

On 21 November 1967 (Fig. 5) the temperature pattern is shown for a night-time case where the northeast wind did not die down. At the time of the traverses it was cloudy ($\frac{3}{4}$ of stratocumulus at 1500 feet) with a northeast wind of 10 knots. The air was thus well stirred and there was only 4°F difference between central city temperatures and those on the outskirts. The temperature contrasts between warm and cool areas were much reduced and the temperature minimum over Hagley Park was not present. The reality of the warm areas in the northwest, for which no explanation was found, was verified by a number of intersecting traverses.

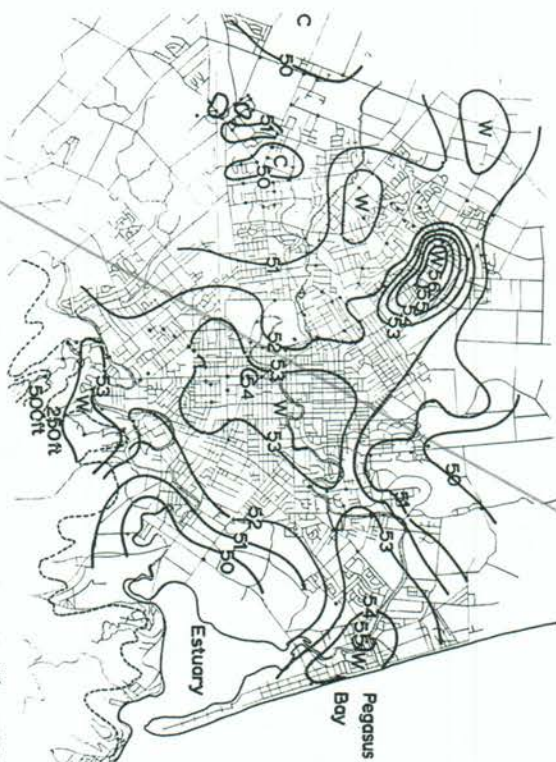


Fig. 5. Surface temperature at 2200-2330 hours NZST on 21 November 1967. The weather was cloudy with a northwest wind of about 10 knots.

CONCLUSIONS

The city of Christchurch is able to modify considerably the temperature field over the city area. At night in all cases studied a heat island was present whose size and intensity depended on the daytime heating, and on the cloud amount and wind at the time the temperatures were measured.

In calm or light wind conditions temperatures were warmest in the city centre (Cathedral Square) area and there was a large temperature gradient between the Square and Hagley Park.

In the small sample of temperature patterns obtained it was seen that expansion of the city between 1954 and 1967 has had only minor effect on the night-time temperature fields. The effect is seen in an increase in gradient between the northern suburbs and their neighbouring undeveloped outskirts.

Beach Erosion and Coastal Development in the Canterbury Bight

R. M. KIRK

A DISTINGUISHING FEATURE of many New Zealand beaches is the mixed sand and shingle nature of the beach deposit. This is especially true of many East Coast, South Island beaches where the sediments are derived from the outwash products of multiple Pleistocene glaciation of the alpine greywackes. Such beaches have been little studied in the past.

The largest beach of this type is the 'Ninety Miles Beach' of the Canterbury Bight and the primary aim of this report is to describe the present state of the coast in relation to equilibrium theories of beach development.¹ Previous study of the Canterbury Bight has been concerned with the history and development of the Canterbury Plains as a whole and with overall coastal changes in the post-Pleistocene interval.² Though these studies provide the setting for the present investigation the major concern here is with present coastal processes. This will involve a consideration of changes in the beach over the last century.

The present coast of the Canterbury Bight is geologically Recent. It is composed of cut and built elements developed on alluvial gravels, sands and silts known to be more than 2000 feet thick.³ Shoreline elements comprising the 84 miles between headlands include the cliffed retreating margin of the combined alluvial fans of the major rivers, the present river mouths and lagoons, and wave-built barrier beach ridges. The latter, together with their associated dunes, tie the plains to Banks Peninsula in the north and to the Timaru lava flows in the south (Fig. 1). Gravels underlie the shallow, gently sloping floor of the bight for a distance of several miles and a maximum Pleistocene lowering of

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¹ This report presents some of the information gathered during the preparation of a Masters Thesis at the University of Canterbury.

² J. von Haast: *The Geology of Canterbury and Westland*, Christchurch, 1879, pp. 309-401; R. Speight: 'The Lake Ellersmere Spit', *Trans. N.Z. Inst.*, Vol. 61, 1930, pp. 147-69; R. Speight: 'An Eroded Coastline', *Trans. Roy. Soc. N.Z.*, Vol. 78, 1950, pp. 3-13.

