cleared of all loose materials and oversteepened. Small amounts of material falling from the cliff began to build up the profile again. In June, after more storms, a section of the cliff fell, the resulting material being rapidly worked down the foreshore. The temporary aggradation of the profile produced by cliff fall was rapidly removed so that within a short time a near return to the former position and slope was made. In this manner the cliffed section of the coast recedes, maintaining a profile envelope of small amplitude that rapidly adjusts itself after local increases in supply.

Hence, the main process of cliff erosion is mass-movement. Sections of cliff locally oversteepened become saturated with ground water and fail along prominent shear planes (Fig. 23, Plate 3). Though the soils of the area are dry much of the year they contain much silt and reach field capacity rapidly at times of heavy rainfall. Also many farmers along this zone irrigate their land in summer, a feature which substantially increases the probability of cliff-fall. Many such falls have been observed during the course of this investigation. Many observed in the summer were completely removed by winter whilst others were newly formed. Cliff-fall along the Canterbury Bight is thus a continuing phenomenon only slightly more pronounced in winter

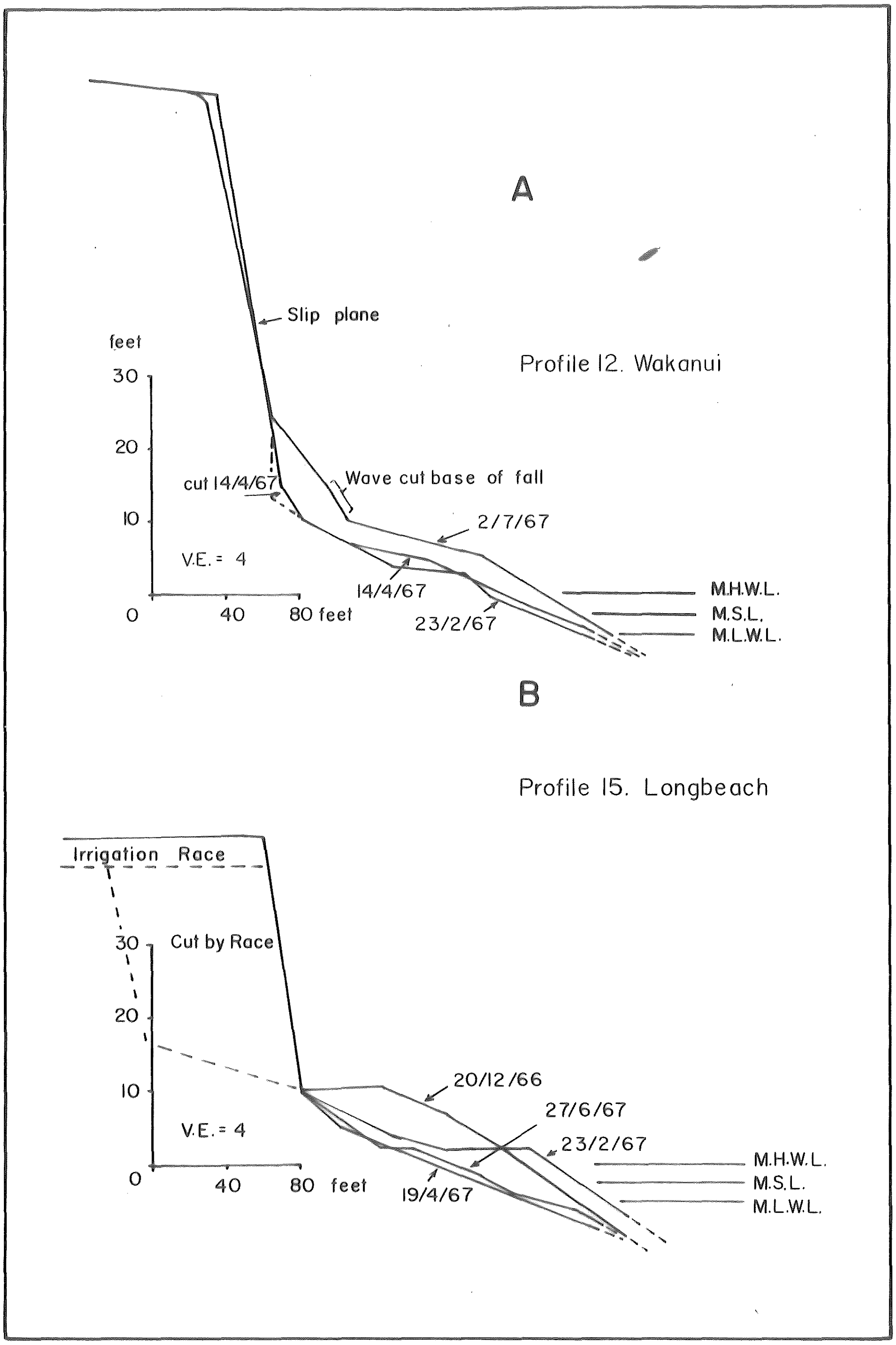


Figure 23. Cliff erosion.

than in summer.

Aerial photographs reveal extensive networks of rills in the fields inland of the cliffs. These drain to the numerous and often large gully systems leading out to the beach. However, only in the case of the slip at Longbeach Station (profile 15, Fig. 23B), can the primary cause of cliff erosion be ascribed to running water. In this case the rare combination of storm waves occurring on a spring tide sapped the base of the cliff beneath the piped outfall of an irrigation race, during December 1966. The result was a steep gully cut 90 feet back into the cliff and a fan of debris extending across the foreshore to below low tide level (Fig. 23B, Plate 14). By February most of the fan had been removed from the upper foreshore and much progradation of the lower foreshore had resulted (Plate 15). Subsequent surveys in May and June revealed a much lower, flatter profile that was stable despite considerable variations in wave conditions. This is the sequence of events for recovery of profile equilibrium that occurred for all profiles where cliff-fall took place.

However, the Longbeach slip is the only one in the area where running water was the prime process of erosion. It is therefore suggested that mass-movement processes, (especially slumps and slides resulting from basal clearance of debris and increases in ground water), are the major mode of cliff erosion along the Canterbury Bight. Plate 3 is significant in this

Plate 14. Cliff debris fan across the profile at longbeach (profile 15). 20/12/66. Note that the storm berm has been buried.

Plate 15. Clearance of the cliff debris at longbeach. 23/2/67. Erosion of the profile has removed all cliff debris as far landward as the storm berm.

respect. It can be seen that both slips in the photograph have occurred immediately marginal to, and not below the channels of the gullies. Most of the larger gullies along the coast are well vegetated and have dry floors. The mouths are frequently cloked with flotsam transported along the shore by storm waves, and pebble berms across the mouths are slowly retreating back along the floors. Beach berm materials were found to overlie gully-floor soils at many places, suggesting that the gullies, save for slip scars, were not recently formed.

It has been demonstrated that the coastal cliffs must be considered as a major potential source of beach materials. However the clearance of cliff-fall materials and the erosional equilibrium morphology adopted by cliff-front profiles suggests that, relative to wave energy, this supply is small. Hence seasonal variations in beach volume are also small.

Average changes in Beach Volume. Average profile change during the period of the investigation is shown in Figure 24. Areas under the profile curves at each survey were converted to volumetric changes by considering a one foot wide strip along each profile line. It can be seen that erosion and deposition occur at all times of the year but there is a change in balance from net deposition in summer to net erosion in winter. The analysis applies only to the beach zones landward of low water mark. Because the study period was only of 7 months duration it was not possible to determine an average annual budget for the

Figure 24.

A. Average volumetric change in profiles.

B. Isopleth diagrams of profile change. 0 - 200 feet is the distance from cliff-base, dune etc. to surf zone.

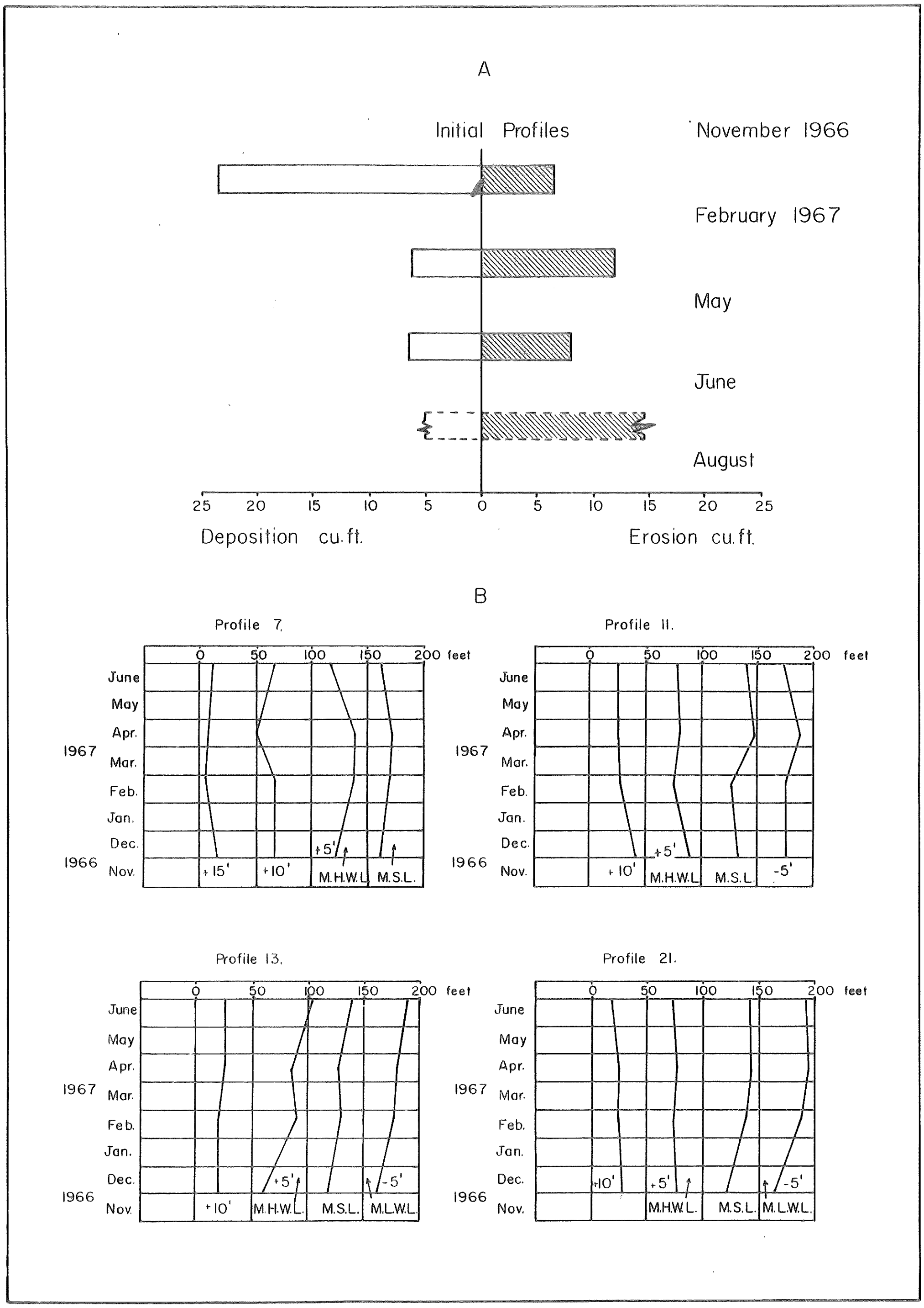


Figure 24. Seasonal changes in beach profiles.

profiles. Storm incidence since the cessation of survey suggests that later in the winter erosion exceeds summer accumulation.

However, the feature of greatest importance is the small magnitudes of the changes. The maximum deposition observed was 69.25 cubic feet, and the maximum erosion was 52.3 cubic feet. (Both of these values were observed on the northernmost profile, No. 1 at Birdlings Flat in summer and in winter respectively). Minimum figures for both erosion and deposition were of the order of 2-3 cubic feet between surveys. The discussion of short term changes in beach morphology indicates that changes of this order probably occur over single tidal cycles. Larger accumulations require a succession of cycles under low wave conditions. The maximum erosional change can occur in a single storm, there being little subsequent change until cliff-fall occurs again.

The average values of profile change shown in Figure 24 can be partly ascribed to survey errors since an Abney level cannot be used to greater accuracy than half of one degree. Thirty minutes of arc on a range of 100 feet is equivalent to a vertical distance of 0.87 feet. Since the profiles are all 200 feet or longer an average change of even 25 cubic feet between surveys amounts to little more than 0.125 feet of erosion or deposition per linear foot of the profile. Thus, the indicated volume changes contain some survey error. Where inter-survey change has been great (as on some cliff-front profiles, river mouth profiles and the foreshore zones of all profiles), the figures have more validity.

This serves to emphasise the point that, in general there is little seasonal change in the beach profiles. Relative to the remainder of the coast cliff-falls such as those shown in Plates 3 and 14 have minor effects on beach volume. A low order of seasonal amplitude is compatible with the suggestion that there is little net longshore transport to the north in the Canterbury Bight.

Figure 24 also shows the seasonal sequence of movement of beach contours for four profile stations. The low order of magnitude of the changes is clearly indicated. The foreshore zones build up and out in summer and are cut down and back in winter. The backshore zones exhibit smaller variations and may be cut in summer, for example, (profile 7), or built by cliff-fall, for example, (profile 13). Profiles in the south are more stable in all seasons owing to a low rate of supply of materials. Profiles at the higher energy northern end of the beach directly face the southerly storm waves and fluctuate in volume much more.

The small amplitudes of the profile envelope curves and the consistently low mean grain size-foreshore slope relationship discussed previously indicate a tendency for the beach to achieve profile equilibrium conditions. As shown in connection with swash-backwash transportation conditions and with movements of the beach materials this is an erosional equilibrium related to the day to day incidence of swell and storm waves. It is a dynamic phenomemon which can be temporarily over-balanced by cliff-fall, but it has been shown that recovery of concave backshore zones is rapid. Equally rapid is the development of the swash berm after a storm.

Long Term Changes in Beach Morphology

Much of the evidence already presented indicates that relative to wave energy, the supply of materials to the beach is small. Thus, the beach profiles may be classified as "under-nourished" according to the terms proposed by Bruun (1954). The coast is retrograding relative to a set of fixed co-ordinates, over much of its length.

Evidence for these long term changes in beach profiles and in the position of the coastline is derived from the Black Map Surveys of Canterbury. These date back to 1850. Other data is derived from engineering surveys made at four points along the coast, dating to 1931. Estimates of past and present rates of retrogression were also obtained from residents along the coast.

