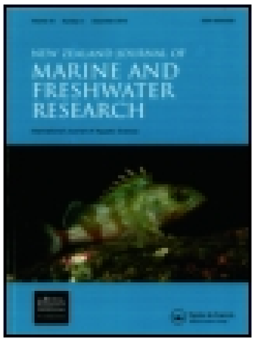

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VARIATIONS IN GRAIN-SIZE AND SORTING ON TWO KAIKOURA BEACHES

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SUMMARY

Two exposed, high-energy beaches on the Kaikoura coast of New Zealand are composed of sand and gravel derived from a greywacke terrain. Both beaches can be classified as mixed beaches although the sediment varies from dominantly gravel at the ends of the beach to dominantly sand at the centre, through transition zones in which sand and gravel are mixed. Sixty-four surface samples were analysed for grain size; two sediment parameters, mean grain size (M_z) and sorting (σ_I), were calculated.

A striking feature of the cumulative frequency curves is that both unimodai and bimodal distributions include median sizes over the whole range of sampled material, even though bimodal samples display two strong modes in the sand and gravel grades. The general deficiency of sediment in the very coarse sand and granule classes (0 to -2ϕ) noted by numerous authors in many parts of the world is apparent in the poorly-sorted bimodal samples. However, the best-sorted samples also occur in these two classes.

Mean grain size of samples ranges from medium sand (1.82ϕ) to medium pebbles (-4.7ϕ), and sorting ranges from very well sorted (0.25ϕ) to very poorly sorted (2.69ϕ). Mean grain size on the northern beach is significantly greater than on the southern beach, but values of sorting are comparable. The greater mean size on one beach compared with the other is thought to be a function of the grade of material supplied by local rivers; the similarity in sorting presumably reflects the similarity of the processes acting on the two beaches.

Mixed sand-shingle beaches are relatively rare on a world scale but common in New Zealand. Sediment distributions along the Kaikoura beaches do not reveal a regular decrease in size away from the rivers which supply material to shore at present. Instead, the beaches are differentiated into a number of sediment zones composed of either sand, or mixed sand-gravel, or gravel. On each beach a gravel zone is located furthest from the river outlets. Sorting generally improves toward the Kaikoura Peninsula. Explanations for these trends are not given. Variations in size and sorting across the two beaches do not show a well developed zonation because of the high level of wave energy which continually mixes the material across the beach.

INTRODUCTION

To date investigations of New Zealand beach sediments have been carried out mainly on sandy beaches (e.g., Blake 1968; Hodgson 1966; Schofield 1967; Sevon 1966), and especially on sand beaches containing valuable heavy minerals (e.g., Gow 1967; Martin and Long 1960: Nicholson 1967). Some gravel beaches, specifically the Nelson Boulder Bank, have also been described (Marshall 1925; Worley 1899). Between these two pure beach types are beaches which contain mixtures, in roughly equal proportions, of both end-member populations, sand and gravel. Such beaches can be classified as mixed sand-shingle beaches, or mixed sand-gravel beaches.

In a recent major publication on coasts, Zenkovich (1967, p. 271) noted that mixed beaches are comparatively rare on a world-wide scale. In New Zealand, however, and particularly on the east coast, South Island, they are not rare. For instance, from Oamaru to Banks Peninsula, a distance of about 150 miles, the coast is fringed by a long, almost continuous stretch of mixed sand-shingle beach. Similar but smaller scale mixed beaches occur at the mouths of the Hurunui, Waiau, and Conway Rivers, and, further north, from the Kahutara River to Blue Duck Stream (Kaikoura area), from the delta-fan of the Clarence River to Kekerengu, and from Cape Campbell to Rarangi, Cloudy Bay. In the North Island, comparable beaches are found around Palliser Bay and in Hawke Bay, notably between Clifton and Nuhaka.

All the larger of these mixed beaches embody certain common features:

(1) they contain a wide range of sediment sizes (sand to boulders);
(2) they are derived from the same dominant rock type (greywacke);
(3) they are backed by Pleistocene and Holocene alluvial plains and fans often crossed by major rivers; and
(4) they are exposed to the high energy waves of an East Coast Swell Environment (Davies 1964).

Two areas of mixed sand-shingle beaches, the Canterbury Bight and Hawke Bay, have been the subject of recent study by Kirk (unpublished, 1967) and Smith (unpublished, 1968) respectively, following earlier studies by Speight (1930; 1950) and Marshall (1929). I began detailed investigation of the sediment, morphology and dynamics of a third area, Kaikoura, in 1966.

SEDIMENT VARIATION

Zenkovich (1967, p. 271) argued that morphology and dynamics of mixed beaches are more complicated than either pure sand or pure shingle beaches, because of the different ways in which the separate components are displaced. Therefore the spatial distribution of sediments on mixed beaches may be expected to be more complicated than on sand or shingle beaches. Variations in particle properties across sand beaches have been described by Fox, Ladd and Martin (1966), Sevon (1966) and others, and on gravel beaches by Bluck (1967). These variations are the result of particle responses to the different energy zones arranged parallel with the shore (Ingle 1966, p. 181). On mixed beaches possessing a large range of sizes, a well developed zonal pattern could be expected. However, this is not found on the two Kaikoura beaches.

Alongshore changes in sediment characteristics have been described for some New Zealand sand beaches by Blake (1968), Sevon (1966) and Summerhayes (1969), and on shingle beaches elsewhere by Carr (1969) and King (1959, p. 167). Because the sediment population of a mixed beach covers a wide range of particle sizes, intuitively one would expect the various modal sizes to be distributed alongshore in a regular manner to form what has been called a linear series. The commonest type of linear series is one in which gravel occurs at one end of the beach, or near some cliff source or a river mouth, and there is a regular decrease in particle dimensions alongshore resulting from either attrition, or some selective sorting process in the environment which varies regularly from point to point (Pettijohn and Ridge 1932).

Marshall (1929) describes a linear series on a 40-mile sector of mixed beach north of the Mohaka River, Hawke Bay. The Mohaka River carries into the sea an unsorted mixture of greywacke material ranging from medium sand to cobbles. Sorting improves away from the river as the particle size becomes smaller; the modal size class declines from 25.4 mm (medium pebbles) to 0.59 mm (coarse sand) along the beach. Surprisingly, no such clear cut particle size : distance relationship is evident on the 90 miles of mixed greywacke beach along the Canterbury Bight (Kirk, unpublished, 1967, pp. 53–5, 65–8). Along this shore, cliff erosion in the central portion of the beach provides a considerable quantity of mixed material, but no significant decrease in mean grain size away from this source was noted. Instead, at any point Kirk found a range of sizes as great as that along the whole beach.

