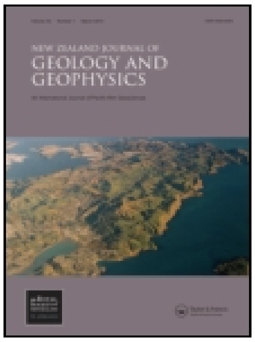

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COASTAL PROCESSES, BEACH MORPHOLOGY, AND SEDIMENTS ALONG THE NORTH-EAST COAST OF THE SOUTH ISLAND, NEW ZEALAND

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ABSTRACT

An analysis of the wave climate within Cook Strait, New Zealand, and wave refraction diagrams for the Marlborough coast between Rarangi and Cape Campbell, identify two littoral cells. Cloudy Bay in the north is dominated by a northward movement of foreshore sediments under southerly swell waves. Clifford Bay in the south is dominated by a southward movement of material under locally generated northerly seas. Beach morphology and the longshore sediment distribution, measured at 16 stations, reflect the dominance of sections of the coast by either the southerly or northerly wind/wave régimes.

INTRODUCTION

The wave climate of the east coast of the South Island has been defined by Davies (1964) as an "east coast swell type", which receives long-period swell and storm waves generated in zones of unrestricted fetch to the south of New Zealand. Along the Otago coast Hodgson (1966) showed 10–15 sec period southerly swell to be the dominant waves. At the Port of Timaru, Tierney (1976) showed the predominant wave direction to be from the south-east around to the east. Further north in the Canterbury Bight and along the Kaikoura coast, McLean & Kirk (1969) concluded that the prevailing waves approach from the south-east, but that there is also a strong north-east component and that the coast is a high energy one with breaker heights averaging 1–2 m.

The beaches along the east coast have developed primarily in response to the southerly swell and storm waves. McLean (1967) assessed the plan, shape, and orientation of 80 east coast, South Island, beaches and found most of them approximated a circular arc form, oriented to the deep water swell approach direction from the south-east. The beaches around the Otago peninsula have evolved in response to the southerly swell (Hodgson 1966), while the 90 mile (145 km) Canterbury Bight has developed equilibrium in profile and plan form in response to waves from the south-east (Kirk 1969). The swell approaches the coast line obliquely, generating north-eastward flowing littoral currents along the Otago coast (Marshall 1905; Bardsley 1972), at the Port of Timaru (Tierney 1976), and around the Canterbury Bight (Kirk 1969; Armon 1970; 1974). Elliott (1958) and Kirk (1969) consider that weaker counter currents to the south-west are set up during north-easterly conditions. Similarly, Carter & Heath (1975) suggest

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the sediment movement on the continental shelf off the Otago–Canterbury coast is probably controlled by storm-driven components associated with south-westerly storms, and the direction of transport is along the shelf, from south to north, rather than across it.

The Marlborough coastline north of Cape Campbell, in southern Cook Strait, faces the north-east and is partially sheltered from the dominant southerly swell and storm waves that control shoreline development along the remainder of the east coast (Fig. 1). Also, unlike the remainder of the east coast, fetch lengths to the north and east are severely restricted by the North Island landmass, while the funnelling of winds through Cook Strait generates a local wave régime unique to the immediate area. This paper describes the wave climate within Cook Strait and its effects on shoreline development along the Marlborough coast.

WAVE CLIMATE

Estimates of significant wave-height and wave-period were made at the Cape Campbell lighthouse (see Fig. 1). The direction of wave approach was strongly bimodal (Fig. 2A) with waves from the north-west and north travelling south through Cook Strait, and southerlies and south-easterlies moving up the east coast of the South Island and into the Strait. Surface winds in this area are channelled north–south through Cook Strait (Garnier 1958, p. 47). The records from the Cape Campbell meteorological station (Fig. 2B) are bimodal and reflect this channelling. The bimodal wind régime is reflected in the bimodal wave climate.

When wave and wind conditions at the lighthouse were compared (Table 1), northerly waves had following winds for 95% of the time, while southerlies had following winds for 70%. Regression analysis between wave height and wind speed for the two wave-approach directions shows wave height from the north increases as a function of wind speed such that

$$\text{Significant wave height (m)} = 0{\cdot}33 + 0{\cdot}04 \text{ wind speed (km hr}^{-1}\text{)}.$$

This relationship is significant at the 99.99% confidence level and explains 59% of the variation within the height régime. By contrast, the regression equation for the southerly mode only explains 6% of the variation and is not significant at the 95% level.

The northerly component is, therefore, probably a locally generated sea, the characteristics of which are directly controlled by the local wind régime within Cook Strait. The southerly mode, although frequently accompanied by following winds, is probably generated outside Cook Strait by storm winds in the southern ocean between New Zealand and Antarctica.

Wave characteristics of the two components support such a suggestion (Fig. 3). Waves from the north are short-crested, low-amplitude, steep waves, typical of those generated by local winds in restricted fetch conditions (Zenkovich 1967, p. 25). The southerly component has higher amplitudes, much longer periods, and lower steepness values.