The beach fronting the Kaitorete Spit appears to be almost stable. Speight (1930) cited, but did not specify, an old survey dating to 1850. It shows that at that time the mouth of Lake Forsyth near Birdlings Flat was open. A Maori boat harbour there was navigable by small trading schooners. This has been closed since at least 1862 (Black Map Survey, Sheet 71), by a berm which is now 35 feet high. No further change in height or position appears to have occurred since then. It appears also that this is true of all of Kaitorete Spit. There has been little change in the 18 miles of beach along the spit over the last 15 years, as indicated by a local resident, Mr D.A. Turnbull, (Pers.Comm.).

Retrogression of the coast is pronounced south of Taumutu. Beach profiles have been surveyed at four swamp drainage culverts between Taumutu and the mouth of the Rakaia River since 1931. These give reliable data on coastal retrogression and profile morphology in that area, (E.B. Dalmer, and G.D. Stephen. North Canterbury Catchment Board. Pers. Comm.). Copies of these surveys are reproduced in Figure 25, while Table 15 shows the average annual erosion rates between surveys.

The average rate of erosion is approximately 3 feet per year but there has been considerable variation so that extrapolation over a long time period is not possible. Significantly, the profile at McEvedy's Culvert (profile 7 in this study), has been broadening and flattening, the berm slowly retreating landwards. It has been shown that the distributions of grain-size and sorting reflect this mode of coastal recession. Pebbles are eroded from the face of the beach while the larger sizes move onshore and over the topmost berm.

South of the Rakaia River in the cliffed section of the Canterbury Bight accurate estimates of cliff erosion are difficult to obtain. This is because the old surveys at a scale of 10 chains to an inch cannot be accurately compared with modern maps at a scale of one mile to an inch. However, local residents

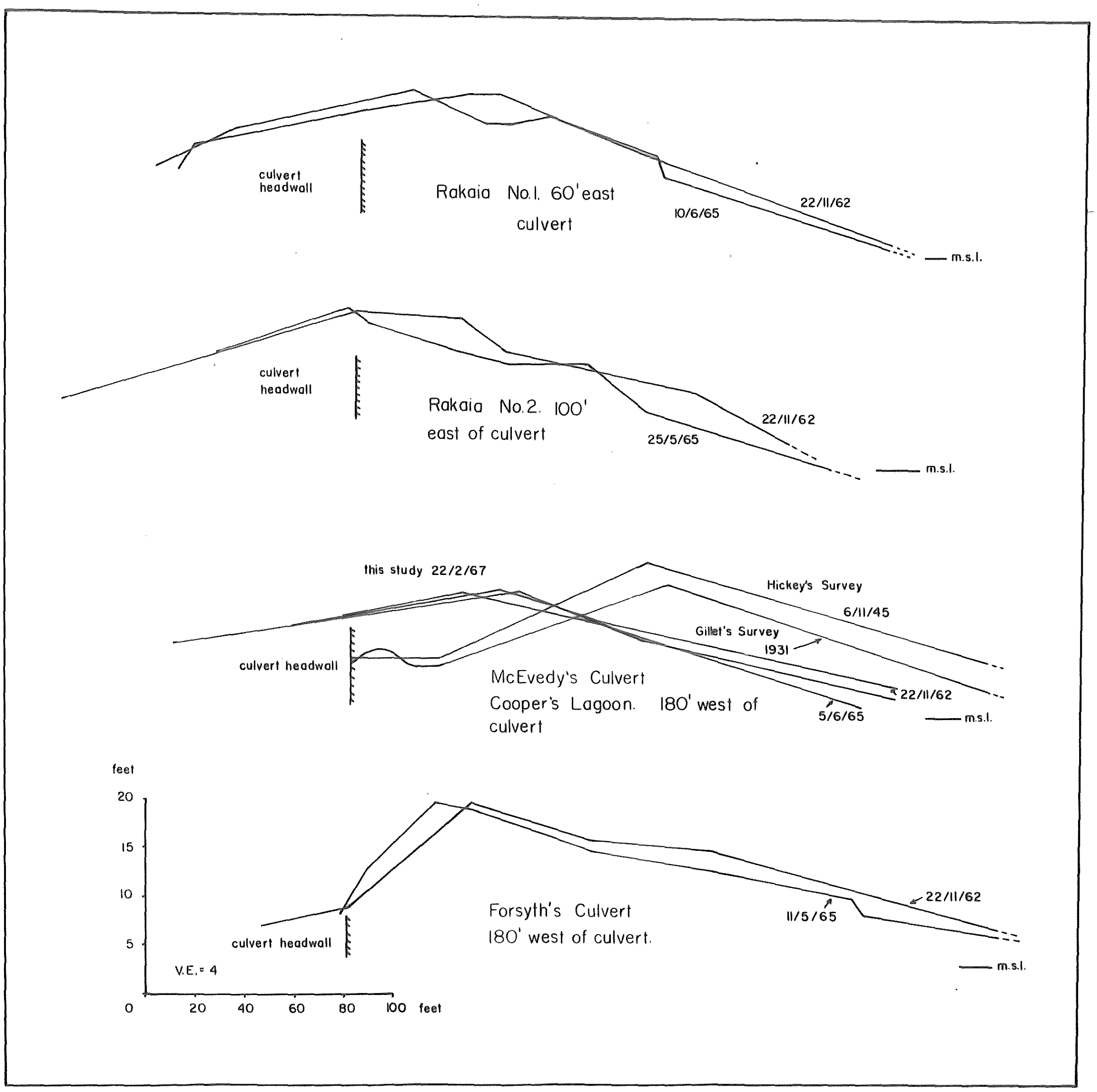


Figure 25. Long term changes in beach profiles.

Source: North Canterbury Catchment Board drawings Nos. L.125 and Gch.4846.

suggest that erosion of the cliff occurs currently at a rate of 2-3 feet per year. Early maps show that this figure is probably of the correct order of magnitude and that erosion is most pronounced near the mouth of the Rangitata River. The mode of cliff retreat has been shown to be dominantly due to mass movement processes aided by wave removal of the cliff-base debris. Cliff-fall results in parallel retreat of the face by 5-10 feet. Zeigler, Hayes and Tuttle (1959) observed cliff retreat of similar mode and magnitude in glacial drift at Cape Cod, Mass. U.S.A.

South of the cliff zone no accurate rates of recession were obtained. Hassall (1955) notes recent coastal erosion at Dashing Rocks, Timaru as a result of the building of the harbour breakwater. A shingle bar across the mouth of Waimataitai Lagoon (immediately south of Dashing Rocks), was removed. Sand accretion has prograded much of Caroline Bay. Gravel buildup on the south side of the harbour stabilised by 1926. For the 15 years up to November 1893 the annual accumulation was estimated at 57,000 cubic yards per annum. During a storm in June 1896 an estimated 30,000 tons of gravel was thrown over the breakwater into the harbour. The loss of this supply of materials has resulted in erosion along the southern section of the Canterbury Bight. It would appear that only small amounts of medium and coarse sand reach the Canterbury Bight from south of Timaru under present conditions. A resident of 45 years standing notes

Table 15

Average Rates of Coastal Erosion Between Taumutu and Rakaia River Mouth

Profile Location	1931-45	Recession Rate. Ft/Year.		
		1945-62	1962-65	1965-67*
180' west of Forsyth's Culvert	--	--	3.2	--
180' west of McEvedys Culvert	0.15	3.0	1.67	5.0
100' east of Rakaia No.2 Culvert	--	--	Nil $*_1$	--
60' east of Rakaia No.1 Culvert	--	--	3.2	--

* = data gathered during this investigation.

$*_1$ = no retrogression but the beach was lowered by erosion of the seaward face.

- *Source*. North Canterbury Catchment Board Drawings Nos. L.125 and Gch.4846.

that during this time the beaches have retreated, broadened and flattened in the same manner as illustrated in profile 7. A significant change to finer grain sizes was also reported. Current estimates of erosion on the beaches in this area are in the range 0.5 - 1.0 feet per year.

Thus the pattern of coastal erosion along the Canterbury Bight falls into three classes relating to the distribution of wave energy and to the sources of materials. In the north, from Birdlings Flat to Taumutu (where the orientation of the shore changes rather sharply), is a relatively stable, near equilibrium area. From Taumutu to south of the Rangitata River, two thirds of the length of the Canterbury Bight, is an area that is eroding at approximately 3 feet per year. South of the Rangitata River erosion is pronounced but less rapid. Here the recent history of the beach owes much to the construction of the Timaru breakwater. If the river mouths are included with the cliff-zone it can be seen that this pattern of erosion corresponds to the topographic units of the coast previously discussed.

Discussion of Changes in Beach Morphology

In the preceding discussion it has been demonstrated that short term changes in beach volume are small. The situation over most of the Canterbury Bight is thus one in which there is little short term fluctuation in beach profiles, despite wide variations in wave conditions. The narrow, small amplitude beach envelope curves (Fig. 22), are retreating landward, slowly developing flatter, broader slopes that minimise erosion by the long turbulent swashes of southerly storm waves. Warnke (1967) observed a similar pattern of change in beach profiles at Alligator Spit in the Gulf of Mexico, where hurricane surges are responsible for rapid erosion of sand beaches. Between hurricane surges the beaches adopt equilibrium profiles related to the prevailing swell. In this situation the beaches were concluded to be in "sub-equilibrium" because though the beach profiles attain a short term equilibrium, the long term condition is retrogression.

The Canterbury Bight beach is in a very similar condition. In terms of profile morphology the beach is quickly attenuated by the swash-backwash of storm waves. Between storms there is rapid development of swash berms and winnowing and resorting of the mixed sands and pebbles moved by the storm waves. Hence, minor changes in beach profile morphology and distribution of materials result from the prevalent south-east and easterly swells. The position of the beach profile envelope curve at any time, however, is a function of the power of the southerly storm waves. It is the swash-bakcwash of these waves that sweeps debris from the cliff-base and which moves the larger pebbles and cobbles over the topmost berm.

Therefore the beach of the Canterbury Bight, with the exception of Kaitorete Spit, may be said to be in sub-equilibrium. There is a short term erosional equilibrium form, around which the profiles fluctuate but little; but the beach has not achieved a balance between the energy of the dominant storm waves and the supply of materials to the littoral zone. There is an excess of energy over materials so that the long term trend is to coastal erosion.

Kaitorete Spit appears to be more stable. It faces the southerly storms and is entirely a depositional feature. Over the last century its beaches have apparently changed little. It has similar profile geometry characteristics to the remainder of the beaches but its materials tend to be better sorted, suggesting a closer approach to equilibrium conditions.

There is a close relationship between the long-term coastal sub-equilibrium demonstrated above, and the characteristics of the beach deposit. It was shown that the beach deposit is texturally sub-mature. Little rounding of sands is being accomplished in the present environment. There is a wide range of sorting, skewness and kurtosis characteristics which reflects the perpetually "young" nature of the materials on beaches that are eroding. There is insufficient time for the waves to greatly modify the materials. Stable beach profiles in the north are not compatible with a high rate of net longshore transport to the north under present conditions.

<u>Equilibrium Conditions in Plan</u>. With regard to the plan morphology of beaches general considerations such as those relating to profiles have been developed. It has been shown that incomplete refraction of waves in the Canterbury Bight, as in other bays, leads to the generation of longshore currents which may be capable of moving sediments in more than one direction

along the shore. A combination of updrift erosion and downdrift deposition leads to concavity of the shoreline, equilibrium being attained when the two phases are balanced, so that there is only sufficient wave energy available to move the sediments supplied. It has already been shown that this condition does not obtain in the Canterbury Bight. Analysis of the plan-morphology of the beach also indicates a sub-equilibrium stage of shoreline development.

Hoyle and King (1958) have defined the equilibrium plan shape of beaches in relation to a circular arc. Dicken (1961) lists the criteria set by Hoyle and King to test for equilibrium plan shape. First, the beach must be supported at both ends; second, it must have a curved outline representing the arc of a circle with the angle subtended by the radii of the beach ends of 0.25 radians; third, the slope of the beach must be in equilibrium; and fourth, the orientation of the beach must be oriented consistent with the prevailing wave direction. The second requirement is given by the ratio of chord length (c) to maximum perpendicular length (p). If $\frac{c}{p} = 15.0$ then the plan shape of the beach is considered to be stable, provided the other conditions are satisfied. The plan shape characteristics of the Canterbury Bight are shown in Figure 26. It can be seen that for the study beach $\frac{c}{p} = 9.926$ so that it can be considered thus far to be a near equilibrium form, since the beach is supported at both ends by hard rock masses. It has been demonstrated that the beach is in short term erosional equilibrium

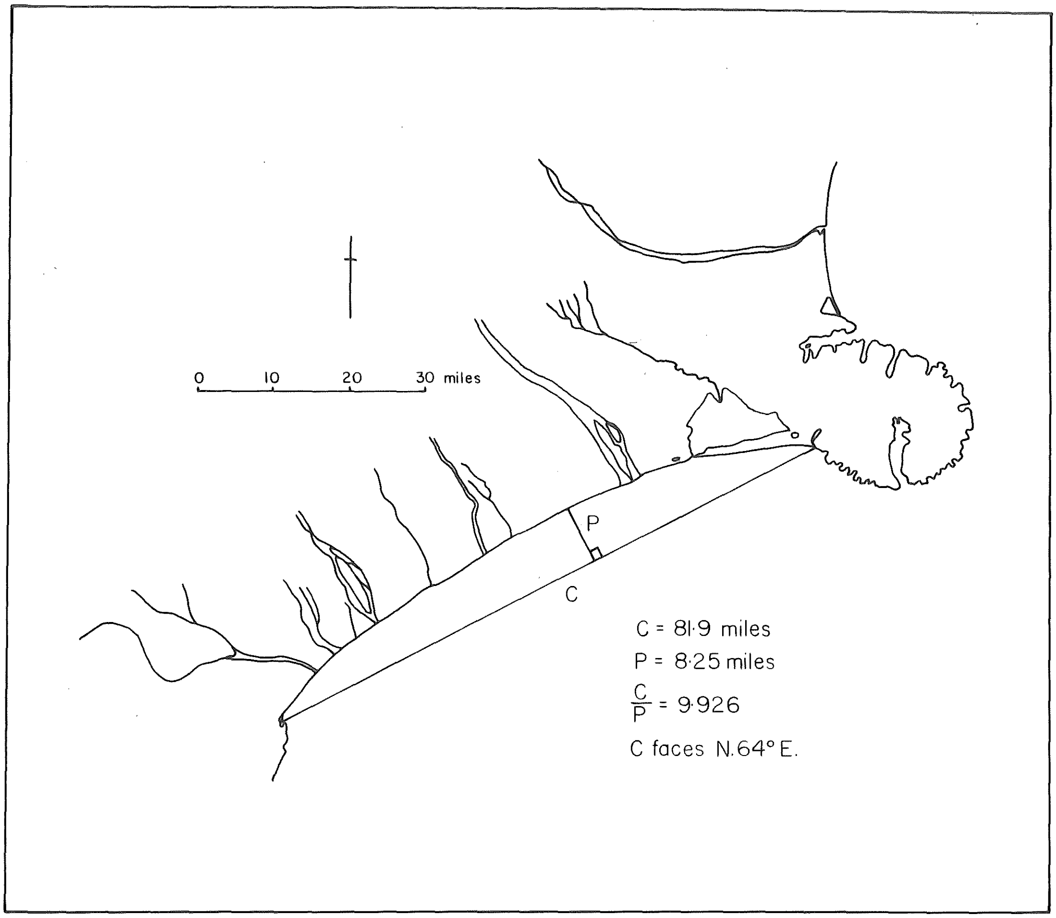


Figure 26. Plan-shape characteristics of the Canterbury Bight.

with the prevailing south-easterly swells so that the third requirement is met. Figure 26 indicates that the chord of the Canterbury Bight faces N.64°East. The beach may therefore be considered to face the prevailing south-easterly swell waves. However, an analysis of the plan shapes of all the beaches of the East Coast of the South Island reveals that only Kaitorete Spit is aligned to face the dominant storm waves in the Canterbury Bight (McLean, 1967, Fig.3). This has been shown to be the most stable portion of the study beach.