In the two investigations reported above, Marshall sampled at approximately 7 mile intervals, and Kirk at intervals of 3 miles. Marshall analysed one sample from each station and Kirk two samples (foreshore and backshore). Because of the contrasting results from these two different mixed beaches, a more detailed investigation of the beaches in the Kaikoura area was undertaken to see if either a linear series in size and sorting existed or if the distributions were random. However, the distributions on the two beaches studied were neither linear nor random. Instead, several distinct size/sorting zones were distinguished, distributed cyclically alongshore in a "differentiation series" (Pettijohn and Ridge 1932, p. 76).

PURPOSES

The objectives of the present paper are to:

(1) Describe certain characteristics of the sediments on the two beaches immediately north and south of the Kaikoura Peninsula. Of the particle properties, only mean grain size and sorting and the relationships between these two parameters are considered.

(2) Compare the textural characteristics between the two beaches by examining the hypothesis that the sediments of both beaches are drawn from the same population.

(3) Describe the spatial variation in size and sorting values in general terms, and more specifically along and across the shore of both beaches.

METHODS

In March 1966, 21 profiles were surveyed across the beach from the vegetation limit on the backshore to approximately low water level (LWL), at the positions shown in Fig. 1. There were 10 profiles

(1–10) spaced about 0.5 miles apart on the beach to the south ("South Beach") and 11 profiles (12–22) averaging 0.8 miles apart to the north ("North Beach") of the Kaikoura Peninsula. (Profile 11 was not surveyed or sampled at this time.) Constant heights above LWL were abstracted from the profiles to prepare contour maps of both beaches. Surface sediment samples were collected to a depth of 10 cm at various positions; the number of samples not necessarily being the same on every line. The selection of sample sites was non-random, the objective being to sample representative sedimentological or morphological divisions of the beach. Samples varied in weight, but were never less than 200 g. A total of 64 samples was collected; 37 from "South Beach" and 27 from "North Beach". (These beaches have no approved names as separate entities, hence inverted commas.)

All samples were washed and dry seived. Materials between 0.125 in. and 2.5 in. were seived by hand through five screens, while materials finer than 0.125 in. were shaken for 15 minutes in an "Endrock" shaker through 0.5ϕ seive intervals. Sizes larger than 2.5 in. were not considered. Cumulative curves were plotted and the relevant percentile values abstracted for calculation of Folk size parameters (Folk 1965). Calculation of the Graphic Mean Diameter (M_z) and Inclusive Graphic Standard Deviation (σ_I;= Sorting) in phi units (ϕ) was performed on the IBM 1620 Computer, University of Canterbury. Results are tabulated in Appendix I. The grain-size : grade scale used throughout this paper is based on the Wentworth-Krumbein ratio scale (Griffiths 1967, p. 76) and is outlined in Table 1. The sorting scale follows that of Folk (1965, p. 46) and is presented, along with the formulae for computation of mean grain size and sorting, in Table 2.

RESULTS AND DISCUSSION

CUMULATIVE FREQUENCY DISTRIBUTIONS

Thirteen of the 64 cumulative curves, including examples from 10 of the 21 stations are plotted in Figs. 2 and 3. These representative curves have been selected to illustrate frequency distributions over the size range of material and locations sampled. However, they do not cover the sizes potentially available from the rivers. The beds of the Hapuku, Kowhai and Kahutara Rivers reveal an extremely heterogeneous sediment population, with material varying in size from mud to large boulders. On the cumulative curves the lack of material finer than very fine sand (4.0 ϕ) and coarser than pebbles (−6.0 ϕ) is quite evident. The absence of mud clearly results from its inability to stay on these high wave energy beaches. The absence of cobbles and boulders, on the other hand, results from the sampling programme itself and does not reflect their true absence. For example material coarser than −6.0 ϕ is often exposed near the Hapuku and Kahutara River mouths, where it locally forms the framework of the beach. At the time of sampling these boulder basements were covered with a veneer of smaller material.

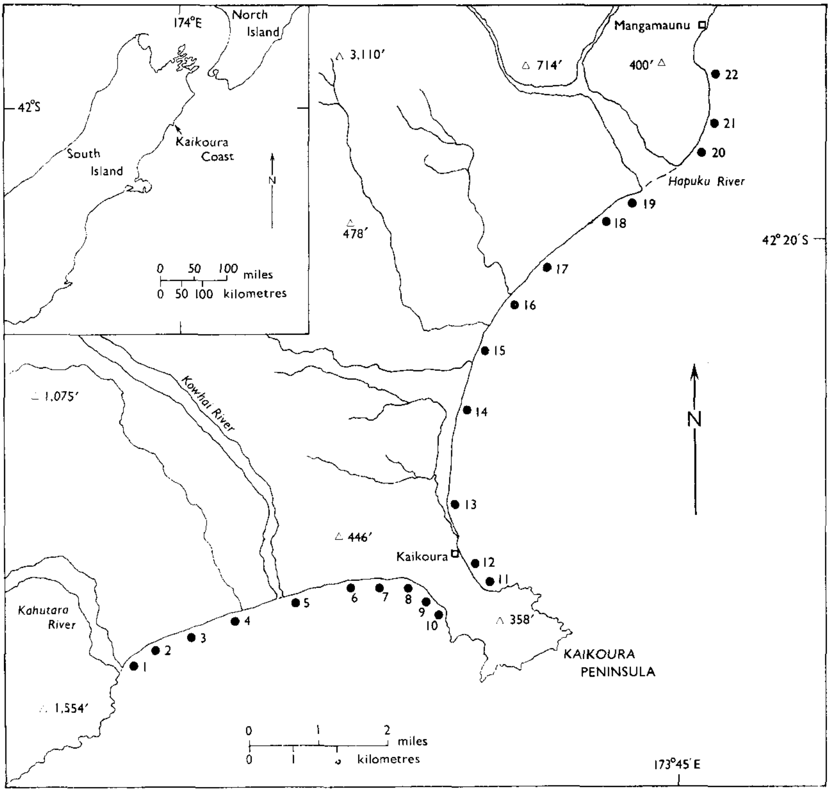

FIG. 1—Location of profile stations along Kaikoura coast. Inset: position of Kaikoura coast on east coast, South Island

UNIMODAL CURVES

Unimodal curves have been plotted on Fig. 2 and bimodal curves on Fig. 3. This is not just for convenience in draughting: it also reflects the fact that the surface sediments below $-6.0\,\phi$ diameter are often either unimodal or bimodal. Only a small percentage of the curves were polymodal.

One feature of the unimodal curves is that the median diameters (found at the intercept of the 50th percentile with the cumulative curve) are distributed over the whole range of sampled sizes, from medium sand (curve 4c) to medium pebbles (curve 18b). The mean grain sizes range from $1.32\,\phi$ to $-3.98\,\phi$. In all cases the mode (the most frequently occurring grain diameter) is close to the mean and medium size, and sorting values are high, ranging from $0.33\,\phi$ (curve 10c), very well sorted, to $0.65\,\phi$ (curve 12), moderately well sorted.