³ J. Henderson: 'The Chertsey Oil Bore', *N.Z. Geol. Survey 16th Annual Report*, Wellington, 1922, p. 12.

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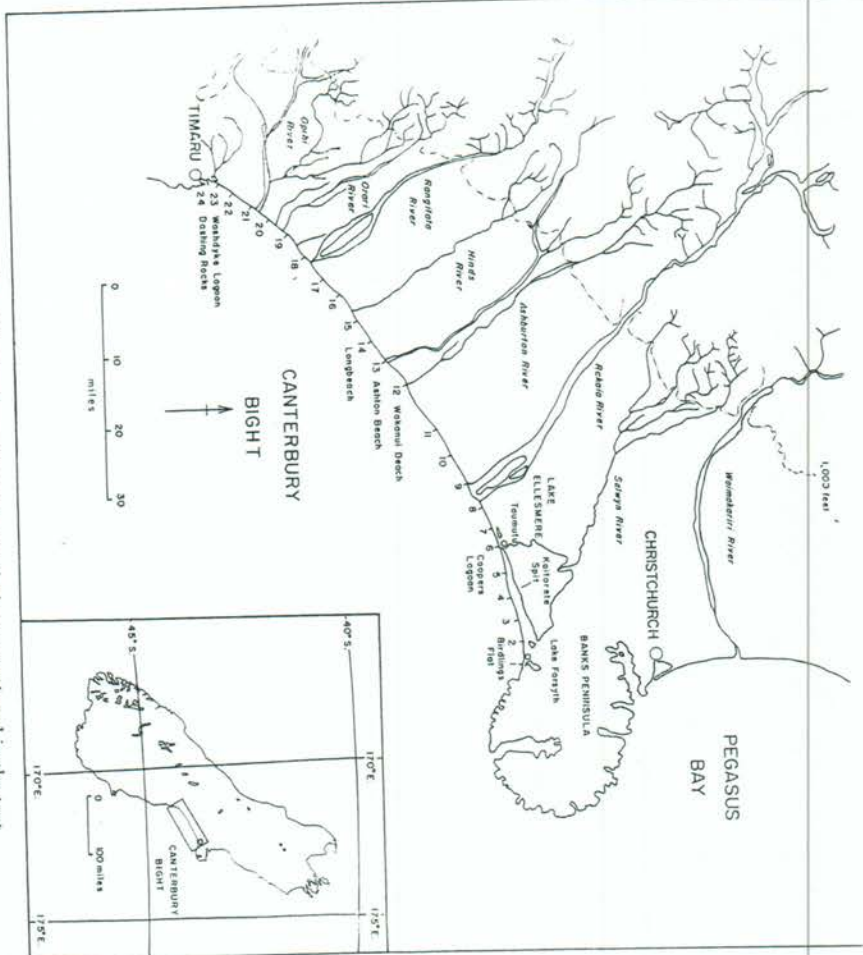


Fig. 1. Location of the beach profile stations and places mentioned in the text

sea level by 100 metres, a generally accepted figure, would place the shoreline 30 miles further east than the present position.⁴

Coastal adjustments to the post-Pleistocene rise in sea level have resulted in cliffing, gullying and erosion of the seaward edges of the fans and a northward drift of sand and gravel forming the 12,000 acres of Kaitorete Spit.⁵ The six major rivers reaching the sea along the coast must also be considered as sources of the sediments involved in this northward drift. Old barrier beaches on Kaitorete Spit standing at 12 to 15 feet above present sea level attest to a probable post-Pleistocene higher level of the sea which has been dated to 5000 years B.P. in the Christchurch area.⁶ Subsequent time has seen a fall in sea level to the present stand and the building of an extensive dune system rising to 26 feet above sea level along the seaward edge of the spit.

Figure 1 shows that the present shoreline is oriented NE-SW and faces to the SE. As such it is a high energy shore exposed to highly variable and often severe wave action emanating from storm centres in the Pacific Ocean. Fetch is unlimited since the largest waves known can probably be generated in a fetch length of 500 miles. There are thus considerable variations in the size of waves received at the beach as well as rapid changes in wave approach direction. It has been suggested that under present conditions there is a persistent northward drift of gravel in the Canterbury Bight and the high rate of erosion of much of the coast has been noted, but beyond these observations very little is known of the nature of coastal erosion and the movements of beach materials along the Canterbury Bight.⁷ Some of the results of an investigation into these problems are presented and discussed in this report. The results are derived from two separate but closely related avenues of beach research. A consideration of field observations and analysis of the beach profile forms and changes over short term, seasonal and long term periods is followed by a discussion of the beach plan-form characteristics.⁸ In both sections comparisons with established theories of beach equilibrium are made. Finally conclusions about the present stage of coastal development are drawn from the discussion.