Two groupings can be identified within the southerly waves. The wave period histogram (Fig. 3B) is bimodal, with peaks between 0 and 5 sec, and

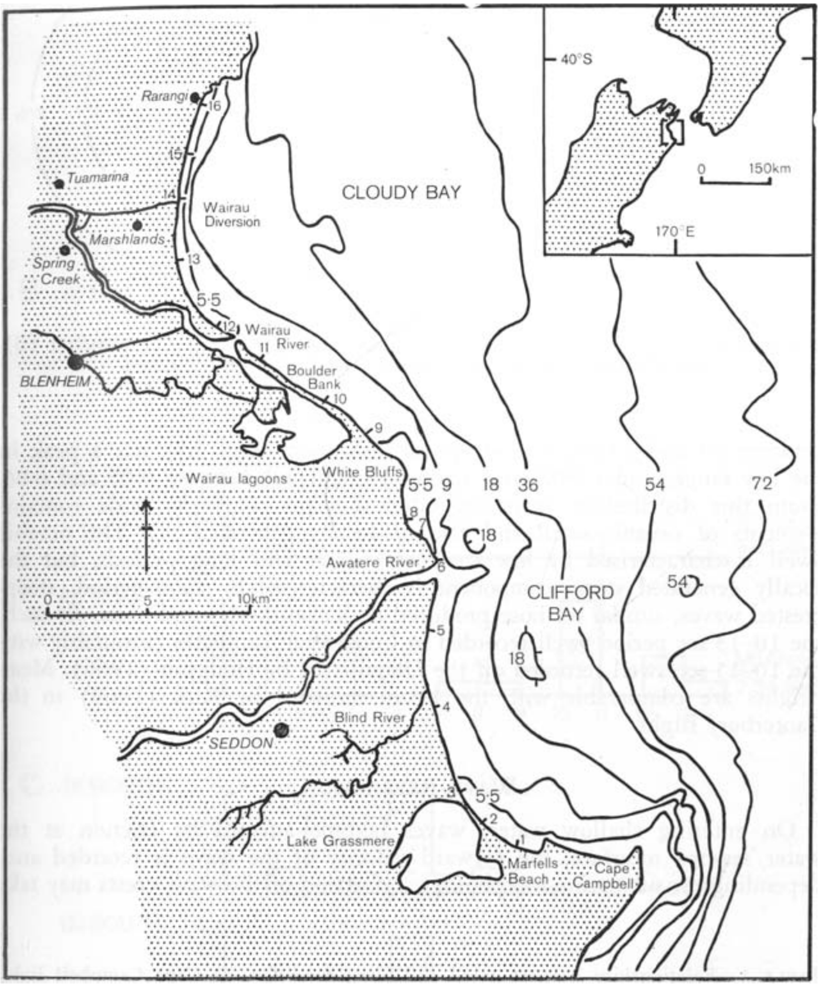

FIG. 1—The coastline from Cape Campbell to Rarangi, South Island, New Zealand. Sampling and profile stations are numbered 1–16. The bathymetry is in metres.

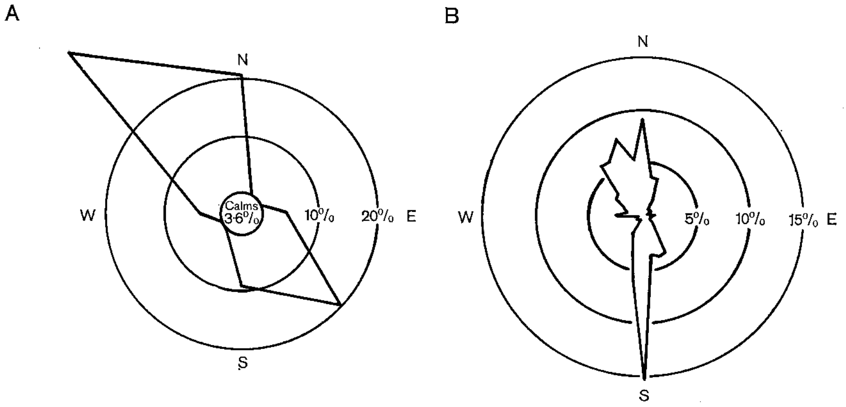

FIG. 2—Estimates of the directions of wave approach (A), and wind direction (B), for 85 days between April and July 1973, at Cape Campbell.

between 10 and 13 sec. The steepness histogram (Fig. 3A) has a peak in the low range, under 0·02, and a second small peak between 0·05 and 0·06. From this distribution, it is suggested that the southerly mode contains elements of oceanic swell and also of locally generated sea. The oceanic swell is characterised by low steepness values and long periods, but the locally generated storm component is characterised by short-period, steep-crested waves, similar to those produced under northerly conditions. As such, the 10–13 sec period swell recorded in Cook Strait compares favourably with the 10–15 sec swell recorded off the Otago coast by Hodgson (1966). Mean heights are comparable with the 1·3 m recorded by Kirk (1969) in the Canterbury Bight.