Thus, a consideration of the plan shape characteristics of the Canterbury Bight suggests that in plan, as well as in profile, the beach is in sub-equilibrium. While the downdrift erosion is vigorous, the updrift adjustment appears to be almost complete. Movements of materials to the north appear to be of a small order, sufficient only to maintain the form and position of the beach. Significantly, the curve of the shoreline is too flattened in the central area by comparison with the theoretical stable shape. This is the area where present erosion is most vigorous. Agreement between theory and the observed shape is better in the south where present erosion rates are lower.

In conclusion it may be stated that the Canterbury Bight beach is a sub-equilibrium form that is still in the process of adjustment to post-glacial fluctuations of sea-level and to possible changes in sediment supply. It cannot be doubted that longshore drift of large amounts of gravel in the past accounts for the development of the 12,000 acres of Kaitorete Spit, but this adjustment to wave energy and sediment supply appears to be completed. Further south, adjustment appears to be incomplete while near Timaru coastal change over the last century has been mostly related to the disruption of the littoral transport system created by the construction of the harbour breakwater.

CONCLUSIONS

The rates and modes of coastal erosion and deposition along the Canterbury Bight have been described and analysed in relation to beach process factors and considerations of sediment supply. Variations in beach morphology, sediment distribution and rates of coastal erosion over both time and space have been examined in relation to accepted principles of beach study. While many studies have been carried out on either sand or shingle beaches, there have been few studies principally concerned with a mixed sand-shingle beach. Such beaches display a considerable complexity of form and process. This results from the mixing of the two size populations and their differing responses to wave energy. This investigation has, however, shown that, in the case of the Canterbury Bight at least, these forms and processes are explainable in terms of accepted principles of beach study. Many processes and beach forms believed to be characteristic of the mixed sand-shingle beach have been described.

The present shoreline of the Canterbury Bight is a Recent one resulting from coastal adjustments to the post-glacial rise of sea-level. It is probable that sea-level stood 12-15 feet higher than now some 5,000 years before the present. During this time coastal sedimentation in the north of the Canterbury Bight reached and passed a maximum, as evidenced by the large volume of materials in Kaitorete Spit.

Present coastal erosion has been shown to be most intense in the central area between Taumutu and south of the Rangitata River. Further to the south erosion proceeds more slowly and, over the last century, appears to have been related to the cessation of littoral drift of gravels from south of Timaru. The nature of the beach deposit and the distribution of mass transport velocities near the bed for typical storm waves suggest transport of small amounts of sand across the flat, shallow continental shelf around Timaru. On the other hand, in the north, from Taumutu to Birdlings Flat the beaches have been stable for at least the last century. It seems probable that longshore transport into this sector from the south is small but sufficient to maintain the present position of the shoreline.

The distribution of storm wave mass transport velocities in this area indicates transport of the fine sands mantling the continental shelf towards Banks Peninsula, for up to 6 miles from the coast. Dingwall (1966) suggests that transport of this material around Banks Peninsula in deeper water is by attenuation of the flood-tide current, particularly during stormy weather from the south-east. It is therefore clear that though the Canterbury Bight can be meaninfully treated as one beach system, it cannot be regarded as a physiographic unit that is isolated from the areas adjacent to it. It is probable that there are minor net northward movements both into and out of the area.

Surprisingly, in view of the high energy waves received at the shoreline, the beaches are in sub-equilibrium in both plan and profile. It has been shown that the transverse beach profiles are well adjusted to the prevailing south-easterly swells and to the largely shore-normal swash-backwash component of the dominant southerly storm waves. Consequently, beach profile envelope curves are of small amplitude even where coastal erosion is rapid. In plan the curvature of the beach is too flat in the central region, by comparison with the theoretical stable shape. Significantly, this is where present erosion rates are highest.

The latter result also has value in relation to the general field of coastal research. Wave induced and other changes in beach profiles have been extensively studied both in the field and in laboratory model tanks, whereas the plan-form aspects of beaches have been little studied. The emphasis on studies of changes in profile has partly arisen from the interest in shoaling transformations in wave form and energy, and partly from the fact that changes in profile are rather more easily measured than changes in plan. The correspondence between beach profile conditions along the Canterbury Bight and the distribution of erosion and plan-form characteristics thus provides evidence of the value of studies of plan-form in considering problems of beach development.

It has been demonstrated from the analysis of wave data that beach morphology is closely related to the incidence of storms. The high energy zone under storm waves is in the north.

Here the beach profiles are highest and widest. The typical profile form has been shown to be comprised of a steep, narrow foreshore rising to a low swash berm at, or a little above the mean high water mark; and a planar or concave upward backshore zone extending from the swash berm to the highest storm berm. Intermediate berms between the swash berm and the crest of the profile are rare since storm swash traverses all of the profile. This profile form is largely worked by swash-backwash because the breaker zone is confined to the foreshore step. Because the nearshore bottom slope is steep the characteristic breakers are the plunging type and there is little tidal translation of the breaker zone. These release almost all of their energy in breaking and deliver comparatively small volumes of water to the foreshore. Storm waves spill more before breaking and so their energy is diminished over a wider zone. Consequently, storm waves on the study beach deliver relatively larger amounts of water to the foreshore. The backwash under storm waves has a strong erosive effect on the beach profile, since compared to swell waves, a lesser proportion of the original swash volume is lost by percolation into the beach. It is expected that similar profile morphology and swash-backwash processes operate on other mixed-sand shingle beaches.

It has been shown that almost all of the materials in the littoral zone of the study beach are alluvial in origin and that the bulk are alpine greywackes. Because of the rapidity of erosion in the central area the beach deposit is texturally sub-mature. This is consistent with the beach plan and profile morphological sub-equilibrium previously demonstrated. The two morphological indices together with the latter textural index of maturity of the beach deposit effectively summarise and characterise the observed beach changes of the Canterbury Bight. Sands are little rounded and pebbles are uniformly rounded. The distribution of pebble shapes reflects the manner of breakdown of the parent rock. There is some selection for pebble shape between the present river environments, the alluvial cliff environments, and the littoral, as there is within the littoral; but this is of a small order because of coastal erosion.

Distributions of size-sorting, skewness and kurtosis demonstrated that the two main size fractions are transported in fundamentally different ways. This would be an expected characteristic of any sand-shingle beach. Pebbles and cobbles are moved by bed-load transport, the type of movement depending upon particle shape. Sand moves as bed-load under low wave conditions and as intermittent suspended load under storm swash-backwash conditions. Because of this, complex movements of sand take place both across the shore and along it. Sand is deposited while pebbles are being eroded under storm swash-backwash conditions. Pebbles moved offshore of the breaker zone are unlikely to be returned to the foreshore because of the high velocities required to lift them up the steep nearshore slopes. Sands however, may be recycled between the offshore and foreshore zones many times. The high energy surf of the study beach winnows mixtures of sand and gravel to produce a "surf break" in the range -1.5 to -3.00.

The manner of retreat of the alluvial coastal cliffs is due to mass-movement processes, accelerated by clearance of the cliff-base by storm swash. The process of retreat of berms not backed by cliffs is by swash overspill and erosion of pebbles from the beach face. This has proceeded to such a degree in the south that the alluvial basement is exposed between the beach deposit and the capping foredunes. Surveyed profiles dating back to 1931 testify to a variable rate of retreat and to slow adjustment of beach widths and slopes to forms that more closely approach equilibrium between the supply and loss of materials. Wider, flatter slopes dissipate more swash energy and increase the area over which percolation takes place, thus reducing the volume of the backwash so that erosion of the profile is minimised.

With respect to the observed wave energy levels the supply of materials alongshore from cliffs and rivers is of a low order so that the beach profiles are "undernourished". Continued erosion will result in further changes in plan and profile morphology and, less rapidly, in the texture of the beach deposit, though a stable equilibrium may never be attained.

SUGGESTIONS FOR FURTHER RESEARCH

A major problem which remains is one that relates to many other areas as well as to the Canterbury Bight. Very little is known about the role of the rivers in the supply of sediments to the coast. It has been shown that angular medium and coarse sands are probably abundantly supplied to the coast during floods. Suspended sediment concentrations are high (even at low flows), in some of the rivers. Erosion rates in the high country are high and have been greatly accelerated over the last century. The rivers have steep gradients and unconsolidated beds. Little, if anything, is known of the amounts of bed-load material supplied to the coast by these rivers. Two rivers, the Rakaia and the Rangitata, are potentially large suppliers in both the sand and pebble fractions, but there is little evidence at the coast to suggest that pebbles are abundantly supplied. Tracing experiments with fluorescent or radioactive materials would indicate more clearly the movements of pebbles at river mouths.

Similarly, much work with tracers might be done over small sections of the beach to quantify the movements of materials under swell and storm conditions. Also, tracing methods and statistical analytical methods based on grain size modes and sorting trends, such as those used by Owens (1966) might be employed. Continued study of the rates of coastal recession is necessary to more clearly determine the rates and magnitudes of change.

Detailed sampling and analysis of both nearshore and offshore bottom deposits would clarify the nature of sediment sorting processes in these zones. This is of particular significance in the north and south where net transfers into and out of the area appear to take place. Extension of the beach profile surveys below low water would give much information on the nature of losses of beach pebbles and the movements of sand.

Much detailed study of the sorting processes of pebble and sand fractions in combination might be undertaken. This would be especially valuable in the light of the close relation demonstrated between these processes and beach morphology. Of particular significance here are the relationships between mean grain size and foreshore slope, and between skewness and kurtosis. The former gives an insight into the net effects of transportation on the beach face and the latter yields much information about the nature of these transport processes. Studies of these mixing processes are particularly valuable in New Zealand where mixed sand-shingle beaches are common. Most previous work on sediment sorting has been concerned either with sand (most U.S. studies) or with pebbles (many U.K. studies).

It has been indicated that, in the case of the Canterbury Bight beach, there is a close correspondence between morphological indices of beach development and textural characteristics of the beach deposit. It is apparent that these indices taken together effectively characterise the beach. Therefore it is suggested that these indices constitute a useful way of comparing the stages of development of different beaches, whether they are sand, shingle or mixtures of the two. Such comparative studies would be of greater use than existing classifications based on structural criteria or post-Pleistocene crustal or eustatic movements, because they relate directly to the wave environment on the one hand and to local structures, geology and the supply and dispersal of beach sediments on the other. One of the greatest values of such a classification would be that it refers to the state of coastal development at the present time rather than to post-Pleistocene or even older events, and therefore would be of considerable applied value in dealing with coastal problems. The terms used are defineable in a precise and quantitative manner and the data can be collected using well-proven standardised methods.

Finally, in the light of the apparent coastal changes over the last century and their difference from those of earlier periods, a detailed study of the geological and geomorphological history of the Canterbury Bight would be most valuable. Considerable field evidence for past conditions exists in the Lake Ellesmere - Kaitorete Spit area where there are old barrier beaches, buried forest remnants and good exposures of the beach gravels in shingle pits. To the south along the cliff zone there are many large, apparently dry gullies that provide clues to the past history of the area. Near Timaru there are small treestumps in position of growth on the foreshore. These may yield datable materials. No study of these features was undertaken during this investigation since its primary concern was the description and analysis of the present beach of the Canterbury Bight.

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REFERENCES

Bagnold, R.A. 1941: *The Physics of Blown Sand and Desert Dunes*. Methuen and Co., London, 265pp.

Bascom, W.N. 1951: "The Relationship between Sand-Size and Beach-Face Slope." *Trans. Am. Geophys. Union. 32(6)*: 866-74.

Blake, G.J. 1964: *Coastal Progradation in Pegasus Bay*. Thesis for M.A. University of Canterbury. Deposited in University Library, Christchurch.

Blalock, H.M. 1960: *Social Statistics*. McGraw-Hill, New York. 465pp.

Bowen, A.J. and Inman, D.L. 1966: "Budget of Littoral Sands in the Vicinity of Point Arguello, California." *U.S. Army C.E.R.C. Tech. Memo. 19*. 41pp.

Brodie, J.W. 1960: "Coastal Surface Currents Around New Zealand." *N.Z. J. Geol. Geophys. 3(2)*: 235-52.

Bruun, P. 1954: "Use of Small-Scale Experiments with Equilibrium Profiles in Studying Actual Problems and Developing Plans for Coastal Protection." *Trans. Am. Geophys. Union. 35.*: 445-50.

Chandler, A. 1967: "Hydrology of South Canterbury." *Soil and Water*. 3(3): 17-20.

Cherry, J. 1965: "Sand Movement along a Portion of the Northern California Coast." U.S. Army C.E.R.C. Tech. Memo. 14.

Davidsson, J. 1963: Littoral Processes and Morphology on Scanian Flat Coasts. Lund Studies in Geography. Ser. A. Physical Geography. No.23. 232pp.

Dicken, S.N. 1961: Some Recent Physical Changes of the Oregon Coast. U.S. Office of Naval Research. Project. N.R. 388-062.

Dingwall, P.R. 1966: Bay-Head Beaches of Banks Peninsula. Thesis for M.A. University of Canterbury. Deposited in University Library, Christchurch.

Duncan, J.R. 1964: "The Effects of Water Table and Tide Cycle on Swash-Backwash Sediment Distribution and Beach Profile Development." Marine Geol. 2. : 186-97.