TABLE 1—Relationship of grain size to grade and type

Size (mm)	Phi units (σ)	Grain Type
SAND		
0.062– 0.125	4 to 3	Very fine sand
0.125– 0.25	3 to 2	Fine sand
0.25 – 0.50	2 to 1	Medium sand
0.50 – 1.0	1 to 0	Coarse sand
1.0 – 2.0	0 to −1	Very coarse sand
GRAVEL (= SHINGLE)		
2.0 – 4.0	−1 to −2	Granules
4.0 – 8.0	−2 to −3	Very small pebble
8.0 –16.0	−3 to −4	Small pebble
16.0 –32.0	−4 to −5	Medium pebble
32.0 –64.0	−5 to −6	Large pebble

TABLE 2—Grain size parameters (after Folk 1965)

Graphic Mean

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

where ϕ 16, ϕ 50, etc. = the phi value of the 16th (50th, etc.) percentile abstracted from the cumulative curves

Inclusive Graphic Standard Deviation (Sorting)

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

Verbal Classification

Value of σ_I (ϕ units)	Description
< 0.35	Very well sorted
0.35–0.50	Well sorted
0.50–0.71	Moderately well sorted
0.71–1.0	Moderately sorted
1.0 –2.0	Poorly sorted
2.0 –4.0	Very poorly sorted
> 4.0	Extremely poorly sorted

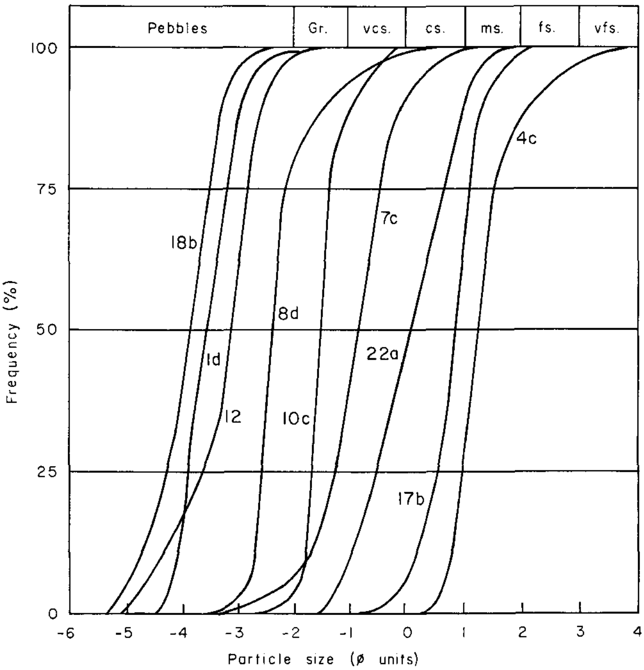

FIG. 2—Selected examples of unimodal curves for cumulative frequency of particle sizes from nine different stations on two Kaikoura beaches (numerals refer to station numbers, letters to specific samples)

BIMODAL CURVES

Although the median diameters of the bimodal curves cover the same size range as the unimodal distributions, the mean sizes and modal classes are not close together. This is reflected in poorer sorting values; the four curves fall into the poorly sorted or very poorly sorted categories. Comparing, for instance, samples 4c (unimodal) and 2d (bimodal) which have approximately the same mean grain size, 1.32 ϕ and 1.26 ϕ respectively, the first has a sorting value of 0.5ϕ (well sorted) and the second 1.33 ϕ (poorly sorted).

Despite the great range of mean grain sizes the two modes are strong ones and, as shown in Fig. 3, occur in approximately the same places. In each case there is a population in the medium–coarse sand (0 to 2 ϕ) category, and another in the pebbles (-2.5 to -4.5 ϕ).

This suggests a mixing of two somewhat normally distributed populations such as would result from mixing material from say curve 4c or 17b (medium sand) and either curve 1d, 12 or 8d (pebbles) (Fig. 2). Essentially, it is the differences in proportions of these two size components, rather than variation in the range of grain sizes that accounts for the variations in the group of bimodal curves.

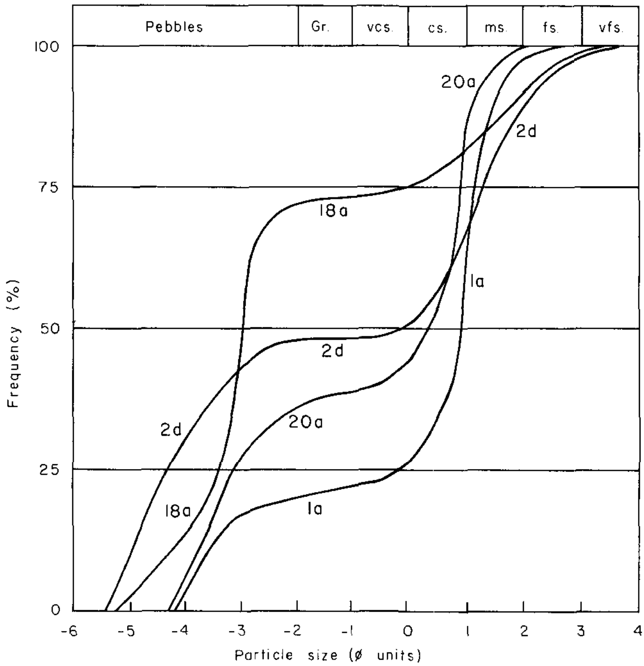

FIG. 3—Selected examples of bimodal curves for cumulative frequency of particle sizes from four different stations on two Kaikoura beaches (numerals refer to station numbers, letters to specific samples)

A clear break between the two modal classes is evident on each bimodal curve. This gap, between 0 to $-2\,\phi$ (very coarse sand–granules) indicates a lack of material in these size categories. Such a deficiency is not uncommon in natural size distributions and has been described elsewhere (Folk 1965, p. 5; Pettijohn 1957, p. 46–51; Rogers, Krueger and Krog 1963; Spencer 1963). Folk (1965, 1966) argues that the basic cause of this gap is simply because nature commonly provides only three dominant modal populations (gravel, sand and clay) in the source material. Thus samples with mean sizes in the 0 to $-2\,\phi$ range are likely to be mixtures of sand and gravel.

However, it is evident from the unimodal curves for Kaikoura that material in this critical intermediate size range is *not always* a mixture of two separate populations. Instead, curves 7c, 10c and 22a on Fig. 2 all approach normal distributions, the samples being relatively well sorted. This points to the possibility that greywacke rocks in the source area breakdown to all sizes and not just into specific size grades, and that there are efficient sorting mechanisms at work on the beach that work to separate out the various size grades.