WAVE REFRACTION

On entering shallow water, waves become affected by friction at the water/sea-bed interface, the forward velocity of the wave is retarded and, depending on submarine morphology, refraction of the wave crests may take

TABLE 1—Relationships between wind and wave conditions at Cape Campbell lighthouse, April–July 1973.

Wind Conditions	Southerly Waves* (%)	Northerly Waves* (%)
Opposing	3·7	1·7
Following	70·3	94·8
Calm	25·9	3·5

*The measured sample consisted of 27 days for southerly waves, and 58 days for northerly waves.

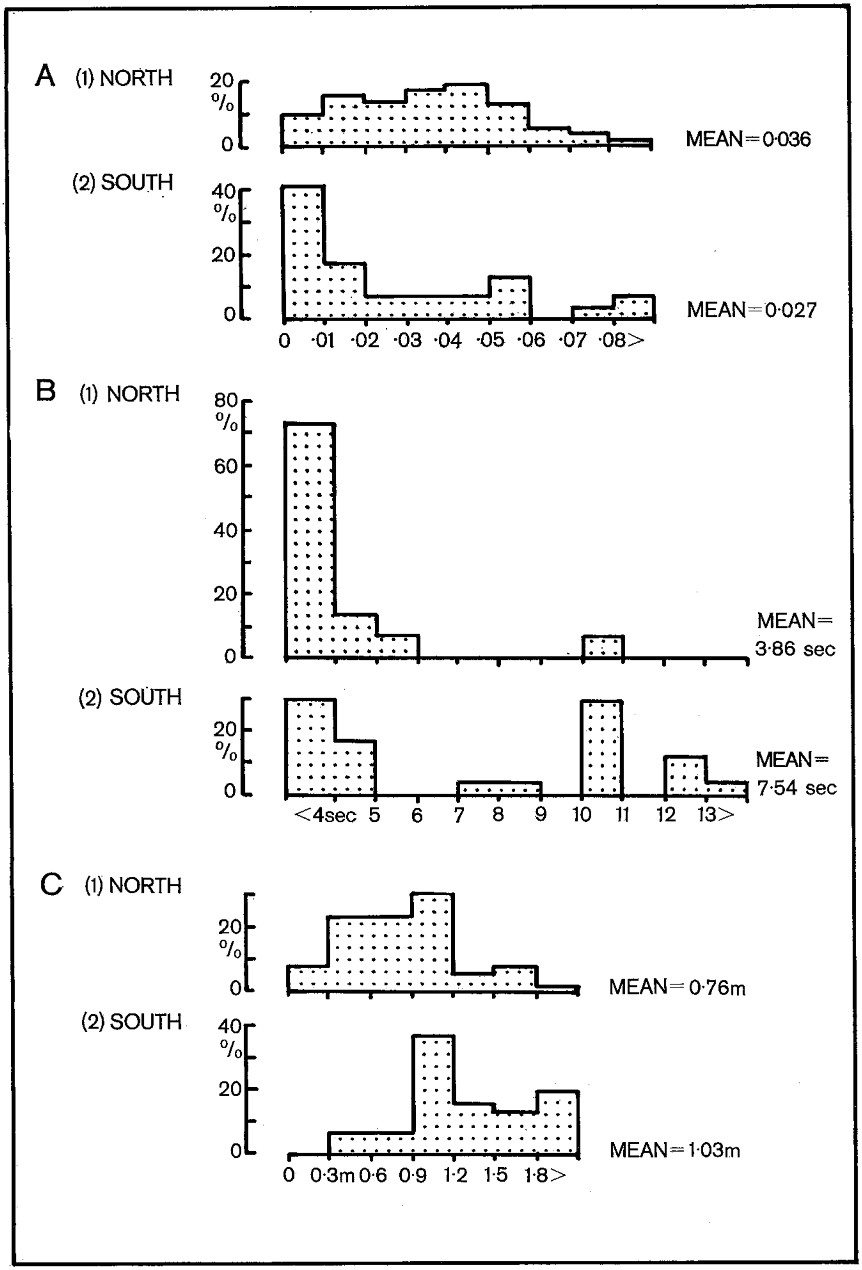

FIG. 3—Wave characteristics of the northerly and southerly components of seas observed at Cape Campbell. A—Steepness ratio (H/L); B—Period (in seconds); C—Height (in metres).

place. Wave refraction and the amount of energy received at the shore control both the direction and rate of littoral drift, and the type of beach profile produced.

Cloudy and Clifford Bays are both shallow. Consequently 10 sec period swell waves from the south-east first feel bottom up to 10 km offshore, in approximately 84 m of water (depths equal to half the wave length), although significant refraction is not initiated in depths greater than 42 m. By the time this refracted swell reaches the coast it has undergone considerable modification. In the refraction diagram (Fig. 4) the shallow-water refraction factor (K_b), the relative amount of convergence or divergence (i.e., increase or decrease in relative wave energy and wave height) due to refraction, has been marked (Munk 1949). Highest relative energy levels are found at Rarangi, in the north, and at the eroding headland of White Bluff, south of the Wairau Lagoons. Lowest energy levels are found in southern Clifford Bay, in the lee of Cape Campbell.