Elliott, E.L. 1958: "Sandpits of the Otago Coast." N.Z. Geogr. 14(1): 65-74.

Emery, K.O. 1955: "Grain Size of Marine Beach Gravels." J. Geol. 63. : 39-49.

__________ and Foster, J.F. 1948: "Water Tables in Marine Beaches." J. Marine Res. 7. : 644-53.

Folk, R.L. 1965: Petrology of Sedimentary Rocks. University of Texas Manual. Hemphills, Austin. 154 pp. 2nd Ed.

Grant, U.S. 1948: "Influence of the Water Table on Beach Aggradation and Degradation." J. Marine Res. 7. : 655-60.

Hassall, C.E. 1955: A Short History of the Port of Timaru. Timaru Harbour Board. 212pp.

Henderson, J. 1922: "The Chertsey Oil Bore." N.Z. Geol. Survey. 16th Annual Report. P.12.

Hodgson, W.A. 1966: "Coastal Processes around the Otago Peninsula." N.Z. J. Geol. Geophys. 9(1&2): 76-90.

Hoyle, J.W. and King, G.T. 1958: "Origin and Stability of Beaches." Proc. 6th Coastal Eng. Conf. : 281-301.

Hydrology Annuals Nos. 7-11. 1959-63. N.Z.M.O.W. Wellington.

Inman, D.L. 1957: "Wave Generated Ripples in Nearshore Sands." U.S. Army B.E.B. Tech. Memo. 100.

Ippen, A.T. and Eagleson, P.S. 1955: "A study of Sediment Sorting by Waves Shoaling on a Plane Beach." U.S. Army B.E.B. Tech. Memo. 63.

Ippen, A.T. (Ed.) 1966: Estuary and Coastline Hydrodynamics. McGraw-Hill, New York. 744 pp.

Johansson, C.E. 1965: "Structural Studies of Sedimentary Deposits." Lund Studies in Geography. Ser. A. Physical Geography. 32. Lund.

Kidson, C.; Carr, A.P.; and Smith, D.B. 1958: "Further Experiments Using Radioactive Methods to Detect the Movement of Shingle Over the Sea Bed and Alongshore." Geog. Journ. 124(2): 210-18.

Kidson, C.; Carr, A.P. 1959: "The Movement of Shingle Over the Sea Bed Close Inshore." Geog. Journ. 125(3-4): 380-89.

King, C.A.M. 1951: "Depth of Disturbance of Sand on Sea Beaches by Waves." J. Sedim. Petrol. 21(3): 131-40.

__________ 1953: "The Relationship Between Wave Incidence, Wind Direction, and Beach Changes at Marsden Bay, County Durham." Inst. Brit. Geog. Trans. and Papers. 19: 13-23.

__________ 1959: Beaches and Coasts. Edward Arnold Co. London. 403 pp.

Kirk, R.M. 1966: "Depth of Disturbance by Waves on a Shingle Beach over Single Tidal Cycles."

Unpublished Mss. Geography Department, University of Canterbury.

Krumbein, W.C. 1947: "Shore Processes and Beach Characteristics." U.S. Army B.E.B. Tech. Memo. 3.

____________ 1953: "Statistical Designs for Sampling Beach Sand." Trans. Am. Geophys. Union. 34(6): 857-69.

____________ 1959: "The 'Sorting Out' of Geological Variables Illustrated by Regression Analysis of Factors Controlling Beach Firmness." J. Sedim. Petrol. 29(4): 575-87.

____________ 1961: "The Analysis of Observational Data from Natural Beaches." U.S. Army B.E.B. Tech. Memo. 130.

____________ 1963: "A Geological Process-Response Model for Analysis of Beach Phenomena." U.S. Army Bull. B.E.B. 17: 1-16.

____________ and Lieblein, 1956: "Geological Application of Extreme-Value Methods to Interpretation of Cobbles and Boulders in Gravel Deposits." Trans. Am. Geophys. Union. 37(3).

____________ and Pettijohn. 1938: Manual of Sedimentary Petrography. Appleton, Century, Crofts Inc. New York. 549 pp.

Kuenen, Ph. H. 1964: "Experimental Abrasion: 6. Surf Action."
Sedimentology. 3(1): 29-43.

Lewis, W.V. 1931: "The Effect of Wave Incidence on the Configuration of a Shingle Beach."
Geog. Journ. 78. : 129-48.

Marschner, A.W. 1953: "A Method for the Size Analysis of Sand on a Number-Frequency Basis."
J. Sedim. Petrol. 23(1): 49-59.

McCammon, R.B. 1962: "Efficiencies of Percentile Measures for Describing the Mean Size and Sorting of Sedimentary Particles."
J. Geol. 70: 453-65.

McLean, R.F. 1967: "Plan Shape and Orientation of Beaches Along the East Coast, South Island."
N.Z. Geogr. 23(1): 16-22.

Miller, R.L. and Kahn, J.S. 1962: *Statistical Analysis in the Geological Sciences*.
Wiley. New York. 484 pp.

Norrman, J.O. 1964: "Lake Vättern:- Investigations of Shore and Bottom Morphology."
Geografiska Ann. 46(1-2): 238 pp.

New Zealand Tide Tables 1967. Marine Department, Wellington.
Govt. Printer. 62 pp.

Oram, 1941: *On the Origin and Morphology of the Canterbury Plain*.
Thesis for M.A. University of Canterbury.
Deposited in University Library, Christchurc

Otvos, E.G. 1965: "Sedimentation-Erosion Cycles of Single Tidal Periods on Long Island Sound Beaches."
J. Sedim. Petrol. 35(3): 604-09.

Owens, I.F. 1966: "Distribution of Sediment Characteristics on a Shingle Beach."
Unpublished Mss. Geography Department, University of Canterbury.

Powers, M.C. 1953: "A New Roundness Scale for Sedimentary Particles."
J. Sedim. Petrol. 24(2): 117-19.

Raeside, J.D. 1964: "Loess Deposits of the South Island, New Zealand, and Soils Formed on them."
N.Z. J. Geol. Geophys. 7(4): 811-38.

Saville, T. 1950: "Model Study of Sand Transport along an Infinitely Long Straight Beach."
Trans.Am. Geophys. Union. 31(3): 555-65.

Schofield, J.C. 1967: "Sand Movement at Mangatawhiri Spit and Little Omaha Bay."
N.Z. J. Geol. Geophys. 10(3): 697-722.

Sevon, W.D. 1966: "Sediment Variation on Farewell Spit, New Zealand."
N.Z. J. Geol. Geophys. 9(1,2): 60-75.

Shepard, F.P. 1963: *Submarine Geology*.
Harper and Row. 557 pp. 2nd Edition.

Shepard, F.P. and Inman, D.L. 1950: "Near Shore Circulation Related to Bottom Topography and Wave Refraction."
Trans. Am. Geophys. Union. 31(2): 196-212.

Smalley, I.J. 1966: "The Expected Shapes of Blocks and Grains."
J. Sedim. Petrol. 36(2): 626-29.

Sneed, E.D. and Folk, R.L. 1958: "Pebbles in the Lower Colorado River, Texas. A study in Particle Morphogenesis."
J. Geol. 66(2): 114-50.

Speight, R. 1930: "The Lake Ellesmere Spit."
Trans. N.Z. Inst. 61: 147-69.

Strahler, A.N. 1966: "Tidal Cycle of Changes in an Equilibrium Beach, Sandy Hook, New Jersey."
J. Geol. 74(3): 247-68.

Suggate, R.P. 1958: "Late Quaternary Deposits of the Christchurch Metropolitan Area."
N.Z. J. Geol. Geophys. 1: 103-22.

Tanner, W.F. 1958: "The Equilibrium Beach."
Trans. Am. Geophys. Union. 39(5): 889-99.

__________ 1966: "The Surf 'Break': Key to Paleogeography."
Sedimentology. 7(3): 203-10.

Trask, P.D. 1955: "Movement of Sand Around Southern California Promontories."
U.S. Army B.E.B. Tech. Memo. 76.

Warnke, D.A. 1967: "Conditions of Beach Retrogression in a

low Energy Environment."
Zeits. fur. Geomorphologie. N.S. 11(1): 47-61.

Wolman, M.G. 1954: "A Method of Sampling Coarse River Bed Materials."
Trans. Am. Geophys. Union. 35(6): 951-56.

Zeigler, J.M. 1964: "Some Modern Approaches to Beach Studies."
Oceanogr. Mar. Biol. Ann. Rev. 2: 77-95.

___________ ; Hayes, C.R. and Tuttle, S.D. 1959: "Beach Changes During Storms on Outer Cape Cod, Mass.".
J. Geol. 67: 318-36.

LIST OF SYMBOLS

Symbol		Units
C	Wave velocity in deep water. $C = \frac{gT}{2\pi} = 5.12\,T$	ft. sec.$^{-1}$
C_s	Wave velocity in shallow water. $C_s = \sqrt{g.d.}$ - limits of application = d = $\leq \frac{L}{2}$	ft. sec.$^{-1}$
d	Depth of water below still water level.	ft.
D_e	Equilibrium motion particle diameter. That sized particle which saltates about a mean position under given wave energy conditions.	φ,
D_i	Incipient Motion diameter. The smallest particle which can undergo net motion in one direction under given wave energy conditions.	φ
g	Acceleration due to gravity.	32 ft. sec.$^{-2}$
H_o	Wave height in deep water.	ft.
H_b	Breaker height.	ft.
$\frac{H}{L}$	Wave steepness. Deepwater ($-_o$). Shallow water ($-_b$).	Dimensionless.
K_b	Shallow water wave refraction factor. $K_b = \left(\frac{S_o}{S_b}\right)^{\frac{1}{3}}$ Where: S_o = Spacing between deepwater wave orthogonals.	Dimensionless.

S_b = Spacing between shallow water wave orthogonals.

L	Wave length. $L_o = \frac{gT^2}{2\pi} = 5.12\ T^2$.	ft.
T	Wave period.	Seconds
U_b	Mass Transport velocity near the bed and in the direction of Wave propagation.	ft. sec.$^{-1}$
$U_{max.}$	Maximum horizontal component of wave orbital velocity near the bed and under the wave crest (onshore). -Solitary Wave Theory.	ft. sec.$^{-1}$
$U_{p\ max.}$	Maximum horizontal component of wave orbital velocity near the bed and under the wave crest (onshore). -Oscillatory Wave Theory.	ft. sec.$^{-1}$
$V_{crit.}$	Critical erosion velocity of a particle of given size, shape and density.	cm. sec.$^{-1}$
Ψ (psi)	Effective Settling Sphericity of a particle of given shape in relation to a sphere of the same volume.	Dimensionless.

GLOSSARY OF TERMS

BACKSHORE:	That zone traversed only by storm wave swashes and worked by wind, extending from the upper limit of swell wave swash (near mean high water level), inland to the dunes or cliffs.
BACKWASH:	Seaward return of water following the swash of waves.
BEACH CUSP:	One of a series of naturally formed low mounds of beach material separated by crescent shaped depressions, spaced at more or less regular intervals along the beach face.
BEACH FACE:	Sloping seaward side of berm.
BED-LOAD:	Type of transport in which the grain weight is borne by the grain bed. Grains move by rolling, sliding or saltating on or very near the bed.
BERM, SWASH:	Low ridge or step on foreshore formed by deposition of material by wave action near ordinary high water swash level.
BERM, CREST:	The highest uprush point on the depositional beach face.
BERM, STORM:	Berm at the highest uprush point on the backshore. The backshore and topmost berms on the open beach. Cliff-base is the equivalent in the cliffed zone.
BERM TREAD:	Nearly horizontal portion of berm above berm crest.
BREAKER, PLUNGING:	One in which the crest of the wave falls into the trough enclosing a pocket of air.

BREAKER, SPILLING: One which breaks over a considerable distance. The wave does not lose its identity, but gradually decreases in height until it becomes swash on the beach. Usually delivers a longer swash than plunging breaker, cet. par.

CURRENT, COASTAL: One of the offshore currents flowing generally parallel to the shore and with a relatively uniform velocity.

CURRENT, EBB: The current that runs with a falling tide. Also EBB STREAM. In the Canterbury Bight sets to the south.

CURRENT, EDDY: Circular movement of water over a comparatively limited area, formed marginal to a main current.

CURRENT, FLOOD: The current which runs with a rising tide. Also FLOOD STREAM. Sets to the north in the Canterbury Bight.

CURRENT, LITTORAL: Nearshore current primarily due to wave action. Hence, varies in direction and magnitude with changing wave conditions.

CURRENT, TIDAL: A current, caused by the tide-producing forces of the moon and sun, which is part of the same general movement of the sea manifested in the vertical rise and fall of the tides.

EQUILIBRIUM BEACH: That configuration that the water would eventually impart to the beach deposit, in plan, profile and texture, if allowed to carry its work to completion. This would be a "steady state", or dynamic balance between energy and materials such that any change would occur about a long term mean configuration, rather than to net erosion or net accretion.

FORESHORE: That part of the shore, lying between the swash berm crest (or the upper limit of swell swash at high tide) and the ordinary low water mark, that is subjected to swash as the tide rises and falls.

FORESHORE SLOPE: The angle between the horizontal and the foreshore surface. Measured at the reference point. Angle becomes larger for larger particles and net deposition.

KURTOSIS: Measures the peakedness or flatness of a frequency curve of grain-size distribution. Measures the ratio between the sorting in the "tails" of the curve and the sorting in the central portion.

LONG-TERM: Lengths of time in decades as distinguished from seasons or other short-term periods.

NEARSHORE BOTTOM: A zone extending from mean low water to an arbitrary depth of 30 feet below mean sea level.

OFFSHORE BOTTOM: A comparatively flat zone of variable width extending from the nearshore zone to the seaward edge of the continental shelf.

PHI UNIT:	The negative logarithm to the base two of particle size in millimeters. $\phi = -\log_2$ diameter in mm.
REFERENCE POINT:	That part of the foreshore which is traversed by swash at mid-tide.
RIDGE, BEACH:	An essentially continuous mound of beach material beyond the beach, in which a wave-formed base is overlain and dominated by a cap of wind-blown material.
ROUNDNESS:	Curvature or roughness of the surface of grains. The measure is independent of grain shape.
SHORT-TERM:	Lengths of time in hours and days rather than in seasons or longer periods.
SKEWNESS:	Measures the degree of asymmetry of the frequency curve of grain-size distribution.
SLACK WATER:	State of the tidal current when its velocity is near zero, especially the moment when a reversing current changes direction.
SORTING:	The uniformity or dispersion of grain sizes. Results from the adjustment of individual grains to an equilibrium with local hydrodynamic environment.
SPHERICITY:	The shape of a particle. The ratio states quantitatively how nearly equal the three axes of the particle are.
SURF ZONE:	The zone of breaking waves and turbulent water

between the breakpoint and the effective seaward limit of the backwash.