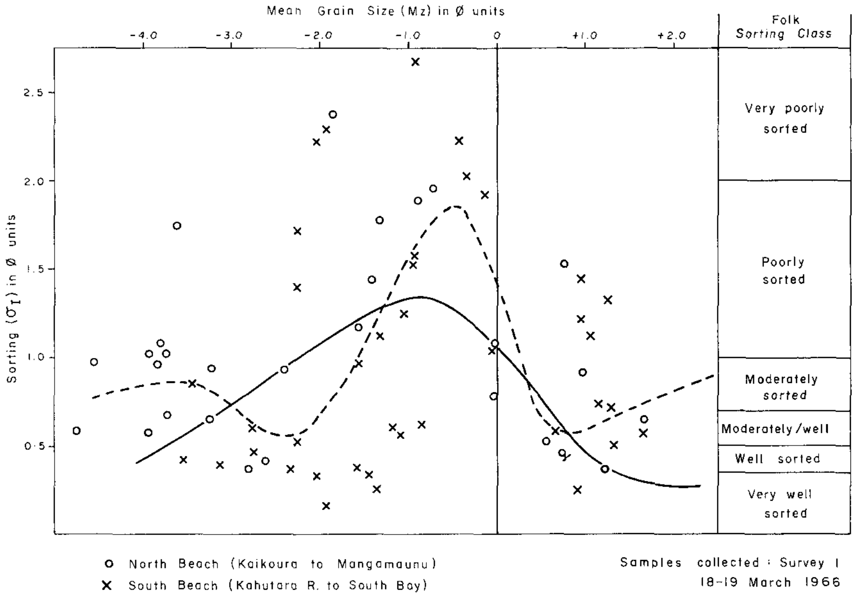

FIG. 4—Scattergram of observed mean grain size against observed mean sorting values of all samples from two Kaikoura beaches. Solid curve is the average curve illustrated in Folk (1965, p. 6); the average curve for the Kaikoura data is shown dashed

In summary, unimodal sediments occur over the whole range of particle sizes, while the bimodal distributions contain two strong modal classes separated by a break, the position of which appears relatively constant in all samples.

GRAIN SIZE: SORTING RELATIONSHIPS

A scattergram, Fig. 4, relating mean size and sorting for all samples indicates a great range in values. Very well to moderately well-sorted materials occur throughout all size grades, while the poorly to very poorly sorted samples are more restricted in terms of their size range; the largest group occur between 0 to -2.5 ϕ.

It is also obvious that there is no meaningful linear relationship between the two variables. Instead a best fit curve is likely to be of the second, third or higher order as indicated by results from other foreshore samples from the same Kaikoura beaches (McLean and Kirk 1969, p. 146–9). Two sketch curves have been plotted on Fig. 4. The first from Folk (1965, p. 6), which indicates an "average" size : sorting relationship for a large number of samples from different sedimentation environments. The second is based on the median sorting value in each 1 ϕ size division for the present Kaikoura data. Despite the differences in magnitude and detail of the two curves, the same general trends are apparent, with poorest sorting occurring in the size grades intermediate between medium-coarse sand and small-medium pebbles. This region of poorer sorting can, as indicated above, be interpreted as a response to mixing of the sand and pebble fractions. Less expected, however, is the cluster of 9 or 10 very well- to moderately well-sorted samples in the -0.8ϕ to -2.2ϕ range, which includes samples 7c, 10c and 22a illustrated on the cumulative curves (*see* Fig. 2). Thus, within this intermediate size range there are two distinct groups of sediments; one consisting of a mixture of sand and pebbles, and the other consisting of well sorted granules. Sorting rather than mean size distinguishes the two types of sediment.

COMPARISONS BETWEEN THE TWO BEACHES

In the preceding comments no attempt was made to distinguish between samples obtained from "North Beach" and those from "South Beach". Because of:

(1) the proximity of the beaches;
(2) the comparable characteristics of source rocks in the hinterland; and
(3) the general similarity in environmental factors,

it can be hypothesised that samples from both beaches have been drawn from the same population.

The average and standard deviation of mean grain size and sorting values are given in Table 3. Little difference is apparent in the sorting values, but a difference of 1.25 ϕ and 0.40 ϕ for mean and standard deviation respectively in the size values is evident. The average mean size for samples from "North Beach" falls in the granule category, while for "South Beach" it occurs in very coarse sand.

Student's t tests were applied to these data to see if the differences were significant. The results for 62 degrees of freedom showed a t value of 2.8 and a P level of 0.01 for mean grain size, and a t value of 0.1 and a P level of 0.90 for sorting. These results confirm that the size of material on "North Beach" differs significantly from that of "South Beach", whereas there is no significant difference in the sorting values. It seems likely, therefore, that the material contributed by the Hapuku River—the probable main source of material for "North Beach"—includes larger sizes than that contributed to "South Beach" by either the Kowhai or Kahutara Rivers. The sorting mechanisms are however similar as both beaches are swash-dominated high-energy beaches.

SPATIAL DISTRIBUTION OF SEDIMENTS

Figs 5 and 6 show the plan position of samples, height of sample points above LWL, and distributions of mean grain size and sorting. The plan position of sample stations is drawn to scale, while maps of the other three distributions have a distorted vertical scale (the spacing between points being dependent on the number of samples taken across the profile), to simplify visual presentation.

TABLE 3—Comparison of sediment textures on two Kaikoura beaches (n = number of samples; $\bar{x}$ = grand mean; s.d. = standard deviation)

	"NORTH BEACH"			"SOUTH BEACH"		
	n	$\bar{x}$ (ϕ units)	s.d. (ϕ units)	n	$\bar{x}$ (ϕ units)	s.d. (ϕ units)
Size	27	−1.97	1.95	37	−0.72	1.55
Sorting	27	0.98	0.59	37	0.99	0.65

"SOUTH BEACH"

Figure 1 shows that in plan the beach between the Kahutara River and the Kaikoura Peninsula has an arcuate shape but with the central portion distinctly flatter than its theoretical circular arc (McLean 1967). Fig. 5A indicates how the active part of the beach, i.e., seaward of the vegetation limit, varies in width. It is narrower at the extremities than in the centre, where it reaches over 150 yards wide. In this central section the foreshore and backshore are equally wide and the foreshore slope is low. At the northern and southern ends where the beach narrows, foreshore slopes are steeper and the backshore is poorly developed. Two distinct salients with elevations above 20 ft are depicted on the contour map. These two areas are backed by low dunes and are separated from one another by the mouth of the Kowhai River which accounts for the decrease in backshore elevation around stations 4 and 5 (*see* Fig. 5B).