Where refraction is incomplete and waves arrive at the beach at an oblique angle, littoral drift is initiated. There are three major sub-aerial sources for such drifting of foreshore sediments: the eroding cliffs at White Bluffs; the eroding cliffs between Marfells Beach and Cape Campbell; and the Awatere River. Textural and lithological differentiation of material contributed by these sources was not possible. The Wairau River is not thought to contribute large quantities of foreshore sediment to the beaches, because the lower 9 km of the river has a fine sand and silt bed, quite dissimilar in size range to the mixed sand-shingle beaches of Cloudy Bay (P. Thompson, Marlborough Catchment Board, pers. comm. 1972).

The direction of approach of the shallow-water waves in relation to the shoreline suggests that, under southerly conditions, material is moved northward, away from the source areas, into Cloudy Bay north of the Wairau Diversion. Northward-growing bars across both the Awatere and Wairau Rivers support such a suggestion. Furthermore, the Wairau Boulder Bank formed as a free-form spit. It grew from the south, enclosing a shallow arm of the sea, after a steadying in the rate of sea-level rise approximately 6500 yrs B.P. (Pickrill 1976). Following enclosure of the lagoons, deposition continued on the north side of Cloudy Bay, against the resistant schist cliffs of the Sounds Block. The beach has subsequently prograded almost 5 km at Rarangi, so that the shoreline north of the Wairau Diversion has changed orientation from NE to ESE and is now well-oriented to the approaching swell from the south.

The short-crested northerly seas only begin to feel bottom in half the water depths of the southerly swell. While wave heights and energies from the north are smaller, the refraction diagram (Fig. 5) suggests that counter longshore currents to the south are established, and that Marfells Beach, at the downdrift end of this system, has developed an equilibrium plan-form in response to these waves. Lake Grassmere has been enclosed by a barrier beach, similar to that enclosing the Wairau Lagoons, although the area of deposition is considerably smaller. No extensive area of progradational ridges has developed, implying that perhaps these counter currents to the south are much weaker than those to the north. The orientation of the river mouths supports such a suggestion.