SUSPENDED LOAD: Type of transport in which the grain weight is borne by the flow. Flow velocity is greater than the settling velocity of the grain.

SWASH: The translation or rush of water up on to the beach following the breaking of a wave. Maximum under breakers.

SWASH-BACKWASH ZONE: That part of the shore subjected to the action of swash and backwash as the tide rises and falls. Coincides basically with the foreshore, though under storm conditions may be the whole profile.

SWEEP ZONE: That portion of the vertical plane perpendicular to the coastline within which movement of beach material may take place by wave action. It may be established if several profiles, surveyed along the same line and referred to a permanent reference point, are superimposed and enclosed within envelope curves.

WAVE REFRACTION: That process by which the direction of a train of waves moving in shallow water at an angle to the submarine contours is changed. The part of the wave train advancing in shallower water moves more slowly than that part still advancing in deeper water, causing wave crests to bend toward alignment with underwater contours. Because of dispersion and concentration of the energy in the wave train there are also corresponding changes in wave height and length along the crests.

APPENDIX

SUMMARY OF DATA

INDEX TO APPENDICES

APPENDIX IA

Grain-Size scales used in this investigation

Size Class	Size mm.	Size Ø
Boulder	> 256	-8 to -12
Cobble	64 - 256	-6 to -8
Pebble	4 - 64	-2 to -6
Granule	2 - 4	-1 to -2
Very Coarse Sand	1 - 2	0.0 to -1
Coarse Sand	0.5 - 1	1.0 to 0.0
Medium Sand	0.25 - 0.5	2.0 to 1.0
Fine Sand	0.125 - 0.25	3.0 to 2.0
Very Fine Sand	0.0625 - 0.125	4.0 to 3.0

- From Folk (1965, p.25).

Scales and Formulae used in computation of Grain-Size Parameters

The following values and formulae for grain-sizes parameters were taken from Folk (1965).

Graphic Mean Diameter (M_z):

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

Inclusive Graphic Standard Deviation (σ_I):

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

under 0.35φ, very well sorted.

0.35 to 0.5φ, well sorted.

0.50 to 0.71φ, moderately well sorted.

0.71 to 1.0φ, moderately sorted.

1.0 to 2.0φ, poorly sorted.

2.0 to 4.0φ, very poorly sorted.

over 4.0φ, extremely poorly sorted.

Inclusive Graphic Skewness (Sk_I):

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

Sk_I from +1.0 to +0.30. Strongly fine skewed.

+0.3 to +0.10. Fine skewed.

+0.1 to -0.10. Near Symmetrical.

-0.1 to -0.30. Coarse skewed.

-0.3 to -1.00. Strongly Coarse skewed.

Graphic Kurtosis (K_G):

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

K_G	under 0.67	Very Platykurtic.
	from 0.67 to 0.90	Platykurtic.
	0.90 to 1.11	Mesokurtic.
	1.11 to 1.50	Leptokurtic.
	1.50 to 3.00	Very Leptokurtic.
	over 3.00	Extremely Leptokurtic.

McCammon (1962) has reviewed the efficiencies of measures of Graphic Mean Diameter and of Inclusive Graphic Standard Deviation. He demonstrated that the measure of mean diameter used in this study is 88% efficient and that the above measure of sorting (σ_I) is 79% efficient.

APPENDIX IB

Location of Transverse Profile and Sediment Sampling Stations

1) Location of Transverse Profiles and Beach Sampling Stations

Profile No.	Map Reference	Orientation (Magnetic)
1.	NZMS 1.S.94.070201	150°
2.	NZMS 1.S.94.019198	160°
3.	NZMS 1.S.94.965196	160°
4.	NZMS 1.S.94.915188	150°
5.	NZMS 1.S.93.865182	145°
6.	NZMS 1.S.93.753164	142°
7.	NZMS 1.S.93.703151	145°
8.	NZMS 1.S.93.664134	135°
9.	NZMS 1.S.93.613114	150°
10.	NZMS 1.S.93.537084	135°
11.	NZMS 1.S.93.473052	125°
12.	NZMS 1.S.103.319966	125°
13.	NZMS 1.S.103.259929	130°
14.	NZMS 1.S.103.216905	135°
15.	NZMS 1.S.103.165877	127°
16.	NZMS 1.S.103.106843	120°
17.	NZMS 1.S.103.065814	123°
18.	NZMS 1.S.102.998763	125°
19.	NZMS 1.S.102.944724	120°
20.	NZMS 1.S.111.906688	117°
21.	NZMS 1.S.111.860646	110°
22.	NZMS 1.S.111.821600	111°

23.	NZMS 1.S.111.798571	96°
24.	NZMS 1.S.111.784547	35°

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2) Location of River Bed Samples

Sample No.	Map Reference
RB1	NZMS 1.S.103.265937
RB2	NZMS 1.S.93.615117

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3) Location of Cliff Samples

Sample No.	Map Reference
BC1	NZMS 1.S.103.216905
BC2	NZMS 1.S.93.537084
BC3	NZMS 1.S.93.473052
BC4	NZMS 1.S.103.319966

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4) Location of Dune Samples

Sample No.	Map Reference
D1	NZMS 1.S.94.109200
D2	NZMS 1.S.94.965196
D3	NZMS 1.S.94.165188
D4	NZMS 1.S.93.864183
D5	NZMS 1.S.93.753164
D6	NZMS 1.S.93.703151
D7	NZMS 1.S.102.944724
D8	NZMS 1.S.111.906688

APPENDIX IC

Percentile Values from Cumulative Frequency Curves of Grain-Size Distributions for each Survey

1) Survey A. Carried out 7-9, 20-21 December, 1966.

Samples number consecutively from north to south.

'A' denotes a foreshore sample.

'B' denotes a backshore sample.

? 5%

Sample No.	Percentiles						
	5Ø	16Ø	25Ø	50Ø	75Ø	84Ø	95Ø
1A	-2.3	-2.6	-2.7	-2.8	-3.2	-3.4	-4.0
2A	0.7	0.5	-0.4	-0.1	-0.6	-0.9	-1.4
3A	1.2	1.1	0.9	0.6	-0.2	-0.5	-1.5
4A	0.7	0.4	0.3	-0.2	-0.7	-0.9	-1.3
5A	0.7	0.5	0.4	0.1	-0.3	-0.8	-1.7
6A	-2.7	-3.3	-3.4	-3.6	-3.8	-3.9	-4.1
7A	-3.3	-3.3	-3.3	-3.5	-3.9	-4.0	-4.2
8A	-2.3	-2.6	-2.7	-2.9	-3.1	-3.3	-3.7
9A	0.7	0.6	0.5	0.3	-0.1	-0.2	-1.1
10A	3.2	2.4	1.9	0.9	0.7	0.3	-1.0
11A	2.9	1.9	1.3	0.6	-1.3	-2.7	-3.4
12A	0.7	0.5	0.4	0.2	-0.2	-0.5	-1.7
13A	1.2	0.9	0.8	0.4	-0.2	-2.3	-3.1
14A	3.2	2.7	2.6	1.2	-0.1	-1.4	-3.0
15A	-0.8	-1.3	-1.5	-1.9	-2.6	-2.7	-3.2
16A	-1.8	-2.2	-2.3	-2.4	-2.7	-2.8	-3.2

Sample No.	Percentiles						
	5φ	16φ	25φ	50φ	75φ	84φ	95φ
17A	-1.3	-1.9	-2.1	-2.3	-2.5	-2.6	-3.0
18A	0.8	0.6	0.5	0.2	-0.1	-0.3	-1.2
19A	0.7	0.6	0.5	0.3	0.1	-0.1	-0.2
20A	1.2	0.8	0.7	0.4	0.1	-0.1	-0.3
21A	1.1	0.7	0.6	0.4	0.1	-0.1	-0.2
22A	2.5	2.0	1.9	1.6	1.3	1.0	0.7
23A	1.3	1.2	1.1	1.0	0.7	0.6	0.1
24A	-1.0	-1.8	-2.7	-3.3	-4.1	-4.8	-8.4
1B	-1.9	-2.3	-2.5	-2.6	-2.9	-3.1	-3.2
2B	0.9	0.6	0.5	0.1	-1.2	-1.5	-2.1
3B	0.5	0.1	-0.2	-0.9	-1.5	-1.6	-2.3
4B	0.8	-0.1	-0.6	-1.3	-1.6	-1.7	-2.2
5B	-1.5	-1.8	-2.2	-2.4	-2.6	-2.7	-3.1
6B	-1.3	-1.9	-2.4	-3.3	-3.8	-4.0	-4.9
7B	-2.9	-3.0	-3.1	-3.2	-3.5	-3.9	-5.2
8B	-3.3	-3.3	-3.4	-3.8	-4.3	-5.8	-7.7
9B	-2.2	-2.4	-2.5	-2.7	-3.0	-3.1	-3.3
10B	-3.3	-3.5	-3.6	-3.8	-4.1	-4.2	-6.7
11B	-3.3	-3.5	-3.7	-4.2	-5.9	-6.8	-8.0
12B	-2.6	-2.9	-3.1	-3.5	-4.0	-4.1	-6.1
13B	-3.3	-3.3	-3.3	-3.7	-4.0	-4.1	-5.6
14B	-3.25	-3.25	-3.25	-3.25	-3.75	-3.8	-4.1
15B	-3.3	-3.5	-3.6	-3.9	-5.4	-6.6	-7.9
16B	-3.3	-3.4	-3.7	-3.9	-4.0	-4.1	-6.2

Sample No.	Percentiles						
	5φ	16φ	25φ	50φ	75φ	84φ	95φ
17B	-3.25	-3.45	-3.55	-3.9	-4.2	-5.0	-7.55
18B	-3.4	-3.4	-3.4	-3.8	-4.9	-6.3	-7.8
19B	-2.9	-3.3	-3.5	-3.7	-4.05	-4.2	-7.1
20B	-2.85	-3.05	-3.2	-3.6	-4.05	-4.2	-6.7
21B	-2.8	-3.1	-3.3	-3.6	-3.95	-4.1	-4.2
22B	-3.3	-3.4	-3.6	-3.75	-4.0	-4.1	-4.2
23B	-2.8	-2.9	-3.0	-3.2	-3.6	-3.8	-4.15
24B	-2.45	-2.85	-3.1	-3.35	-4.0	-4.2	-6.8

2) Survey B. Carried out 15, 22-24 February 1967.

1A	-1.9	-2.2	-2.3	-2.6	-2.9	-3.05	-3.2
2A	0.75	0.75	0.75	0.75	0.4	0.2	-0.15
3A	0.80	0.80	0.80	0.80	0.80	0.80	0.80
4A	0.6	0.45	0.35	0.05	-0.45	-0.8	-1.2
5A	-0.2	-0.2	-0.2	-0.6	-1.05	-1.2	-1.55
6A	-2.8	-3.05	-3.2	-5.05	-6.8	-7.45	-8.25
7A	-3.25	-3.25	-3.25	-3.25	-3.25	-3.6	-4.01
8A	-2.2	-2.8	-2.85	-2.9	-3.1	-3.2	-3.9
9A	-2.5	-2.95	-3.1	-3.45	-3.9	-3.95	-4.15
10A	0.4	-2.5	-2.9	-3.1	-3.55	-3.85	-4.1
11A	-1.65	-2.7	-2.9	-3.15	-3.6	-3.85	-4.1
12A	-2.8	-2.9	-2.95	-3.1	-3.55	-3.8	-4.15
13A	-3.05	-3.4	-3.55	-3.8	-4.0	-4.05	-4.2
14A	-3.80	-3.9	-3.95	-3.1	-3.45	-3.75	-4.1

Sample No.	Percentiles						
	5φ	16φ	25φ	50φ	75φ	84φ	95φ
15A	-2.8	-2.95	-3.0	-3.2	-3.70	-3.85	-4.05
16A	-2.5	-2.8	-2.9	-3.05	-3.45	-3.8	-4.95
17A	0.6	-2.2	-2.65	-2.9	-3.1	-3.15	-3.25
18A	2.75	2.3	1.5	-0.2	-1.9	-2.5	-3.05
19A	1.2	1.15	1.0	0.8	0.2	-0.05	-1.55
20A	0.7	0.45	0.1	-2.2	-3.15	-3.5	-4.0
21A	3.15	2.5	1.8	0.7	-2.3	-2.95	-3.75
22A	1.5	-1.85	-2.9	-3.4	-3.85	-3.95	-4.1
23A	1.95	1.2	1.15	0.9	-0.15	-2.95	-3.8
24A	-2.2	-2.45	-2.65	-3.0	-3.3	-3.75	-4.05
1B	-3.3	-3.5	-3.8	-4.25	-6.3	-7.15	-8.15
2B	-0.4	-1.1	-1.2	-1.6	-3.3	-3.6	-4.0
3B	-1.25	-1.8	-1.95	-2.45	-3.05	-3.2	-3.9
4B	0.6	0.3	0.1	-0.5	-1.3	-1.5	-3.1
5B	0.1	-3.2	-3.3	-3.9	-4.1	-4.8	-7.5
6B	-2.8	-2.9	-3.0	-3.15	-3.6	-3.85	-4.1
7B	-2.85	-2.9	-2.99	-3.1	-3.5	-3.7	-4.05
8B	-3.35	-3.4	-3.5	-3.9	-4.2	-5.4	-7.7
9B	-2.8	-2.9	-3.0	-3.25	-3.8	-3.95	-4.15
10B	-3.3	-3.5	-3.6	-4.0	-4.85	-6.3	-7.95
11B	-3.25	-3.5	-3.55	-3.9	-4.15	-5.65	-7.75
12B	-3.3	-3.45	-3.6	-3.95	-4.5	-6.05	-7.85
13B	-3.3	-3.5	-3.6	-3.95	-4.9	-6.25	-7.9
14B	-3.02	-3.4	-3.5	-3.85	-4.1	-4.4	-7.2
15B	-3.3	-3.5	-3.7	-4.0	-5.35	-6.6	-8.0

Sample No.	Percentiles						
	5φ	16φ	25φ	50φ	75φ	84φ	95φ
16B	-3.2	-3.35	-3.5	-3.85	-4.02	-4.15	-6.4
17B	-2.8	-2.98	-3.05	-3.7	-5.55	-6.7	-7.98
18B	-3.3	-3.6	-3.7	-4.0	-5.75	-6.85	-8.05
19B	2.03	1.1	0.85	0.2	-0.6	-1.2	-1.6
20B	3.05	2.65	2.4	1.98	1.5	1.2	0.85
21B	2.2	1.7	1.2	0.5	-0.9	-1.4	-1.95
22B	-2.8	-2.95	-3.0	-3.3	-3.8	-3.9	-4.1
23B	-2.8	-2.98	-3.05	-3.35	-3.8	-3.98	-4.1
24B	-1.6	-2.01	-2.3	-2.8	-3.25	-3.55	-4.03

3) Survey C. Carried out 16, 18-19 April, 1967.