VARIATIONS IN BEACH PROFILES

Changes in the form, height and width of beach profiles occur with tidal, daily, seasonal and longer terms variations in wave energy. Short term changes are related to the changing pattern of wave energy. It has been established by numerous workers that low swell waves move materials onshore thus building profiles upward and outward. Conversely, high, steep storm waves erode beach profiles. Much sediment is moved offshore, while the larger sizes may be thrown high up the profile to build beach ridges. These short term variations also have a seasonal period since low swell waves tend to occur more frequently in summer while storm waves are more characteristic of winter. Thus beach profiles undergo an annual cycle of summer fill and winter cut.

Long term changes depend upon the balance between the supply of sediments from rivers, cliffs and other sources; and losses due to the winds, waves and currents acting on the beach. 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 profile will

⁴ J. D. Raeside: 'Loess Deposits of the South Island, New Zealand, and Soils Formed on Them', *N.Z. Journ. Geol. & Geophysics*, Vol. 7, 1964, pp. 81-138.
⁵ Speight: 'The Lake Ellesmere Spit', *Trans. N.Z. Inst.*, Vol. 61, 1930, pp. 147-69.
⁶ R. P. Suggate: 'Late Quaternary Deposits of the Christchurch Metropolitan Area', *N.Z. Journ. Geol. & Geophysics*, Vol. 1, 1958, pp. 103-22.

⁷ E. L. Elliott: 'Sandspits of the Otago Coast', *N.Z. Geogr.*, Vol. 14, 1958, pp. 65-74; Speight: 'An Eroded Coastline', *Trans. Roy. Soc. N.Z.*, Vol. 78, 1950, pp. 3-13.
⁸ Short term is defined as periods of time in hours and days rather than in seasons or longer periods, while long term refers to periods of time in decades. The results of detailed study of the beach processes and sediment properties are to be presented in a subsequent paper.

prograde relative to a set of fixed co-ordinates. It is said to be 'over-nourished'.⁹ 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 the profile is 'undernourished' in Bruun's terminology and retro-gradation of a flatter profile occurs. Longshore transport is of a lesser order.

Between these two extremes of long term profile change is an equilibrium configuration where 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.¹⁰ With these general considerations in view it is now possible to describe and interpret firstly the short term and seasonal changes, and secondly, the long term changes in the beach profiles of the Canterbury Bight.

The 24 profile stations shown in Figure 1 were spaced at an average distance of three miles apart along the bight. They were surveyed at four intervals during the seven month period between November 1966 and June 1967, thus covering the seasonal variation in wave activity. Several southerly storms occurred during the period. Survey equipment comprised a compass, tape, ranging rods and an Abney Level. Successive profile curves were superimposed on graph paper and the areas under each set of curves were converted to volumetric changes by considering a one foot wide strip of beach along each profile line.

There are three types of profile along the beach. In the north along Kaitorete Spit and south of the Rangitara River the beach is broad, planar or convex upwards and composed of pebbles, and medium and coarse sand. The second type is the cliff-front profile which is extensive in the area from Taumutu to the Rangitara River. Profiles are typically short, steep and comprised of pebbles and cobbles. Isolated sand stringers occur between high and low water marks and on the backshore near the cliff base. Slumping and sliding of the cliff face ensures a continual supply of fresh sediment to these profiles. The turbulent swash of southerly storm waves serves to remove this material from the profiles thus preparing the face for future slumping. River mouth profiles form the third type and are similar to those of the cliff zone but are wider and have pronounced storm berms. All of the river mouth profiles are backed by lagoons.

Figure 2A demonstrates that the average seasonal profile variation was small. It can be seen that both erosion and deposition occur at all times of the year but a change from net deposition in summer to net