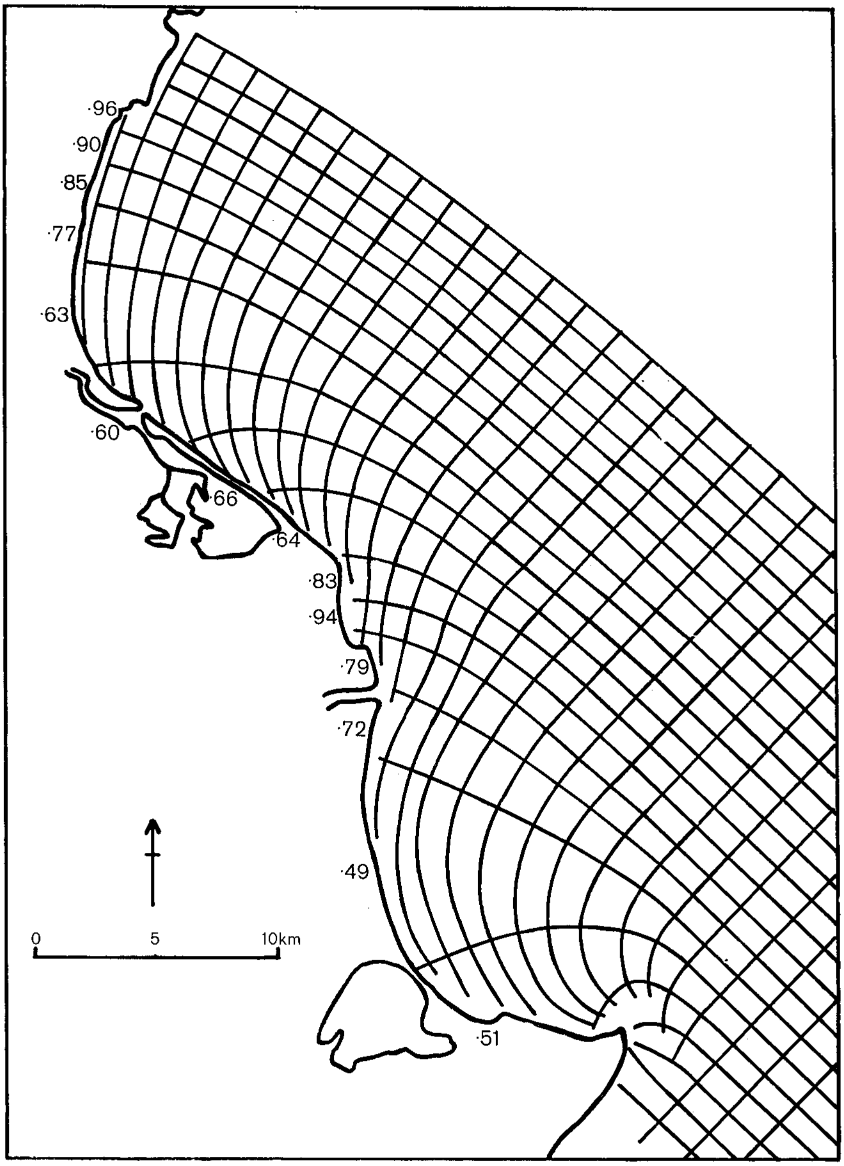

FIG. 4—Refraction diagram (Cape Campbell to Rarangi) for a southerly swell of 10 sec period showing every 14th wave crest. Numbers are K_h values.

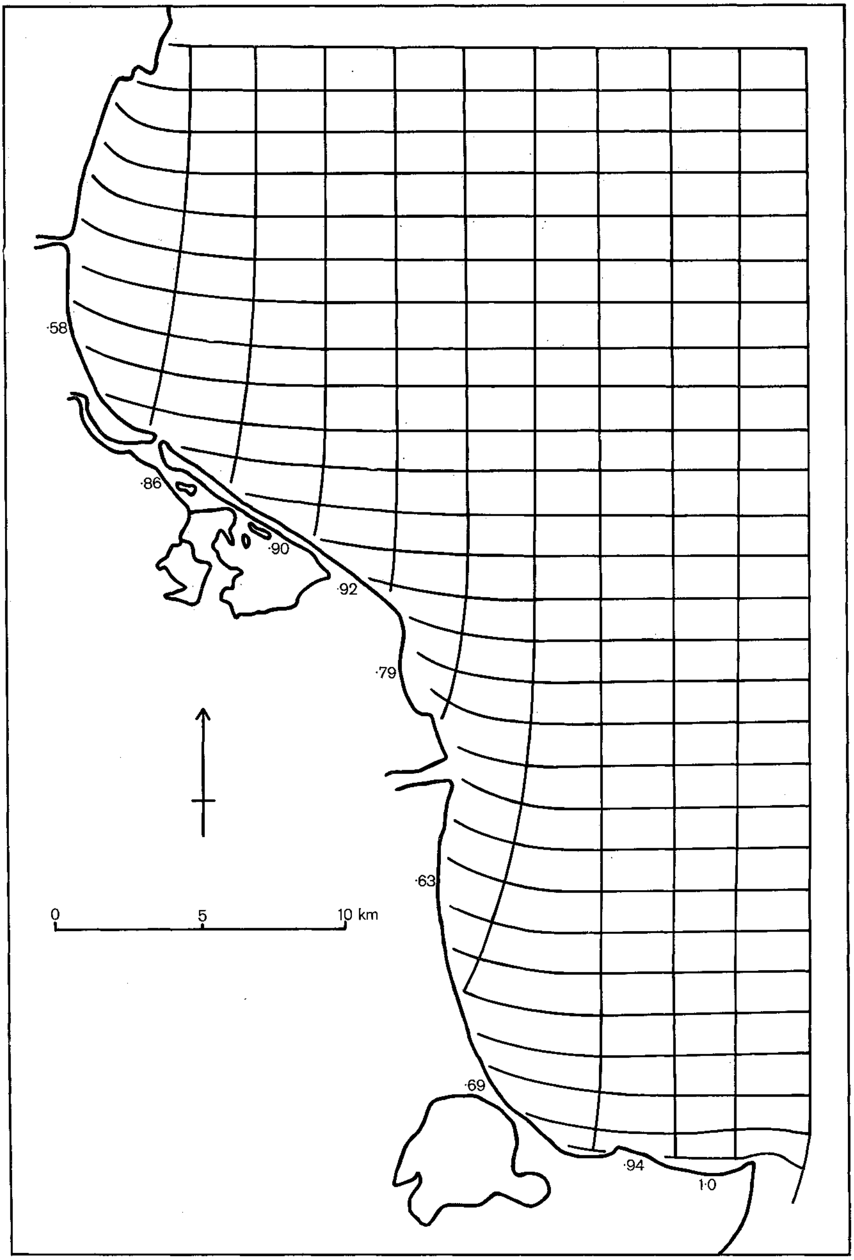

FIG. 5—Refraction diagram (Cape Campbell to Rarangi) for a northerly wave of 5 sec period showing every 96th wave crest. Numbers are K_h values.