Mean grain size (M_z): It is clear from Fig. 5C that there is no single unidirectional variation in size either along or across the beach. Nevertheless, the beach can be roughly divided into two parts; the northern one-third of gravel (-4.0ϕ to -1.0ϕ) and the balance, sand (2.0ϕ to $-1.0\,\phi$), except in the extreme south. The gradient from sand–gravel is steep. Size grades within the gravel type include granules, very small pebbles and small pebbles. The largest sized material is found in the centre of profiles 7 and 8 and there is a decrease in size away from this zone. Across-beach changes are minimal in this northern section; all samples at stations 9 and 10 are in the granule category. Immediately east of profile 10 the beach abuts against a limestone headland (Moa Point) which forms a barrier to littoral transport.

West of station 6, within the sand area, across-beach variations in mean size are more apparent than along-beach changes. Medium sand (1.0–$2.0\,\phi$) dominates both the lower foreshore and upper backshore which are two quite different dynamic zones. These two areas are separated by either coarse or very coarse sand which grades into gravel. The Kowhai River and Stoney Creek discharge in the middle of this sandy area, but at the time of sampling there was no distinct change in mean size associated with either outlet. On the other hand, the proximity of the Kahutara River at the extreme western end of the beach, clearly accounts for the existence of gravel on the lower foreshore at station 1.

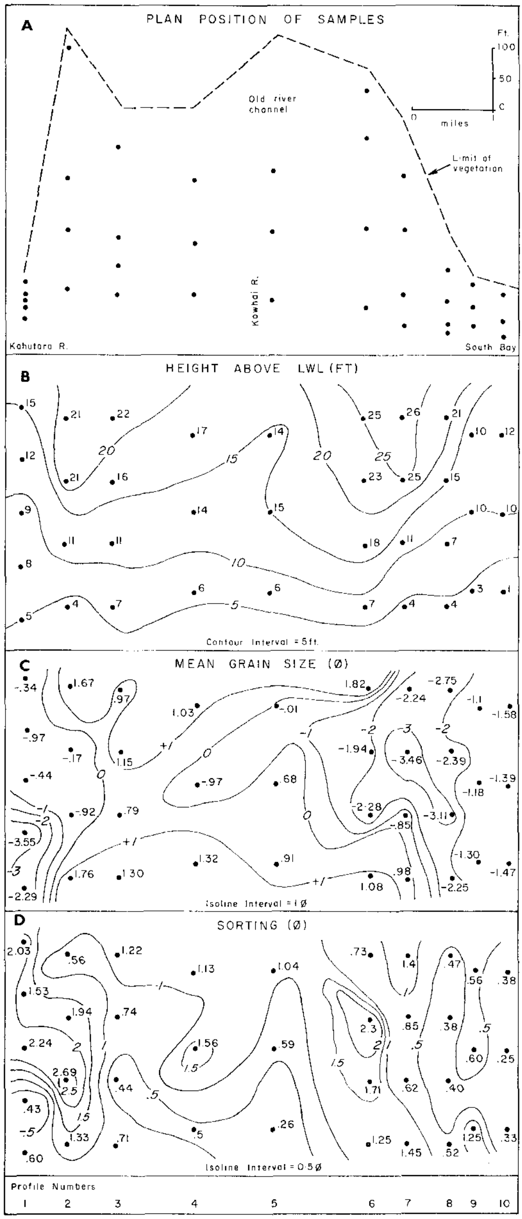

FIG. 5—Spatial and physical parameters of samples from "South Beach", Kaikoura. (A) Plan positions; (B) Topography; figures at each sample position refer to elevation; (C) Distribution of values for mean grain size; (D) Distribution of values for standard deviation (sorting)

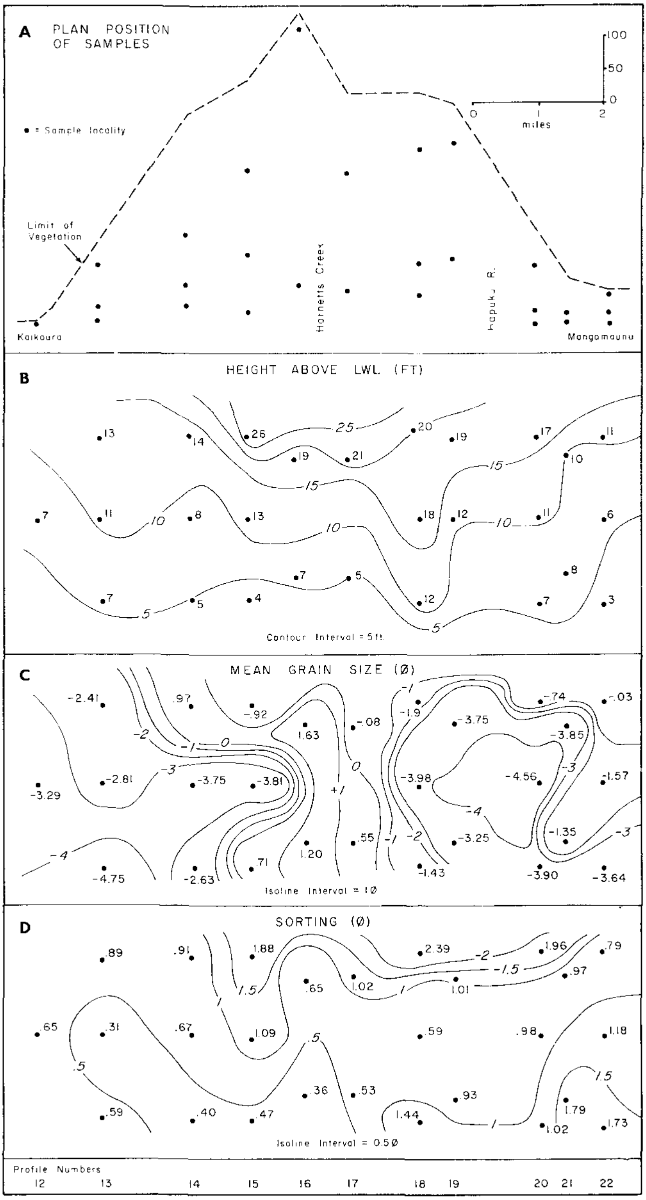

FIG. 6—Spatial and physical parameters of samples from "North Beach", Kaikoura. (A) Plan positions; (B) Topography; figures at each sample position refer to elevation; (C) Distribution of values for mean grain size; (D) Distribution of values for standard deviation (sorting)

Sorting (σ_I): As with mean size, the distribution of sorting values on "South Beach" reveals a complex, but non-random, pattern. Areas of similar sorting can be differentiated (*see* Fig. 5D). The largest area of best sorting occurs at the eastern end of the beach. Seven of the 10 samples at stations 8, 9 and 10 are well or very well sorted, and the other 3 samples have values close to the well sorted class. Clearly the good sorting here is associated with the gravel deposit described above. Good sorting also occurs on the foreshore of the central part of the beach, here being mainly associated with medium-sized sand.