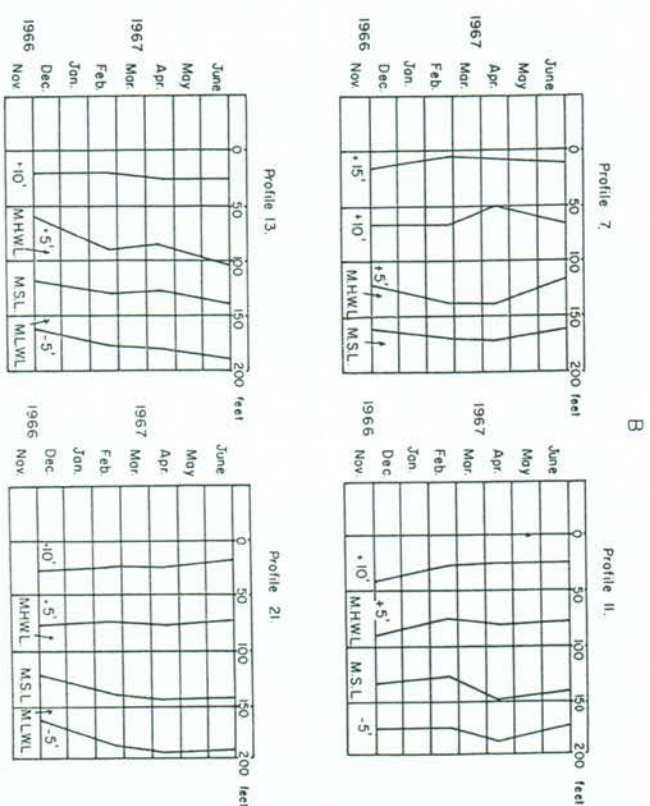
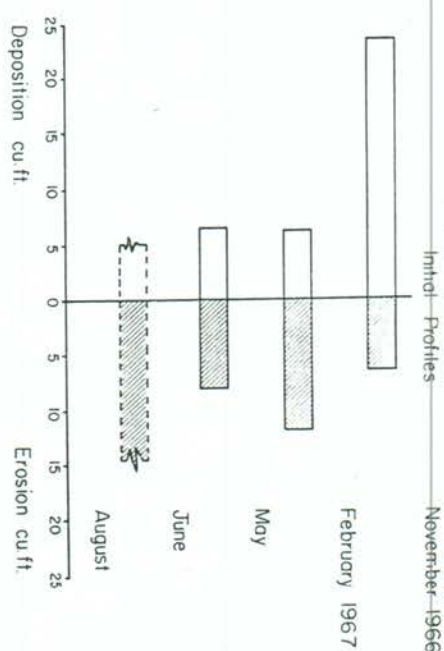


Fig. 2. Seasonal variation in the beach profiles. A. Average volumetric change. B. Isopeith diagrams showing the seasonal movements of selected beach contours at four stations

erosion in winter is also apparent. The average volume of accretion in summer was 25 cubic feet per profile and the average volume of erosion in winter was eight cubic feet. The low figure for winter erosion probably reflects the early cessation of surveying. The dotted segment of Figure 2A indicates the probable orders of erosion and deposition at the end of winter. Maximum recorded deposition was

⁹ P. Bruun: 'Use of Small-Scale Experiments with Equilibrium Profiles in Studying Actual Problems and Developing Plans for Coastal Protection', *Trans. Amer. Geophys. Union*, Vol. 35, 1954, pp. 445-50.
¹⁰ W. F. Tanner: 'The Equilibrium Beach', *Trans. Amer. Geophys. Union*, Vol. 39, 1958, pp. 889-91.

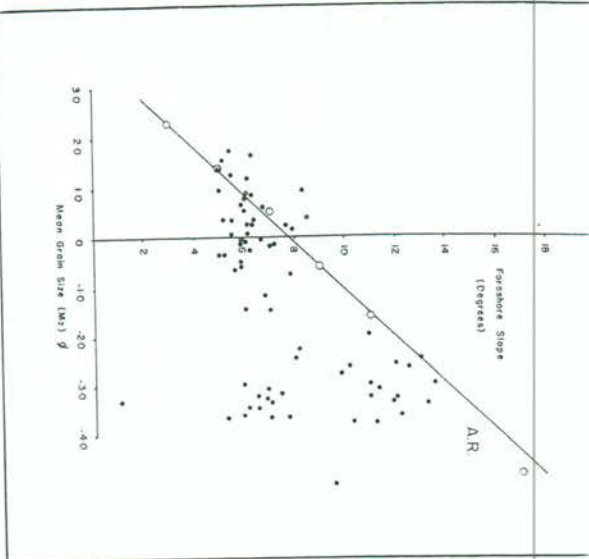


Fig. 3. The relationship between mean grain size (Mz_0) and beach fore-shore slope, A. The average trend. Dots indicate samples taken during this investigation

69.25 cubic feet and maximum erosion was 52.3 cubic feet, (both occurring at profile 1, Birdlings Flat). Minimum figures for both erosion and deposition were of the order of two to three cubic feet per profile. Such small magnitudes of change may be ascribed to survey error. Also, it is probable that variations of this order occur over single tidal cycles.