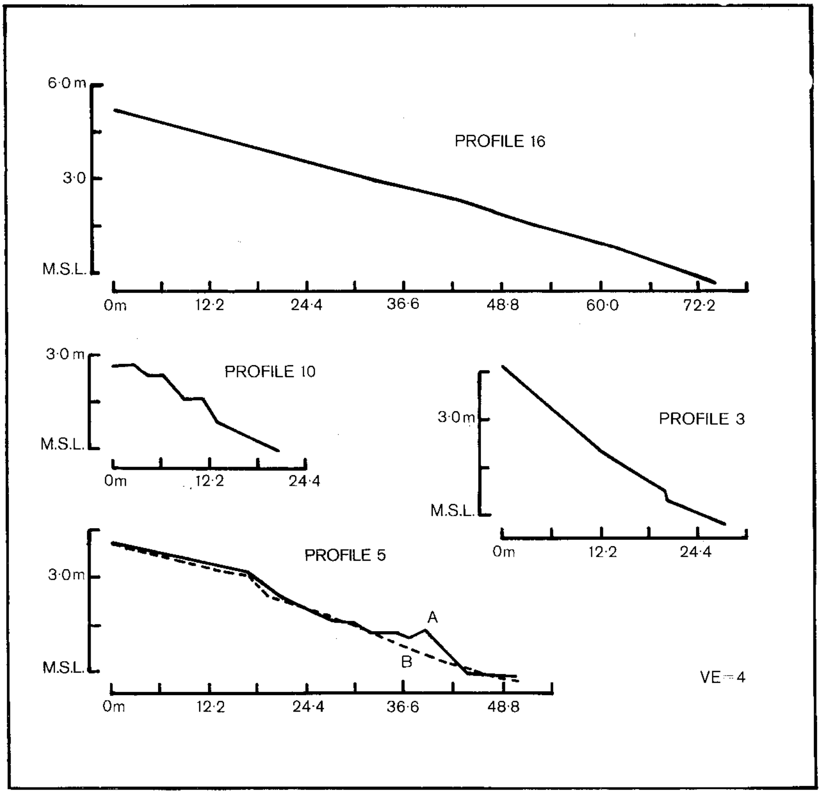

FIG. 6—Examples of typical beach morphologies (see Fig. 1 for locations of profiles). Profile 16—A mixed sand-gravel beach exposed to the south and sheltered from the north. Profile 10—A mixed sand-gravel beach sheltered from the south and exposed to the north. Profile 5—A mixed sand-gravel beach exposed equally to both the north and south: (A) after northerly conditions; (B) after southerly conditions. Profile 3—A sand beach sheltered from the south and exposed to the north.

BEACH MORPHOLOGY

The bimodality of the wave environment and the markedly different characteristics of these two modes produce distinctive variations in beach morphology. The domination of sections of the coast by either one or other of these two modes has led to permanent longshore variations in morphology, while beaches exposed equally to the two modes exhibit distinctive short-term changes (Fig. 6).

Beaches exposed to the south and sheltered from the north, (e.g., between Rarangi and the Wairau Diversion), are dominated by high-energy, long-period, shallow-crested swell waves. Beach profiles are wide with low foreshore slopes, while berm development is limited (Fig. 6). These profiles are similar to those developed in the mixed sand-shingle deposits of the Canterbury Bight (Kirk 1969), and typical of those developed along the east coast of the South Island by long-period swell waves.

By contrast, beaches exposed to the north and sheltered from the southerly swell, such as the sand beach fronting Lake Grassmere, are exposed to lower-energy, short-period, steep, storm waves. The beach profile which results is steep and narrow, and similar in form to the erosional, down-combed storm profiles associated with steep crested waves (King 1953). On the mixed sand-gravel beaches, such as along the Boulder Bank, the foreshores are steep and have a complex series of berms, reflecting storm activity at different elevations up the foreshore (Fig. 6, profile 10).

Between morphologies of southerly swell origin and those of northerly storm wave origin is a range of morphologies with characteristics derived from both these components. Southwards from Rarangi, as exposure to the southerly swell decreases and exposure to the northerlies increases, the beach slope increases, the foreshore narrows, and berms are developed. The reverse holds from Lake Grassmere to the Awatere River, where exposure to the south begins to increase again.

On beaches exposed to both modes of the wave environment, short-term changes in morphology occur in response to periodic relatively high-energy wave activity from both directions. For instance, changes on profile 5 (Fig. 6), south of the Awatere River, show a steepening of the lower foreshore under northerly conditions through accretional berm building, while a return to southerly conditions reduces the foreshore slope and any berms formed under northerly conditions are planed off. Similar changes take place on the beaches just north of the Wairau River mouth.

BEACH MATERIALS

Mixed sand-gravel beaches, similar to those described by Kirk (1969), McLean (1970), and McLean & Kirk (1969) on the east coast of the South Island, make up most of this section of the Marlborough coastline. The coarsest beaches are found between the Awatere River and White Bluffs (Fig. 1) where they approach pure gravel; the gravel content decreases northwards to the mixed beaches of Rarangi. South of the Awatere River there is a rapid decrease in the gravel content. The beach enclosing Lake Grassmere is fine sand.