Sorting values increase (i.e., sorting is poorer) laterally and shorewards from these two modes of good sorting. In the central portion of the beach there is a broadly zonal gradation shorewards from good to poor sorting; the medium sand on the upper foreshore is poorly sorted (1.0–2.0 ϕ). The Kowhai River outlet causes no obvious break in these sorting trends.

Poorest sorting (very poor) is found at stations 1, 2 and 6. The position of these samples on the margins of the major areas of gravel and sand indicate interfingering of these two deposits and mixing of the two size grades to form bimodal curves with mean sizes in the 0 to $-2\ \phi$ range.

"NORTH BEACH"

The plan outline of "North Beach" is less regular than that of "South Beach". Fig. 1 shows it can be divided into two parts, a southern part concave to the sea, and a northern part convex to the sea, which are linked with the delta-fan of the Hapuku River. However, the northern beach, like its southern counterpart, is widest in its central portion and diminishes in width towards the ends (*see* Fig. 6A). Low sand dunes caused the elevations above 20 ft in the central portion (*see* Fig. 6B). Slopes of the beach-face increase away from the centre.

Mean grain size (M_z): Fig. 6C demonstrates that alongshore changes in mean grain size are more distinctive than across-shore changes. At both ends of the beach large deposits of gravel occur, separated from one another by a 2–3 mile stretch of sand. The northern gravel zone has the coarsest material at stations 19 and 20, which are located south and north of the Hapuku River mouth. Further north medium pebbles are replaced by small pebbles, very small pebbles and granules in the mid-shore, and by very coarse sand on the backshore. Nearer the LWL small pebbles form the shore at stations 19, 20 and 22. Beneath the surface in this northern area the basement of much larger sizes—cobbles and boulders—is often exposed.

South of the Hapuku River, between stations 17 and 18, a rapid change in size takes place, from gravel to sand. Coarse and very coarse sand is replaced at station 16 by medium-sized sand. Gravel sizes characterise the whole of the southern segment of the beach. In the mid-shore area a salient of gravel extends northwards to station 15 causing a separation of sand on the lower foreshore from that on the wide backshore. No samples in the southern gravel zone depicted here have means in the granule category, although subsequent sampling at profile 11 (*see* Fig. 1), indicate granules roughly similar in size and sorting to those at stations 9 and 10 on "South Beach". There is thus a decrease in mean grain size south of station 12.

Across shore variations in size are not as noticeable here as on the South Beach, although at most stations the coarsest material occurs on the lower parts of the beach.

Sorting (σ_I): Despite the wide variation in mean grain size and the sharp lateral divisions between the one sandy and two gravel areas, the pattern of sorting values is relatively simple (*see* Fig. 6D). There is no abrupt change in sorting patterns at the Hapuku River. The whole area is characterised by moderate sorting, with 12 of the 27 samples being moderately well or moderately sorted. Moderate sorting is not associated with any one particular size grade on the beach. Instead it occurs in samples with means ranging from the finest to coarsest sizes. Each station has at least one moderately sorted sample.

Sorting is poorest on the backshore from profiles 15 to 21 and on the lower foreshore from profiles 18 to 22. No well-sorted sample occurs north of station 16.

Well-sorted samples, like those of the moderate and poorly sorted sediments, cover a wide range of sizes from sand to gravel. Such samples are limited to the southern segment of the beach, seaward of the mid-shore line at stations 13–16.

In summary, it is evident from Fig. 6D that although moderate sorting values are found all along the beach, materials in the northern portion are on the whole much more poorly sorted than those in the south. Thus, sorting improves the further away one gets from the Hapuku River mouth.

ALONG-BEACH VARIATIONS

Figure 7 portrays the gross changes in size and sorting along the two beaches. To obtain the values plotted, mean grain size and sorting values of samples at each profile station were summed and the mean and standard deviation of the combined samples calculated. Values now refer to the station (profile) as a whole rather than to individual samples. The solid line linking the station means on Fig. 7 gives an indication of the alongshore trends, while the length of the barbed horizontal lines indicates the degree of variation across the beach at each station.

GRAIN SIZE TRENDS

The absence of a single unidirectional change in grain size along either beach is clear. Instead a cyclic pattern is indicated. Two major inflexion points are portrayed on each curve—at stations 3 and 8 for "South Beach" and at stations 16 and 19 for "North Beach". On both beaches there is a change away from the ends of beaches from gravel to sand and back to gravel. In detail, however, the sequence differs: along the southern beach, the trend is from granules (station 1) to coarse sand (2) and medium sand (3) at the inflexion point, then back to coarse sand (4) to very coarse sand (5 and 6) to granules (7) and very small pebbles (8) returning to granules (9 and 10). On the northern beach, the range of sizes covered as well as the strength of the major inflexion point is

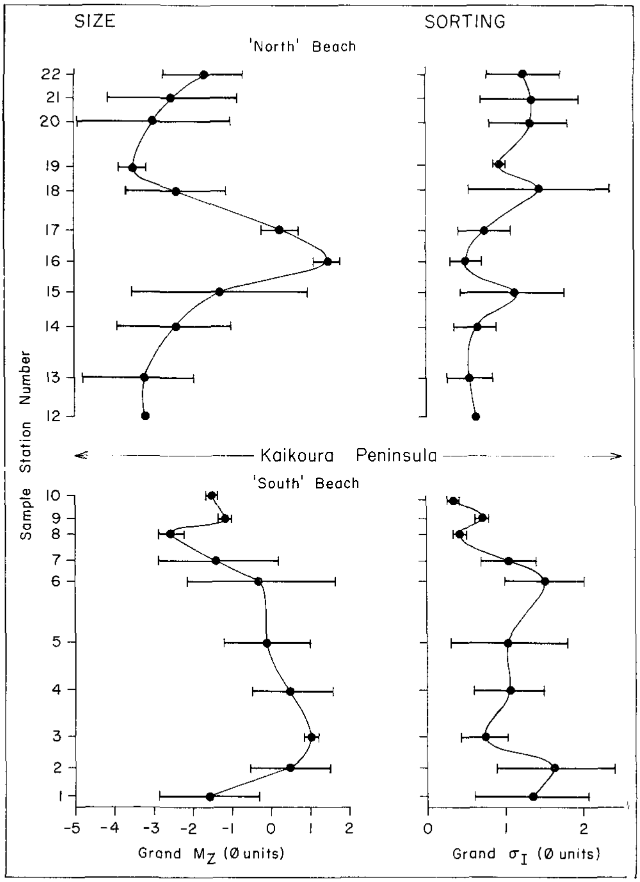

FIG. 7—Summary of along-beach trends incorporating across-beach variations in mean grain size (M_z) and sorting (σ_I) for two Kaikoura beaches. Station means (linked between stations) are shown as solid circles, which bisect horizontal lines representing their ranges of standard deviation

greater. Here the sequence passes from small pebbles (stations 12 and 13) to very small pebbles (14) to granules (15) and medium sand (16) where the strongest inflexion occurs, to coarse sand (17) to very small pebbles (18) and small pebbles (19) at the second inflexion point returning to very small pebbles (20 and 21) and granules (22). The rhythmic nature of the distance : size relationship is readily apparent on both beaches.