1A	-1.75	-1.8	-2.0	-2.2	-2.35	-2.5	-2.6
2A	-1.75	-2.15	-2.25	-2.45	-2.65	-2.7	-3.05
3A	0.65	0.35	0.05	-0.9	-1.6	-1.95	-2.5
4A	2.15	1.7	1.35	0.9	0.05	-0.7	-1.7
5A	0.75	0.7	0.65	0.35	0.1	-0.05	-0.2
6A	-3.25	-3.3	-3.35	-3.7	-3.9	-4.0	-4.15
7A	-3.3	-3.3	-3.3	-3.55	-4.0	-4.05	-6.2
8A	-3.35	-3.35	-3.35	-3.35	-3.35	-3.6	-4.0
9A	-0.1	-0.1	-0.1	-0.5	-0.95	-1.1	-1.4
10A	1.2	1.02	0.85	0.25	-2.1	-2.85	-3.15
11A	1.55	1.10	1.0	0.15	-1.6	-2.3	-2.95
12A	1.8	1.10	0.8	-2.0	-2.3	-2.5	-2.65
13A	2.5	2.2	2.15	1.7	1.3	1.0	0.05

Sample No.	Percentiles						
	5Ø	16Ø	25Ø	50Ø	75Ø	84Ø	95Ø
14A	2.15	1.75	1.65	1.2	0.9	0.8	-1.9
15A	-2.8	-2.9	-3.0	-3.2	-3.65	-3.9	-4.1
16A	-3.3	-3.4	-3.45	-3.75	-4.0	-4.05	-4.15
17A	-3.25	-3.3	-3.35	-3.7	-3.95	-4.0	-4.1
18A	-2.9	-2.95	-3.0	-3.15	-3.25	-3.5	-4.0
19A	1.25	1.2	1.15	0.9	0.55	0.35	-0.01
20A	1.5	1.25	1.2	1.0	0.85	0.55	-0.05
21A	2.6	2.1	1.7	1.25	0.9	0.80	0.15
22A	0.45	-0.15	-0.55	-1.45	-2.1	-2.75	-3.1
23A	0.15	-0.75	-1.3	-1.50	-1.65	-2.0	-2.5
24A	-1.35	-1.7	-2.05	-2.65	-3.05	-3.3	-3.8
1B	-2.2	-2.25	-2.2	-2.4	-2.6	-2.7	-3.0
2B	-2.7	-2.75	-2.9	-3.25	-3.7	-3.9	-4.1
3B	-2.75	-2.8	-2.85	-3.05	-3.3	-3.6	-4.05
4B	-2.4	-2.8	-2.85	-3.0	-3.25	-3.35	-3.95
5B	0.65	0.55	0.45	0.2	-0.2	-0.8	-1.5
6B	-2.75	-2.9	-2.95	-3.1	-3.4	-3.7	-4.0
7B	2.0	1.4	1.2	1.0	0.75	0.45	-0.05
8B	-3.3	-3.4	-3.5	-3.85	-4.15	-5.0	-7.45
9B	-2.75	-3.05	-3.2	-3.6	-3.9	-4.0	-4.15
10B	-2.75	-2.8	-2.9	-3.15	-3.5	-3.7	-4.1
11B	3.3	2.35	2.1	1.65	1.1	0.85	0.4
12B	2.8	2.2	1.75	1.3	1.0	0.9	0.75
13B	3.15	2.75	2.6	2.1	1.5	1.0	-1.15
14B	-3.15	-3.45	-3.55	-3.8	-4.1	-4.25	-6.7

Sample No.	Percentiles 5φ	16φ	25φ	50φ	75φ	84φ	95φ
15B	-3.35	-3.5	-3.65	-4.25	-6.3	-7.2	-8.2
16B	-3.3	-3.5	-3.65	-4.0	-5.5	-6.6	-7.95
17B	-3.35	-3.45	-3.6	-3.95	-4.25	-5.35	-7.6
18B	-2.95	-3.35	-3.55	-4.0	-5.6	-6.7	-8.0
19B	0.5	0.15	-0.3	-1.35	-1.9	-2.35	-2.7
20B	3.1	2.7	2.35	1.8	1.25	1.05	0.75
21B	1.8	1.10	0.8	0.4	-0.1	-0.45	-1.5
22B	-1.5	-2.3	-2.8	-3.1	-3.5	-3.75	-4.1
23B	-2.55	-2.8	-2.85	-3.15	-3.4	-3.7	-4.05
24B	-2.45	-2.75	-2.8	-3.15	-3.7	-3.95	-5.9

4) River bed samples. 1. Ashburton River. - Near coast.
2. Rangitata River. - Near coast.

Grid References for sample locations are given in Appendix IB.

RB1	-2.1	-2.1	-2.3	-3.5	-4.6	-4.9	-5.5
RB2	-3.3	-3.4	-3.45	-3.65	-3.98	-4.05	-4.15

5) Cliff Samples. North to south. Profiles 8, 9, 11, 12.

Grid References for sample locations are given in Appendix IB.

BC1	2.3	-1.7	-2.8	-3.4	-3.9	-4.0	-6.7
BC2	-1.8	-2.6	-2.8	-3.3	-3.75	-3.95	-4.1
BC3	-2.9	-3.15	-3.35	-3.8	-4.20	-5.75	-7.6
BC4	-2.8	-2.9	-2.95	-3.2	-4.15	-5.55	-7.5

6) Dune Samples. Samples number consecutively from north to south, save No. 8, which was taken from profile 19.

Grid References for sample locations are given in Appendix IB.

Sample No.	Percentiles						
	5φ	16φ	25φ	50φ	75φ	84φ	95φ
D1	2.3	1.6	1.5	1.20	0.9	0.8	-0.7
D2	2.7	1.8	1.5	1.10	0.8	0.5	-0.7
D3	2.3	1.7	1.5	1.20	0.9	0.8	0.7
D4	2.9	2.0	1.7	1.10	0.8	0.6	0.1
D5	2.6	1.9	1.7	1.4	1.0	0.8	-0.4
D6	2.4	1.9	1.7	1.4	1.1	0.9	-0.3
D7	3.1	2.6	2.4	1.8	1.4	1.2	0.4
D8	2.9	2.4	2.2	1.5	1.0	0.9	-0.5

7) Samples from old beach ridges. -From gravel pit at Birdlings Flat.

1. From 3 feet below surface.
2. From 12 feet below surface.

ESC1	-2.3	-2.5	-2.6	-2.8	-3.1	-3.2	-4.3
ESC2	4.1	-1.3	-1.7	-2.2	-2.6	-2.95	-3.75

8) Supplementary Samples from profiles. Taken from points between the reference zone samples and backshore samples on the profiles indicated.

1X	-2.2	-2.7	-2.8	-2.95	-3.2	-3.4	-4.0
1C	-4.2	-4.2	-4.2	-4.2	-5.7	-6.8	-8.0
6C	2.8	2.0	1.8	1.3	1.05	0.95	0.75

Sample No.	Percentiles						
	5φ	16φ	25φ	50φ	75φ	84φ	95φ
6D	-2.85	3.1	-3.3	-3.8	-4.75	-6.15	-7.80
9C	-2.80	-3.0	-3.25	-3.65	-4.02	-4.15	-7.05
9D	-2.80	-2.95	-3.0	-3.40	-3.85	-3.95	-4.15
12C	1.05	0.15	-0.65	-1.50	-2.10	-2.5	-3.05
12D	-3.25	-3.55	-3.60	-4.0	-5.4	-6.6	-8.0
20C	2.3	1.10	0.85	0.4	0.15	-0.05	-0.35
20D	2.15	0.95	0.70	-0.65	-1.75	-2.20	-2.90

APPENDIX ID

Grain-Size Parameters calculated from percentile values given in Appendix IC

1) Survey A.

Sample No.	$M_z\phi$	σ_I	Sk_G	K_G
1A	-2.93	0.45	0.83	1.39
2A	-0.16	0.66	0.36	0.86
3A	0.4	0.79	0.73	0.96
4A	-0.23	0.62	0.24	0.81
5A	-0.06	0.68	0.78	1.40
6A	-3.60	0.36	0.02	1.43
7A	-3.60	0.31	0.63	0.61
8A	-2.93	0.38	0.42	1.43
9A	0.23	0.47	0.96	1.22
10A	1.20	1.16	0.04	1.43
11A	-0.06	2.10	0.42	0.99
12A	0.06	0.61	1.09	1.63
13A	-0.33	1.45	0.78	1.76
14A	0.83	1.96	0.50	1.96
15A	-1.96	0.71	0.29	0.89
16A	-2.46	0.36	0.57	1.43
17A	-2.26	0.43	0.12	1.74
18A	0.16	0.52	0.75	1.36
19A	0.26	0.31	0.19	0.92
20A	0.36	0.45	0.13	1.02

Sample No.	$M_z\phi$	σ_I	Sk_G	K_G
21A	0.33	0.39	0.14	1.06
22A	1.53	0.52	0.25	1.22
23A	0.93	0.33	0.83	1.22
24A	-3.30	1.87	0.78	2.16
1B	-2.66	0.39	0.14	1.33
2B	-0.26	0.97	0.63	0.72
3B	-0.80	0.84	0.11	0.88
4B	-1.03	0.85	-0.29	1.22
5B	-2.30	0.46	0.00	1.63
6B	-3.06	1.07	0.00	1.05
7B	-3.36	0.57	1.36	2.35
8B	-4.30	1.29	1.06	1.29
9B	-2.73	0.34	0.25	0.90
10B	-3.83	0.69	2.21	2.78
11B	-4.83	1.53	0.77	0.87
12B	-3.50	0.83	1.07	1.59
13B	-3.70	0.54	1.26	1.34
14B	-3.43	0.26	1.27	0.69
15B	-4.66	1.47	0.95	1.04
16B	-3.80	0.61	1.57	3.96
17B	-4.11	1.03	1.38	2.71
18B	-4.50	1.39	1.02	1.20
19B	-3.73	0.86	1.97	3.12
20B	-3.61	0.87	1.41	1.85
21B	-3.60	0.46	-0.02	0.88

Sample No.	$M_z\phi$	σ_I	Sk_G	K_G
22B	-3.75	0.31	0.07	0.92
23B	-3.30	0.42	0.56	0.92
24B	-3.46	0.99	1.38	1.98
2) <u>Survey B</u>.				
1A	-2.61	0.40	0.07	0.88
2A	0.56	0.27	1.31	1.05
3A	0.80	0.00	0.00	0.00
4A	-0.10	0.58	0.53	0.92
5A	-0.66	0.45	0.47	0.65
6A	-5.18	1.92	0.22	0.62
7A	-3.36	0.20	1.58	0.00
8A	-2.96	0.35	1.21	2.78
9A	-3.45	0.50	0.02	0.84
10A	-3.15	1.01	-0.12	2.83
11A	-3.23	0.65	0.10	1.43
12A	-3.26	0.42	0.74	0.92
13A	-3.75	0.33	-0.15	1.04
14A	-3.58	0.00	-3.16	-0.24
15A	-3.33	0.41	0.51	0.73
16A	-3.21	0.62	1.10	1.82
17A	-2.75	0.82	-0.59	3.50
18A	-0.13	2.07	0.02	0.69
19A	0.63	0.71	1.18	1.40
20A	-1.75	1.69	-0.22	0.59
21A	0.08	2.40	0.38	0.68
22A	-3.06	1.37	-0.57	2.41

Sample No.	$M_z\phi$	σ_I	Sk_G	K_G
23A	-0.28	1.90	0.84	1.81
24A	-3.06	0.60	0.25	1.16
1B	-4.96	1.64	0.73	0.79
2B	-2.10	1.17	0.54	0.70
3B	-2.48	0.75	0.33	0.98
4B	-0.56	1.01	0.70	1.08
5B	-3.96	1.55	0.87	3.89
6B	-3.30	0.43	0.59	0.88
7B	-3.23	0.38	0.76	0.96
8B	-4.23	1.15	1.19	2.54
9B	-3.36	0.46	0.42	0.69
10B	-4.60	1.40	0.96	1.52
11B	-4.35	1.21	1.15	3.07
12B	-4.48	1.33	1.01	2.07
13B	-4.56	1.38	0.99	1.45
14B	-3.88	0.88	1.75	2.85
15B	-4.70	1.48	0.91	1.16
16B	-3.78	0.68	1.57	2.52
17B	-4.46	1.71	0.80	0.84
18B	-4.81	1.53	0.91	0.94
19B	0.03	1.12	0.19	1.02
20B	1.94	0.69	0.17	1.00
21B	0.26	1.40	0.29	0.80
22B	-3.33	0.43	0.35	0.66
23B	-3.43	0.44	0.26	0.71
24B	-2.78	0.75	0.14	1.04

Sample No.	$M_z\phi$	σ_I	Sk_G	K_G
3) <u>Survey C</u>.				
1A	-2.16	0.30	-0.02	0.99
2A	-2.43	0.33	0.23	1.33
3A	-0.83	1.05	0.08	0.78
4A	0.63	1.18	0.55	1.21
5A	0.33	0.33	0.21	0.70
6A	-3.66	0.31	0.03	0.67
7A	-3.63	0.62	2.01	1.69
8A	-3.43	0.16	1.80	0.00
9A	-0.56	0.44	0.44	0.62
10A	-0.52	1.62	0.62	0.60
11A	-0.35	1.53	0.50	0.70
12A	-1.13	1.57	-0.69	0.58
13A	1.63	0.67	0.65	1.18
14A	1.25	0.85	1.60	2.21
15A	- 3.33	0.44	0.49	0.81
16A	-3.73	0.29	0.00	0.63
17A	-3.66	0.30	-0.02	0.58
18A	-3.20	0.30	0.86	1.80
19A	0.81	0.40	0.58	0.86
20A	0.93	0.40	0.74	1.81
21A	1.38	0.69	0.04	1.25
22A	-1.45	1.18	0.03	0.93
23A	-1.41	0.71	-0.02	3.10
24A	-2.55	0.77	0.03	1.00
1B	-2.45	0.23	0.75	0.81