Alongshore trends in mean grain-size and sorting coefficients have been used by various authors to infer the direction of littoral drift (Pettijohn & Ridge 1932; Schalk 1938, etc.). A decrease in grain size or an increase in the degree of sorting away from a source area are seen as a product of selective longshore transport and attrition. Sunamura & Horikawa (1971a; 1971b; 1972) combine grain-size and sorting coefficients to define the preconditions for identifying the direction of drift. Firstly, a sediment source or sources must be identified. Secondly, from the source area, in a "down current" direction, sorting should either remain constant or improve for littoral transport to be inferred in that direction. If sorting deteriorates in

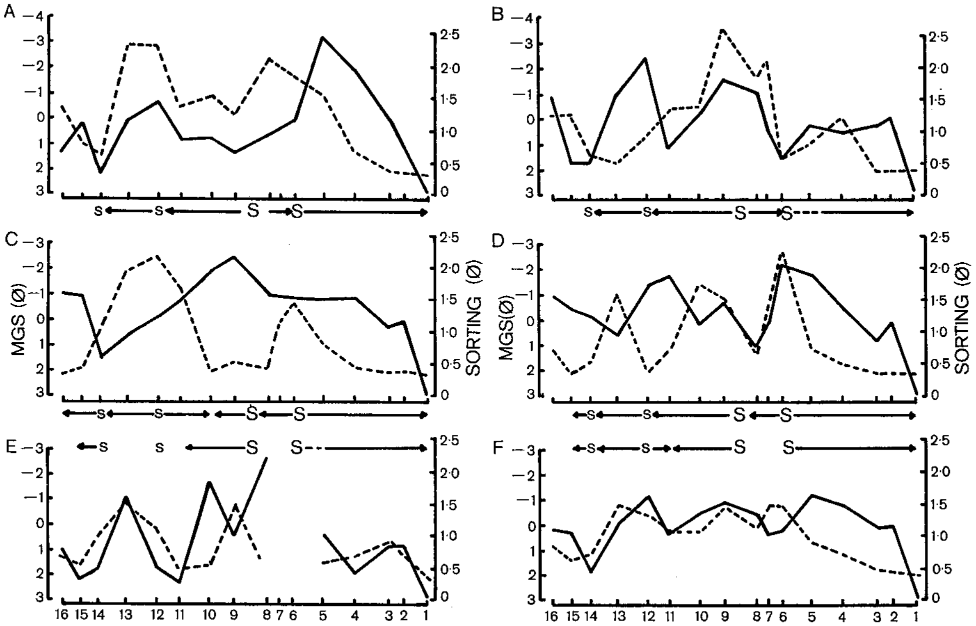

FIG. 7—Longshore trends in mean grain size (*solid line*) and sorting (*broken line*), and inferred directions of littoral drift for foreshore samples from five surveys (A–E) made at the 16 stations located on Fig. 1. (F) shows the average trend for the five surveys. Major (S) and minor (s) sources of sediments are marked, along with the sampling stations of Fig. 1. Arrows indicate general direction of transport.

the down current direction, movement in that direction is inferred not to have occurred. In conjunction with sorting, mean grain size may increase, decrease, or remain constant.

While longshore trends in size and sorting have been used successfully to identify directions of littoral drift on sand and gravel beaches, mixed beaches have presented several problems. Kirk (1967) demonstrated that despite strong littoral currents along the Canterbury Bight no longshore trends in either grain size or sorting could be found. Similarly in a detailed study of the beaches north and south of the Kaikoura peninsula McLean (1970) found no longshore trends away from the river source. He found the beaches are differentiated into a number of sediment zones composed of either sand, or mixed sand-gravel or gravel, but gave no explanations for these patterns.

Foreshore samples were taken from the reference zone (Bascom 1964) of the profiling stations marked in Fig. 1. Five samples were taken from each station over a 9-month period.

Longshore trends in graphic mean grain size and Inclusive Graphic Standard Deviation (Folk 1968) are depicted in Fig. 7. From the Awatere

River, south to Marfells Beach, grain size decreases and sorting improves, implying a southerly drift. Between the Awatere River and White Bluffs trends are mixed, with no one dominant transport direction. Sediment probably moves to both the north and south, away from the major source areas, with the transport direction depending on prevailing wave conditions. North of White Bluffs, the sediment distribution suggests a northerly drift along the Boulder Bank and around Cloudy Bay to the Wairau Diversion. North of the Diversion the trend is again confused, however, the northerly drift is probably maintained. The distinction between the predominant northerly drift in Cloudy Bay, and the southerly drift in Clifford Bay, with a boundary zone of bi-directional movement between the two cells, agrees with the patterns identified in the wave refraction analysis, and confirms the existence of two cells of littoral transport. Between the Awatere River and White Bluffs (at profile 7), a cuspate foreland has developed from an outcrop in the Holocene sea cliffs (Fig. 8). The foreland is symmetrical, with progradational ridges on both the northern and eastern faces. This symmetry suggests that the foreland has been formed by bi-directional longshore currents such as have been proposed for the area. The two active faces of the foreland have prograded to face the two dominant wave approach directions.