It could be argued that these sequences are somewhat unrealistic because of the large across-beach variation in mean size (evidenced by a large standard deviation) at many stations. For instance, at stations 1, 5, 6, 7, 15, 21 and 22, the standard deviation includes both sand and gravel fractions. Such overlapping indicates the presence of a large range of sizes over a small distance and also reveals the truly heterogeneous nature of the materials across parts of a mixed sand-shingle beach. On the other hand, the spread of mean sizes at the other 14 stations are such that they do not cross grades. The means are all restricted either to the sand grade or to the gravel grade. Moreover, at each of the inflexion points, the stations have a low standard deviation for size (as well as a low standard deviation for sorting) showing that at these locations across beach variations in size (and sorting) are minimal. The inflexions for both beaches occur roughly in the same size fractions, medium to coarse sand and small to very small pebbles. These inflexion points can be related back to the scattergram of size-sorting (*see* Fig. 4) where the size : sorting curve shows inflexions towards the best sorting at the same grain sizes. There is thus a link between the three types of sediment differentiated on the size : sorting plot and their spatial distribution along the two beaches.

The three sediment size types distinguished were:

(1) sand,
(2) gravel, and
(3) mixed sand-gravel.

These three types are distributed systematically along both beaches, with the mixed grades interpolated between the sand and gravel.

SORTING TRENDS

The alongshore distribution of sorting values plotted on Fig. 7 like those for size, show considerable variation. Again a distorted cyclic pattern is indicated. In the distance : sorting relationship however, there are five inflexion points, which indicate frequent shifts between better and poorer sorting, along both beaches. If the sorting values are divided into two broad classes—good sorting with mean values $< 1\ \phi$ unit and poor sorting with mean values $> 1\ \phi$ unit—the along-beach rhythms in sorting are as follows:

(1) "South Beach": poor to good to poor to good sorting;
(2) "North Beach", from south to north: good to poor to good to poor to good to poor sorting.

These detailed shifts in sorting are superimposed on an overall trend which indicates sorting improves in general from west to east on "South Beach", and from north to south on "North Beach".

TABLE 4—Textural zones along two Kaikoura beaches

"SOUTH BEACH" (From west to east)			"NORTH BEACH" (From south to north)		
Zone	Size	Sorting	Zone	Size	Sorting
1	Mixed	Poor	1	Gravel	Good
2	Sand	Good	2	Mixed	Poor
3	Mixed	Poor	3	Sand	Good
4	Gravel	Good	4	Mixed	Poor
			5	Gravel	Good
			6	Mixed	Poor

The position of the inflexion points on the distance : sorting plot can be compared with the position of those on the distance : size plot (*see* Fig. 7). Inflexions in the good sorting class correspond to inflexions on the size curves, which are firmly associated either with pure sand or pure gravel. On the other hand, inflexions within the poor sorting class correspond in position to the mixed sand–gravel grade, i.e., to a position intermediate between the inflexion points on the size plot.

In summary, both Kaikoura beaches can be spatially differentiated into characteristic textural zones–based on grand mean grain size and grand mean sorting—which vary rhythmically alongshore. These zones are listed in Table 4.

ACROSS-BEACH VARIATIONS

The magnitude of variations in grain size and sorting across a beach are a response to:

(1) the zonation of hydrodynamic processes, and
(2) the charateristics of the available material.

Where a large size range is available certain sizes may be preferentially deposited and distinctive textural zones parallel with the shore are produced. Large variations in size and sorting values across the beach may result. Conversely, where the material available for shore-normal transport is of a uniform size, grading is not possible and across-beach variations in size and sorting are minimal. Both states occur on the Kaikoura beaches (*see* Fig. 7), e.g., stations 8, 9, 10, 16 and 19 have small standard deviations in both size and sorting. The whole shore, from lower foreshore to upper backshore is texturally homogeneous. On the other hand, the large standard deviations shown for stations 1, 6, 15, 18 and 20 indicate large changes in size and sorting across the beach.

"NORTH BEACH" AND "SOUTH BEACH" COMPARED

Because alongshore shifts in grain size and sorting are roughly similar, it seems reasonable to hypothesise that variations in size and sorting across the two beaches are not significantly different. Student's *t* tests were performed to evaluate the validity of this comment.

TABLE 5—Values for Student's *t* test applied to grain size and sorting for each across-beach level, "North Beach" compared with "South Beach" (d.f. = degrees of freedom; P = probability; S = significant: NS = not significant)

	Level	d.f.	*t*	P	Significance
GRAIN SIZE					
	Lower foreshore	8	1.6	0.2 –0.1	NS
	Middle foreshore	16	2.2	0.05–0.02	S
	Upper foreshore	16	2.1	0.05	S
	Backshore	16	0.91	0.4 –0.3	NS
SORTING					
	Lower foreshore	8	0.51	0.7 –0.6	NS
	Middle foreshore	16	0.71	0.5 –0.4	NS
	Upper foreshore	16	0.44	0.7 –0.6	NS
	Backshore	16	0.46	0.7 –0.6	NS

Both beaches were divided into four levels arranged parallel to the shore; the divisions were based on a 5 ft contour interval. Although such elevations all along the beach cannot be equated with any single morphological unit, the lower foreshore corresponds approximately to the 0–5 ft level, the middle foreshore to the 5–10 ft level, the upper foreshore and berm crest to the 10–15 ft level, and the berm and backshore to the above 15 ft level. These levels and the sample points within them are illustrated in Figs 5B and 6B.

Results of Student's *t* tests for the four levels are given in Table 5. There is no significant difference in sorting at any level. The sizes of material on the lower foreshore and backshore are also similar. It is only at the intermediate levels that the sediments differ appreciably in size. The average sizes in the middle and upper foreshore of "North Beach", $-2.65\,\phi$ and $-2.16\,\phi$ respectively, are coarser than their "South Beach" counterparts, $-0.62\,\phi$ and $0.78\,\phi$ respectively. These differences reflect the fact that:

(1) the material available on the shore is in general coarser on the northern beach; and

(2) frequent mixing and winnowing of the foreshore allows the coarsest material to form a lag deposit in the middle of the beach while the finer material either accumulates on the backshore above the limit of the normal wave action, or on the lower foreshore where it is subjected to temporary deposition but frequent movement.