Sample No.	$M_z \phi$	σ_I	Sk_G	K_G
2B	-3.30	0.49	0.25	0.71
3B	-3.15	0.39	0.73	1.18
4B	-3.05	0.37	0.79	1.58
5B	-0.01	0.66	0.79	1.35
6B	-3.23	0.38	0.65	1.13
7B	0.95	0.54	0.35	1.86
8B	-4.08	1.02	1.35	2.61
9B	-3.55	0.44	-0.10	0.81
10B	-3.21	0.42	0.53	0.92
11B	1.61	0.81	0.11	1.18
12B	1.46	0.63	-0.36	1.12
13B	1.95	1.08	0.99	1.60
14B	-3.83	0.73	1.91	2.64
15B	-4.98	1.65	0.74	0.75
16B	-4.70	1.47	0.90	1.03
17B	-4.25	1.11	1.18	2.67
18B	-4.68	1.60	0.79	1.00
19B	-1.18	1.10	-0.10	0.81
20B	1.85	0.76	0.00	0.87
21B	0.35	0.88	0.46	1.50
22B	-3.05	0.75	-0.04	1.52
23B	-3.21	0.45	0.40	1.11
24B	-3.28	0.82	1.27	1.57

4) <u>River Bed Samples</u>

Sample No.	$M_z \phi$	σ_I	Sk_G	K_G
RB1	-3.50	1.21	0.19	0.60
RB2	-3.70	0.29	0.28	0.65

5) Cliff Samples

Sample No.	$M_z\phi$	σ_I	Sk_G	K_G
BC1	-3.03	1.93	0.21	3.35
BC2	-3.28	0.68	-0.11	0.99
BC3	-4.23	1.36	0.91	2.26
BC4	-3.88	1.37	1.16	1.60
6) Dune Samples				
D1	1.20	0.65	1.07	2.04
D2	1.13	0.84	0.45	1.99
D3	1.23	0.46	-0.18	1.09
D4	1.23	0.77	-0.10	1.27
D5	1.36	0.72	0.69	1.75
D6	1.40	0.65	0.72	1.84
D7	1.86	0.75	0.23	1.10
D8	1.60	0.89	0.45	1.16
7) Samples from old beach ridges				
ESC1	-2.83	0.47	1.10	1.63
ESC2	-2.15	1.60	-0.10	3.57
8) Supplementary Samples for profiles				
1X	-3.01	0.44	0.65	1.84
1C	-5.06	1.22	1.23	1.03
6C	1.41	0.57	-0.30	1.12
6D	-4.35	1.51	0.84	1.39
9C	-3.60	0.93	1.49	2.26
9D	-3.43	0.45	0.20	0.65
12C	-1.28	1.28	-0.14	1.15

Sample No.	$M_z \phi$	σ_I	Sk_G	K_G
12D	-4.71	1.48	0.92	1.08
20C	0.48	0.68	-0.19	1.55
20D	-0.63	1.55	0.04	0.84

APPENDIX II

Sphericity measurements from pebble samples

1) Beach Samples

Sample 2A. Survey C

Sample N = 25 pebbles.

Axes. (cm.)

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
1.7	0.7	0.3	0.18	0.71	0.42
2.3	1.4	0.6	0.26	0.53	0.46
1.9	1.7	1.0	0.53	0.22	0.68
1.5	1.0	0.5	0.33	0.50	0.54
1.6	1.4	0.7	0.44	0.22	0.59
1.7	1.3	0.8	0.47	0.44	0.66
1.5	1.2	0.6	0.40	0.33	0.58
2.1	1.1	0.7	0.33	0.78	0.62
1.8	1.0	0.6	0.33	0.66	0.57
0.8	0.6	0.5	0.63	0.66	0.82
1.6	1.2	0.5	0.31	0.36	0.49
1.6	1.2	0.5	0.31	0.36	0.49
1.5	1.1	0.6	0.40	0.36	0.59
1.6	0.8	0.5	0.63	0.73	0.82
1.3	1.1	0.5	0.38	0.33	0.57
1.2	0.8	0.6	0.50	0.67	0.73
1.0	0.7	0.6	0.60	0.75	0.81
1.8	0.9	0.7	0.39	0.82	0.68

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
1.2	0.9	0.6	0.50	0.50	0.69
1.6	1.0	0.4	0.25	0.50	0.45
1.3	1.0	0.5	0.38	0.38	0.58
1.2	0.7	0.7	0.58	1.00	0.84
1.1	0.9	0.5	0.45	0.33	0.63
1.1	1.0	0.4	0.36	0.14	0.52
1.0	0.9	0.5	0.50	0.20	0.65

Sample 8A. Survey C

Axes. (cm.)

4.5	2.1	1.3	0.29	0.75	0.56
3.1	2.3	1.5	0.48	0.50	0.64
3.8	2.6	1.1	0.29	0.44	0.48
3.5	1.8	1.2	0.34	0.77	0.62
2.7	1.6	1.2	0.44	0.73	0.69
4.0	2.1	1.6	0.40	0.79	0.66
2.7	2.4	1.1	0.40	0.19	0.56
2.8	1.6	1.5	0.53	0.92	0.78
2.0	1.7	1.0	0.50	0.30	0.67
3.5	2.9	1.4	0.40	0.29	0.58
3.6	2.2	1.2	0.33	0.58	0.55
3.0	2.2	1.5	0.50	0.53	0.70
1.8	1.6	1.0	0.56	0.25	0.70
3.4	1.9	0.9	0.26	0.60	0.48
3.6	2.1	1.4	0.39	0.23	0.55
3.3	2.3	1.3	0.39	0.50	0.61
3.3	2.4	1.2	0.36	0.43	0.54

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
3.1	2.7	1.0	0.32	0.19	0.46
3.6	1.6	1.3	0.36	0.87	0.66
2.4	1.8	0.5	0.21	0.32	0.41
2.1	1.9	1.3	0.62	0.25	0.74
2.8	2.2	1.0	0.36	0.33	0.53
2.7	1.7	1.2	0.44	0.66	0.67
2.8	2.6	0.8	0.28	0.10	0.44
2.3	2.0	0.8	0.35	0.20	0.52

<u>Sample 15A. Survey C</u>

<u>Axes (cm.)</u>

1.9	1.6	1.1	0.59	0.37	0.74
2.8	1.9	0.9	0.32	0.47	0.51
3.2	2.4	1.3	0.41	0.42	0.60
4.0	2.0	1.0	0.25	0.66	0.50
4.4	3.9	1.6	0.36	0.18	0.52
3.7	2.6	0.9	0.24	0.39	0.43
2.7	1.9	0.9	0.33	0.44	0.53
2.8	1.8	1.0	0.36	0.55	0.58
4.6	2.5	0.8	0.17	0.55	0.37
3.5	2.8	1.4	0.40	0.33	0.58
4.0	2.4	1.5	0.37	0.64	0.61
4.0	3.1	1.2	0.30	0.32	0.48
3.1	1.6	1.2	0.39	0.79	0.67
2.7	2.3	0.9	0.33	0.22	0.49
4.4	2.5	1.4	0.32	0.63	0.56
3.1	2.2	1.0	0.32	0.43	0.51
2.8	1.7	0.9	0.32	0.58	0.54

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
2.3	1.7	1.1	0.49	0.50	0.68
3.2	3.0	0.8	0.25	0.14	0.40
4.0	2.2	1.0	0.25	0.60	0.48
2.8	2.0	1.1	0.39	0.47	0.59
2.8	2.1	1.2	0.43	0.44	0.63
3.4	2.7	1.0	0.29	0.29	0.47
3.8	2.4	1.2	0.32	0.54	0.53
3.4	2.5	1.4	0.41	0.45	0.61

Sample 18A. Survey C.

Axes (cm.)

5.1	4.6	1.1	0.22	0.13	0.36
5.0	3.6	2.0	0.40	0.47	0.61
2.6	1.8	0.7	0.27	0.42	0.44
2.6	1.5	0.8	0.31	0.61	0.54
2.4	1.5	1.1	0.46	0.69	0.69
1.7	1.5	0.7	0.41	0.20	0.56
2.6	2.1	0.8	0.31	0.28	0.48
3.3	1.5	0.9	0.27	0.75	0.55
5.1	2.1	1.3	0.25	0.79	0.56
2.0	1.6	0.5	0.25	0.27	0.42
2.4	1.5	1.0	0.42	0.64	0.64
2.0	1.4	0.7	0.35	0.46	0.55
2.7	1.6	0.8	0.30	0.59	0.53
2.7	2.1	0.6	0.22	0.29	0.38
4.5	2.9	1.1	0.24	0.47	0.43
3.6	2.2	0.8	0.22	0.50	0.40
5.2	3.2	0.9	0.17	0.47	0.38

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
2.2	1.7	0.8	0.36	0.36	0.54
2.4	1.5	0.6	0.25	0.50	0.45
4.4	3.6	1.0	0.23	0.24	0.40
3.8	1.9	0.7	0.18	0.61	0.39
3.8	1.7	0.8	0.21	0.70	0.46
1.6	1.4	0.6	0.38	0.20	0.55
3.8	2.1	0.8	0.21	0.57	0.41
4.6	2.2	0.8	0.17	0.63	0.39

2) <u>River Bed Sample. RB2</u>

<u>Axes (cm.)</u>

5.5	3.9	2.5	0.4545	0.5333	0.64
5.4	3.8	3.1	0.574	0.6956	0.78
3.7	3.1	1.7	0.4594	0.3000	0.63
4.6	3.1	1.4	0.3043	0.4687	0.50
3.9	2.5	1.6	0.4102	0.6086	0.63
4.2	3.9	2.5	0.5952	0.1764	0.73
6.6	4.0	3.4	0.5151	0.8125	0.75
3.6	2.7	1.2	0.333	0.3750	0.53
3.3	2.2	1.8	0.5454	0.7333	0.77
6.0	3.4	2.5	0.4166	0.7428	0.66
3.3	3.2	3.2	0.9696	0.1000	0.98
4.8	1.3	1.3	0.2708	1.0000	0.65
4.0	2.8	2.1	0.525	0.6315	0.74
3.4	2.9	2.0	0.5882	0.3571	0.75
3.6	2.4	2.0	0.5555	0.7500	0.77
5.5	3.3	1.7	0.309	0.6052	0.54
6.5	3.9	3.4	0.523	0.8387	0.76

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
5.6	4.6	1.2	0.2142	0.2272	0.35
3.8	2.2	1.0	0.2631	0.5714	0.40
4.2	3.2	2.3	0.5476	0.5263	0.73
2.6	2.2	1.5	0.5769	0.3636	0.72
2.5	1.7	1.6	0.6400	0.8888	0.85
3.0	2.6	1.7	0.5666	0.3076	0.71
3.1	2.5	1.5	0.4838	0.3750	0.68
4.0	3.2	1.8	0.4500	0.5454	0.66

3) Cliff Zone Samples. BC2

Axes (cm.)

4.0	2.9	2.3	0.575	0.647	0.77
5.0	3.1	2.7	0.540	0.5757	0.75
5.2	3.4	2.8	0.538	0.7500	0.76
3.2	2.2	1.6	0.5000	0.6250	0.72
4.0	2.7	1.1	0.2750	0.4482	0.47
2.4	2.2	1.8	0.7500	0.3333	0.84
3.2	2.1	1.9	0.5937	0.8461	0.82
4.4	3.5	1.4	0.3181	0.3000	0.47
2.2	1.6	1.3	0.8125	0.6666	0.93
2.2	1.5	0.7	0.3181	0.4666	0.50
5.5	3.4	2.9	0.5272	0.5833	0.72
2.2	2.1	1.5	0.6818	0.1428	0.78
2.3	1.8	1.2	0.5217	0.4545	0.68
2.0	1.4	1.0	0.5000	0.6000	0.71
2.1	1.7	1.2	0.5714	0.4444	0.73
2.7	1.6	1.2	0.4444	0.7333	0.70

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
2.5	2.1	1.3	0.5200	0.3333	0.67
1.9	1.5	1.0	0.5263	0.4444	0.69
3.1	2.1	1.1	0.3548	0.5000	0.56
2.4	1.8	1.4	0.5833	0.6000	0.78
4.0	2.8	1.4	0.3500	0.4615	0.55
3.1	1.6	1.1	0.3548	0.7500	0.62
2.2	1.7	0.9	0.4090	0.3846	0.59
2.3	2.0	0.9	0.3913	0.2142	0.56
3.5	3.0	1.5	0.4285	0.2500	0.58
Cliff Zone Sample. BC3					
6.5	4.4	3.0	0.4615	0.6	0.67
6.5	3.4	2.8	0.4307	0.8378	0.72
2.5	1.6	1.1	0.44	0.6923	0.68
5.8	4.1	4.1	0.7068	1.0000	0.88
6.5	5.3	2.8	0.4307	0.3243	0.63
6.6	4.8	2.8	0.4242	0.4736	0.63
2.4	1.9	1.4	0.5833	0.5000	0.75
5.6	4.3	2.6	0.4642	0.4333	0.64
6.0	5.1	2.5	0.4166	0.2571	0.57
4.5	3.0	2.0	0.4444	0.6000	0.66
5.6	4.3	3.5	0.625	0.619	0.76
5.2	4.0	2.0	0.3846	0.375	0.57
2.7	2.5	1.9	0.7037	0.250	0.82
6.6	3.1	2.4	0.3636	0.8333	0.68
2.7	1.9	1.3	0.4814	0.5714	0.69

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
1.9	1.8	1.2	0.6315	0.1428	0.75
2.6	1.6	1.5	0.5769	0.9090	0.83
5.1	2.7	1.5	0.2941	0.6666	0.54
3.4	2.9	1.7	0.5000	0.2941	0.67
6.6	3.9	2.5	0.3787	0.6585	0.61
2.0	1.9	1.1	0.55	0.1111	0.68
3.2	2.4	1.0	0.3125	0.3636	0.49
2.9	2.4	1.9	0.6551	0.5000	0.80
4.5	3.6	1.6	0.3555	0.3103	0.52
3.4	1.9	1.4	0.4117	0.7500	0.67

Cliff Zone Sample. BC4

Axes (cm.)