Material transported in the two littoral cells differs widely in size range. The beaches of Cloudy Bay encompass a wide range of sizes from coarse sand ($0{\cdot}0\phi$) through to cobbles ($-6{\cdot}0\phi$) while those in Clifford Bay are largely composed of material finer than coarse sand. By inference, it is suggested that southerly swell and storm waves result in a net transport of all sizes to the north, while the lower-energy northerly seas are most efficient at moving sand-sized material southward.

The longshore trends in grain size and sorting identify littoral currents along this part of the Marlborough coast similar to those predicted from the wave climate. Although size-selective longshore transport takes place here, there is no evidence for it along the Kaikoura coast, or Canterbury Bight, which have similar sized sediments and are exposed to equally strong littoral currents. It can only be suggested that longshore energy gradients are generated along the coast between Cape Campbell and Rarangi by extensive refraction under southerly conditions in conjunction with energy gradients created by the bimodality in the wave régime, and these probably lead to selective alongshore transport. On the exposed east coast to the south, wave energy is higher and probably capable of moving all grain sizes present without creating size or sorting trends along the shore.

CONCLUSIONS

The wave climate, as evidenced on the coast of Marlborough between Cape Campbell and Rarangi, is strongly bimodal, with locally generated short-crested seas from the north, and long-period swell and storm waves from the south. The relative exposure of the shoreline to the two components of the wave régime controls the beach morphology. Beaches exposed to the southerly swell are wide and gently sloping while those exposed to the north

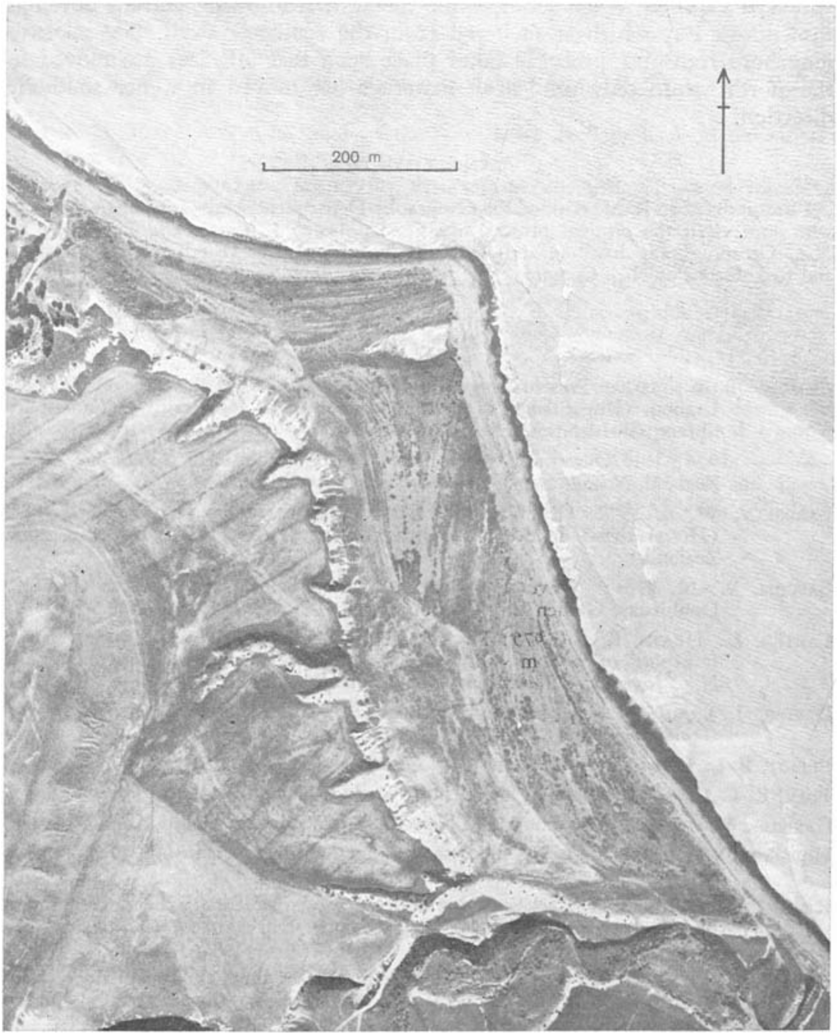

FIG. 8—A cuspate foreland at profile 7 between White Bluffs and the Awatere River. The foreland is under the influence of a refracted southerly swell and a superimposed short-period northerly sea. (Photo by permission of the Department of Lands and Survey.)

and sheltered from the south are narrow, steep and have multiple berms. Beaches exposed to both components of the wave régime exhibit mixed characteristics. Littoral currents, flowing northward, develop in Cloudy Bay which is exposed to the south, while a southward-flowing current develops in Clifford Bay which is sheltered from the southerly swell. Size-selective longshore transport probably takes place such that all sizes are moved to the north while only sand-sized materials are moved in a net southerly direction.

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