CONCLUSIONS

This paper is based on analyses of 64 surface samples collected from two adjacent mixed sand-shingle beaches on the Kaikoura coast. Mixed beaches, rare on a world-wide scale but not uncommon in New Zealand, are complex coastal deposits which merit scientific attention. Because the present investigation was a pilot study, the aims, the descriptive and comparative techniques and even the number of textural properties considered were rather limited. (Subsequent work has involved twelve monthly profile and sediment surveys, plus collection of data on wave processes (height, period and direction), at each of the stations described here. This more complete evidence on the nature and behaviour of mixed beaches will be reported elsewhere.)

Both Kaikoura beaches can be classified as exposed high-energy beaches. They possess sediments derived almost wholly from the greywacke rocks of the Seaward Kaikoura Range which have been transported to the shore by three main rivers, the Kahutara, Kowhai and Hapuku. Sample to sample variation in size and sorting values are large, and along-beach and across-beach distributions are complex. However, certain regularities to do with sediments themselves and their spatial distributions are apparent:

1. Samples with unimodal frequency distributions include median grain sizes distributed over the whole range of sampled sizes, from medium sand to medium pebbles. These samples are very well to moderately well sorted.
2. Samples with bimodal frequency distributions include median grain sizes over the same range of sampled material, but display two strong modes, one in the 0 to 2 ϕ fraction (medium-coarse sand), the other in the $-2.5\ \phi$ to $-4.5\ \phi$ fraction (pebbles). The relative proportions of these two modes account for the range of median diameters. Sorting is poor to very poor.
3. Bimodal samples arise from a mixing of gravel and sand modes. They display a deficiency in the 0 to $-2\ \phi$ (very coarse sand and granules) range. While the source area hyopthesis of Folk is an attractive interpretation for the bimodal sediments, it is by itself unsatisfactory for the Kaikoura beach sediments as a whole, because 10% of the total samples collected were well-sorted, unimodal samples occurring in the 0 to $-2\ \phi$ mean grain size category. A speculative suggestion is that greywacke rocks breakdown into all sizes, and, although the two modal beach populations described by Folk may be important, they are not wholly "dominant" (Folk 1966, p. 81.)
4. A distorted sinusoidal curve describes the average grain size: sorting relationship, with poorest sorting found in size grades intermediate between coarse sand and small pebbles. This curve corresponds roughly to that described by Folk (1965); the poor sorting results from mixing of the sand and gravel fractions. As mentioned above, this is a satisfactory explanation for bimodal samples, possessing mean grain sizes in the 0 to $-2\ \phi$ category, but the best sorted unimodal samples also occur in this size range. Differences in hydrodynamic processes and especially the length of time that these have been operative are possible reasons for this anomalous segregation.
5. All samples, 37 from "North Beach" and 27 from "South Beach", were compared. Student's t tests showed mean size to be significantly different—the material on the northern beach being considerably

coarser than that on the southern beach. The likely reason is that bed material in the Hapuku River, which provides an immediate potential source of sediment to "North Beach", is larger than that in rivers discharging on to "South Beach". Sorting values are, however, not significantly different, presumably because both are similar high-energy beaches.

6. Comparison of samples taken from four levels across the two beaches revealed no significant difference in sorting values. Sizes on the lower foreshore and backshore were also similar, but samples in the middle and upper foreshore of "North Beach" were significantly coarser than those on "South Beach".
7. Plan plots of the two sample parameters indicate complex spatial patterns. No single unidirectional trend, either away from the major rivers or the ends of the beaches, characterises the size and sorting patterns of either beach. Nor are the distributions random: broadly speaking, both beaches possess the coarsest material towards their ends and the finest in the centre. Sorting generally improves towards the Peninsula but not in a regular fashion. These patterns cannot be explained satisfactorily by processes only operating now. The textural maturity of the gravel zones nearest the Kaikoura Peninsula and furthest from any present source river suggests that at least these deposits accumulated in the past.
8. The expected well-developed zonal arrangement of particle properties across the two beaches was not found. Instead, examples of both large and small mean sizes and good and poor sorting were found at all levels from lower foreshore to upper backshore. Two reasons can be given for this situation. Firstly, shore-normal variations are closely allied with gross longshore changes, and, secondly, the very turbulent swash/backwash processes cause continual mixing of the beach deposit.
9. Station size and sorting averages and standard deviations were computed using individual sample values from each transect. Three size and two sorting classes were distinguished for the station aggregates. Both size : distance and sorting : distance plots for the two beaches described S-shaped curves with inflexion points in the good sorting classes, sand and gravel. These were separated spatially by mixed sand–gravel deposits possessing poor sorting. This cyclic pattern, which differentiates textural zones, indicates that although some beaches may be classified as mixed beaches, not all portions of those beaches possess mixtures of sand and gravel.

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APPENDIX 1—Mean grain size and sorting values of samples (figures in the sample column refer to profile numbers, and letters to sampling positions; "a" is the most shoreward station)

Sample	Grain size M_z (ϕ units)	Sorting, σ_I (ϕ units)
1a	− 0.34	2.03
1b	− 0.97	1.53
1c	− 0.44	2.24
1d	− 3.55	0.43
1e	− 2.79	0.60
2a	1.67	0.56
2b	− 0.17	1.94
2c	− 0.92	2.69
2d	1.26	1.33
3a	0.97	1.22
3b	1.15	0.74
3c	0.79	0.44
3d	1.30	0.71
4a	1.03	1.13
4b	− 0.97	1.56
4c	1.32	0.50
5a	− 0.01	1.04
5b	0.68	0.59
5c	0.91	0.26
6a	1.82	0.73
6b	− 1.94	2.30
6c	− 2.28	1.71
6d	− 1.08	1.25
7a	−2.29	1.40
7b	− 3.46	0.85
7c	− 0.85	0.62
7d	0.98	1.45
8a	− 2.75	0.47
8b	− 2.39	0.38
8c	− 3.11	0.40
8d	− 2.25	0.52
9a	− 1.10	0.56
9b	− 1.18	0.60
9c	− 1.30	1.13
10a	− 1.58	0.38
10b	− 1.39	0.25
10c	− 1.47	0.33
12	− 3.29	0.65
13a	−2.41	0.89
13b	− 2.81	0.31
13c	− 4.75	0.59

Sample	Grain size M_z (ϕ units)	Sorting, σ_I (ϕ units)
14a	0.97	0.91
14b	− 3.75	0.67
14c	− 2.63	0.40
15a	− 0.92	1.88
15b	− 3.81	1.09
15c	0.71	0.47
16a	1.63	0.65
16b	1.20	0.36
17a	− 0.08	1.02
17b	0.55	0.53
18a	− 1.90	2.39
18b	− 3.98	0.59
18c	− 1.43	1.44
19a	− 3.75	1.01
19b	− 3.25	0.93
20a	− 4.56	0.98
20b	− 3.90	1.02
20c	− 0.74	1.96
21a	− 3.85	0.97
21b	− 1.35	1.79
22a	− 0.03	0.79
22b	− 1.57	1.18
22c	− 3.64	1.73