9.0	5.4	3.0	0.3333	0.6	0.56
5.5	3.4	2.4	0.4363	0.6774	0.68
3.2	3.2	1.7	0.5312	0.0000	0.65
5.6	3.1	2.4	0.4285	0.7812	0.69
3.5	2.7	1.7	0.4857	0.4444	0.67
3.0	2.7	1.3	0.4333	0.1764	0.59
2.9	1.8	1.6	0.5517	0.8461	0.79
3.2	2.4	0.9	0.2812	0.6153	0.52
3.1	2.1	1.7	0.5483	0.7142	0.75
2.3	1.6	1.4	0.6086	0.7777	0.81
1.9	1.7	0.9	0.4736	0.2000	0.63
3.1	1.9	1.2	0.3870	0.6315	0.62
2.1	1.7	1.3	0.619	0.5000	0.78
1.8	1.6	1.1	0.6111	0.2857	0.74
1.8	1.5	1.1	0.6111	0.4285	0.76

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
2.1	1.8	1.0	0.4761	0.2727	0.63
2.4	1.4	1.1	0.4583	0.7692	0.71
2.0	1.8	1.1	0.55	0.2222	0.69
1.6	1.5	1.0	0.625	0.1666	0.75
1.7	1.3	1.1	0.647	0.6666	0.82
1.6	1.1	0.7	0.4375	0.5	0.63
1.5	1.0	0.9	0.6000	0.8333	0.82
2.2	1.3	0.9	0.409	0.6923	0.65
1.8	1.0	0.7	0.3888	0.7272	0.65
1.2	0.9	0.4	0.3333	0.375	0.52

4) Beach Quartz. (Birdlings Flat)

Axes (cm.)

2.7	2.5	1.4	0.51	0.154	0.64
4.7	2.5	1.8	0.38	0.759	0.65
4.2	2.7	2.2	0.52	0.75	0.74
3.5	3.3	1.3	0.37	0.091	0.52
2.9	2.0	1.2	0.41	0.562	0.62
3.1	1.6	1.3	0.42	0.822	0.69
4.4	3.3	1.5	0.34	0.379	0.50
3.0	2.0	1.2	0.40	0.555	0.62
2.2	1.9	1.2	0.55	0.300	0.70
1.8	1.5	0.9	0.50	0.333	0.68
3.1	2.6	1.5	0.48	0.313	0.66
2.2	1.9	1.1	0.50	0.300	0.66
2.2	1.5	1.0	0.45	0.583	0.67
3.1	2.9	1.7	0.55	0.143	0.68
2.4	1.7	1.5	0.63	0.777	0.83

A	B	C	$\frac{C}{A}$	$\frac{A-B}{A-C}$	Ψ
2.2	1.7	1.2	0.54	0.500	0.73
1.3	1.0	0.7	0.54	0.500	0.73
2.6	1.8	1.3	0.50	0.615	0.72
2.8	1.5	0.9	0.32	0.684	0.56
2.2	1.6	0.9	0.41	0.462	0.61
1.7	1.3	0.6	0.35	0.364	0.53
2.1	2.0	1.5	0.71	0.167	0.81
2.5	1.2	1.0	0.40	0.867	0.69
2.7	1.6	1.1	0.41	0.688	0.65
1.9	1.3	0.8	0.42	0.545	0.63

APPENDIX IIIA

Powers, (1953), Scale of Roundness and Folk (1965 p.11) logarithmic scale of Roundness

Grade Terms	Powers. Class Intervals	Folk. ρ (rho)	Powers. Geometric Means
Very Angular	0.12 to 0.17	0.0 - 1.0	0.14
Angular	0.17 to 0.25	1.0 - 2.0	0.21
Subangular	0.25 to 0.35	2.0 - 3.0	0.30
Subrounded	0.35 to 0.49	3.0 - 4.0	0.41
Rounded	0.49 to 0.70	4.0 - 5.0	0.59
Well Rounded	0.70 to 1.00	5.0 - 6.0	0.84

Roundness Sorting. Folk (1965, p.11).

Grade Terms	Class Intervals
Very Good Roundness Sorting	< 0.60
Good	0.60 to 0.80
Moderate	0.80 to 1.00
Poor	1.00 to 1.20
Very Poor	> 1.20
Extremely Poor	

APPENDIX IIIB

Roundness Values, Roundness Sorting and Angularity of Samples

1) Beach Samples. Survey C.

Sample No.	$M_z\phi$	Mean ρ	σ_ρ	% Angular	Description
1A	-2.61	4.20	2.14	0.0	R. E.
2A	0.50	2.90	2.98	52.0	S. E.
4A	-0.10	3.55	4.76	38.0	S. E.
5A	-0.66	4.25	1.86	0.0	R. V.
6A	-5.18	4.95	3.21	0.0	R. E.
7A	-3.36	4.90	2.73	2.0	R. E.
8A	-2.96	4.90	2.59	0.0	R. E.
9A	-3.45	5.10	2.45	0.0	W. E.
10A	-3.15	5.70	1.57	0.0	W. V.
11A	-3.23	5.65	1.42	0.0	W. V.
12A	-3.26	5.70	1.57	0.0	W. V.
13A	-3.75	5.45	2.55	0.0	W. E.
14A	-3.58	4.90	3.33	2.0	R. E.
15A	-3.33	5.05	4.17	2.0	W. E.
16A	-3.21	4.90	2.66	0.0	R. E.
17A	-2.75	4.75	1.98	0.0	R. V.
18A	-0.13	3.75	5.36	34.0	S. E.
19A	0.63	3.85	3.73	26.0	S. E.
20A	-1.75	4.30	3.07	12.0	R. E.
21A	0.08	3.90	2.60	14.0	S. E.
22A	-3.06	4.30	3.61	18.0	R. E.
23A	-0.28	3.89	2.65	16.0	S. E.

Sample No.	$M_z\phi$	Mean ρ	$\sigma\rho$	% Angular	Description
24A	-3.06	4.35	1.80	2.0	R. V.

2) Roundness of River Sample RB2

RB2	-3.70	3.85	2.69	10.0	S. E.

3) Roundness of Cliff Samples

BC2	-3.28	3.35	1.85	26.0	S. V.
BC3	-4.23	3.50	1.59	24.0	S. V.
BC4	-3.88	3.60	2.43	22.0	S. E.

4) Roundness of Beach Quartz. (Birdlings Flat)

BQ1	-	4.15	2.68	12.0	R. E.

APPENDIX IVA

Synoptic Wave Data Collected at Timaru Harbour

February 1 to May 8, 1967

Date	Wave H. Feet	Wave T. Seconds.	Direction
February 1967	3.0	10.0	E.
2	5.0	30.0	S. E.
3	7.0	6.0	S.
6	5.0	10.0	E.
7	2.5	12.0	E.
8	4.0	10.0	E.
9	4.0	11.0	S. E.
10	4.0	6.0	E.
11	2.5	8.0	N. E.
12	3.0	10.0	E.
13	4.0	10.0	S. E.
14	4.0	5.0	E.
15	4.5	8.0	E.
16	2.0	8.0	E.
17	2.0	9.0	E.
18	1.5	15.0	E.
19	6.0	6.0	S. E.
20	3.0	14.0	E.
21	3.0	10.0	S.
22	3.0	10.0	S. E.
23	2.5	15.0	E.
24	3.0	16.0	E.

Date	Wave H. Feet.	Wave T. Seconds.	Direction
25	2.5	15.0	E.
26	2.0	20.0	E.
27	3.0	12.0	E.
28	5.0	7.0	S.
March 1967	5.0	7.0	S. E.
2	4.0	10.0	S.
3	3.0	20.0	S. E.
4	3.0	15.0	E.
5	7.0	12.0	E.
6	5.0	6.0	S. E.
7	6.0	7.0	E.
8	7.0	7.0	S. E.
9	7.0	7.0	E.
10	5.0	9.0	S. E.
11	5.0	11.0	E.
12	3.0	15.0	S. E.
13	4.0	18.0	S. E.
14	3.0	20.0	S. E.
15	4.0	10.0	S. E.
16	4.5	10.0	S. E.
17	2.5	20.0	S. E.
18	3.0	20.0	S. E.
19	4.0	15.0	S. E.
20	3.0	12.0	S. E.
21	5.0	10.0	S. E.
22	5.5	6.0	E.

Date	Wave H. Feet.	Wave T. Seconds	Direction
23.3.67	5.0	10.0	E.
24	6.0	10.0	E.
25	4.0	12.0	S. E.
27	4.0	10.0	S. E.
28	5.0	12.0	S. E.
29	5.0	15.0	E.
30	4.5	15.0	S. E.
31	2.5	15.0	S. E.
April 1967	2.0	16.0	S. E.
3	5.0	8.0	S.
4	6.0	12.0	S.
5	4.0	7.0	N. E.
6	3.5	7.0	S. E.
7	7.5	7.0	S.
10	5.0	12.0	S. E.
11	3.5	12.0	S. E.
12	3.5	15.0	S. E.
13	5.0	15.0	S. E.
14	12.0	10.0	S.
17	5.0	14.0	S. E.
18	4.0	20.0	S. E.
19	8.0	14.0	S. E.
20	6.0	12.0	S. E.
21	4.0	10.0	S. E.
24	2.0	-	N. E.
26	4.0	-	N. E.

Date	Wave H. Feet.	Wave T. Seconds.	Direction
27.4.67	8.0	-	S.
28	5.0	-	S. E.
May 1967	6.0	-	S.
2	5.0	-	N. E.
3	3.0	-	S. E.
4	4.0	-	E.
5	3.0	-	S. E.
8	7.0	10.0	S. E.

APPENDIX IVB

Wave Records From Profile Surveys

Date	Profile No.	Breaker H. Feet.	Wave T. Seconds.	Wave $\frac{H}{L}$	Direction
December 1967	1	4.0	8.5	0.011	S.
7	2	3.0	8.5	0.008	S.
7	3	2.5	7.5	0.0086	S.
7	4	3.0	10.0	0.0058	S.
7	5	2.0	8.0	0.006	S.
8	6	3.0	8.0	0.0092	E.
8	7	3.0	7.5	0.01	E.
8	8	3.0	8.0	0.0092	E.
8	9	2.5	7.5	0.0086	E.
8	10	2.5	8.5	0.0067	E.
8	11	2.5	8.0	0.0076	E.
8	12	2.0	8.0	0.006	E.
8	13	2.0	7.0	0.008	E.
9	14	3.0	8.0	0.0092	E.
20	15	2.5	5.0	0.02	E.
20	16	2.0	6.0	0.011	E.
20	17	3.0	8.0	0.0092	E.
20	18	2.0	6.0	0.011	E.
20	19	2.0	6.0	0.011	E.
20	20	2.0	6.5	0.0092	E.
20	21	2.0	6.5	0.0092	E.
21	22	3.5	7.0	0.0139	E.
21	23	3.0	6.5	0.0138	E.

Date	Profile No.	Breaker H. Feet.	Wave T. Seconds.	Wave $\frac{H}{L}$	Direction
21.12.1966	24	3.0	6.5	0.0138	E.
February 1967	1	5.0	11.0	0.008	S.
15	2	4.0	12.0	0.0054	S.
15	3	3.5	12.0	0.0047	S.
15	4	4.0	12.0	0.0054	S.
15	5	5.0	11.0	0.0081	S.
22	6	3.5	7.3	0.0128	E.
22	7	3.5	8.5	0.0094	E.
22	8	3.5	7.5	0.012	E.
23	9	3.0	9.5	0.0064	E.
23	10	3.0	8.3	0.0085	E.
23	11	3.0	8.5	0.0081	E.
23	12	2.5	10.0	0.0048	E.
23	13	3.0	10.0	0.0058	E.
23	14	3.5	10.0	0.0068	E.
23	15	3.5	10.0	0.0068	E.
23	16	3.0	10.0	0.0058	E.
23	17	3.0	10.0	0.0058	E.
23	18	3.0	10.0	0.0058	E.
24	19	1.5	6.7	0.0065	E.
24	20	1.5	6.7	0.0065	E.
24	21	2.0	7.5	0.0069	E.
24	22	2.0	7.5	0.0069	E.
24	23	2.0	8.3	0.0056	E.
24	24	0.5	8.0	0.0015	E.

Date	Profile No.	Breaker H. Feet.	Wave T. Seconds.	Wave $\frac{H}{L}$	Direction
March 1967	1	5.0	10.0	0.00976	S.
27	2	4.0	10.0	0.0078	S.
27	3	4.0	10.0	0.0078	S.
27	4	5.0	10.0	0.00976	S.
27	5	3.5	10.0	0.00683	S.
April 1967	1	9.0	11.0	0.0175	S.
16	2	11.0	11.0	0.0177	S.
16	3	10.0	11.0	0.0161	S.
16	4	10.0	11.0	0.0161	S.
16	5	10.0	11.0	0.0161	S.
18	6	2.5	10.0	0.0048	S.
18	7	3.0	10.0	0.0058	S.
18	8	3.5	10.0	0.0069	S.
18	9	2.5	10.0	0.0048	S
18	10	3.0	10.0	0.0058	S.
18	11	3.0	10.0	0.0058	S.
18	12	3.5	10.0	0.0069	S.
19	13	10.0	10.0	0.0195	S.
19	14	10.0	10.0	0.0195	S.
19	15	9.0	10.0	0.0175	S.
19	16	9.0	10.0	0.0175	S.
19	17	10.0	10.0	0.0195	S.
19	18	10.0	10.0	0.0195	S.
19	19	8.0	10.0	0.0156	S.
19	20	6.0	10.0	0.0117	S.
	21	6.0	10.0	0.0117	

Date	Profile No.	Breaker H. Feet.	Wave T. Seconds	Wave $\frac{H}{L}$	Direction
19.4.67	22	7.0	10.0	0.0136	S.
19	23	6.0	10.0	0.0136	S.
19	24	2.0	10.0	0.0039	S.
June 1967	1	3.0	6.0	0.0163	S. E.
26	2	3.0	6.0	0.0163	S. E.
26	3	3.0	6.0	0.0163	S. E.
26	4	3.0	6.0	0.0163	S. E.
26	5	3.0	6.0	0.0163	S. E.
July 1967	6	3.0	8.0	0.0092	S. E.
2	7	3.0	8.0	0.0092	S. E.
2	8	3.0	8.0	0.0092	S. E.
2	9	3.0	8.0	0.0092	S. E.
2	10	3.0	8.0	0.0092	S. E.
2	11	3.0	8.0	0.0092	S. E.
2	12	3.0	8.0	0.0092	S. E.
June 1967	13	3.0	8.0	0.0092	S. E.
27	14	3.0	8.0	0.0092	S. E.
27	15	4.0	8.0	0.012	S. E.
27	16	3.0	8.0	0.0092	S. E.
27	17	4.0	8.0	0.012	S. E.
27	18	3.0	8.0	0.0092	S. E.
27	19	2.5	8.0	0.0076	S. E.
27	20	2.5	10.0	0.0049	S. E.
27	21	2.5	10.0	0.0049	S. E.
27	22	3.0	10.0	0.0058	S. E.
27	23	3.0	10.0	0.0058	S. E.
27	24	-	-	-	S. E.