Since all of the profiles are at least 200 feet long an average change of even 25 cubic feet between surveys amounts to little more than 0.125 feet of deposition per linear foot of profile. This data therefore suggests little short term or seasonal variation in the beach profiles. This is an unusual result on a shingle beach where wave energy levels are consistently high. Such beaches are noted in the literature for rapid and large orders of change.¹¹

Further, analysis of the relationship between mean grain size and foreshore slope (indicated in Fig. 3), reveals that relative to the average trend the beach profiles of the Canterbury Bight have consistently low slopes.¹² This together with the observed low order of profile variation suggests a short term erosional equilibrium related to storm wave action.

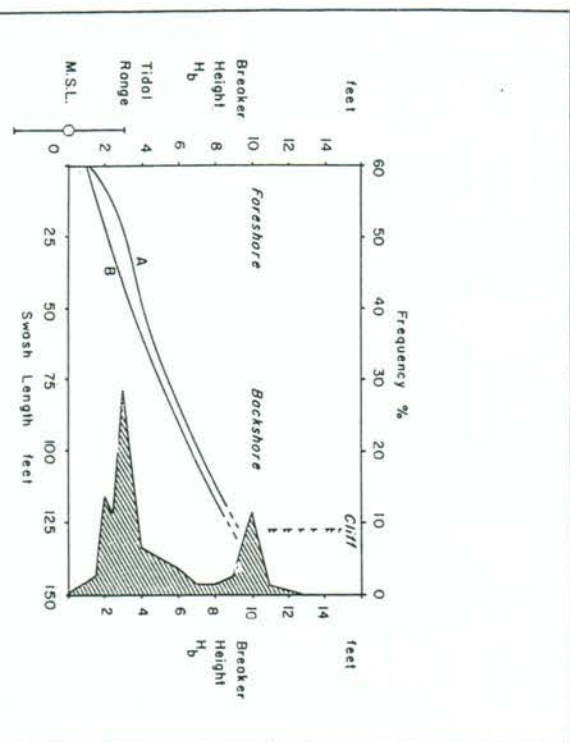
The movements of selected beach contours shown in Figure 2B demonstrate how this is effected. Observations have shown that the surf on the beach is predominantly of the plunging type so that these profile changes are produced almost entirely by variations in the wash and backwash of broken waves.¹³ Figure 4 indicates that the main

control of swash length is breaker height. Higher breakers result in longer, more turbulent swash and hence greater erosion of the profile. It is clear from the frequency polygon in Figure 4 that the distribution of swashes on the beach is strongly bimodal. More than 30 percent of all swash is confined to levels below high water mark. This mode is produced by the prevailing southeasterly swell which results in breakers averaging 4.3 feet high at the shore. The swash of these waves is responsible for producing the swash berms at high water mark on the profiles. Profiles with such a berm have a swash length pattern indicated by line 'A' in Figure 4. The summer growth of these berms is apparent from the movements of the zero and +5 feet contours on Figure 2B. However, it can be seen that the effects of this constructive activity are not large.

Figure 4 also exhibits another swash mode corresponding to breaker heights of approximately 10 feet. This is associated with southerly storm wave action. The swashes of these waves are typically 125 to 150 feet long, more than sufficient to overtop river mouth berms and to scour the cliff base. These conditions are responsible for the retrogressive and/or stationary nature of the +10 feet and +15 feet contours in Figure 2B.

Swash berms built by low swell waves are quickly removed by storm waves and equally rapidly replaced by subsequent swell. However, this activity is usually confined to the lower one third of the

Fig. 4. The relationship between swash length and breaker height (H_b), and frequencies of occurrence of swashes of a given length. A indicates the swash pattern where a berm is present at H.W.L. as for swell conditions. B represents storm wave conditions, when the berm has been eroded



¹¹ For example, lateral erosion of up to five feet in three hours and vertical cut of two to three feet of shingle in one hour have been recorded at Chesil Beach, Dorset, England. See C. A. M. King: *Beaches and Coasts*, London, 1959, pp. 280-81.

¹² E. P. Shepard: *Submarine Geology*, 2nd Edit., New York, 1963, p. 171.

¹³ R. M. Kirk: *Beach Morphology and Sediments of the Canterbury Bight*, Unpub. M.A. Thesis, University of Canterbury, 1967.

available profile length so the effect is small. (Compare lines A and B in Fig. 4). Most of the profiles have low, planar slopes above high water level and these appear to be adjusted to the long, turbulent, erosive swashes of southerly storm waves. Even local additions to profiles caused by cliff fall are quickly removed by storm swash and the beach slopes returned to their former conditions.

However, even though the short term state of the beach profiles is an erosional equilibrium, the long term trend is to pronounced coastal erosion. Analysis of profile records dating to 1931 (taken from four culverts between the mouth of the Rakai River and Taumutu), and

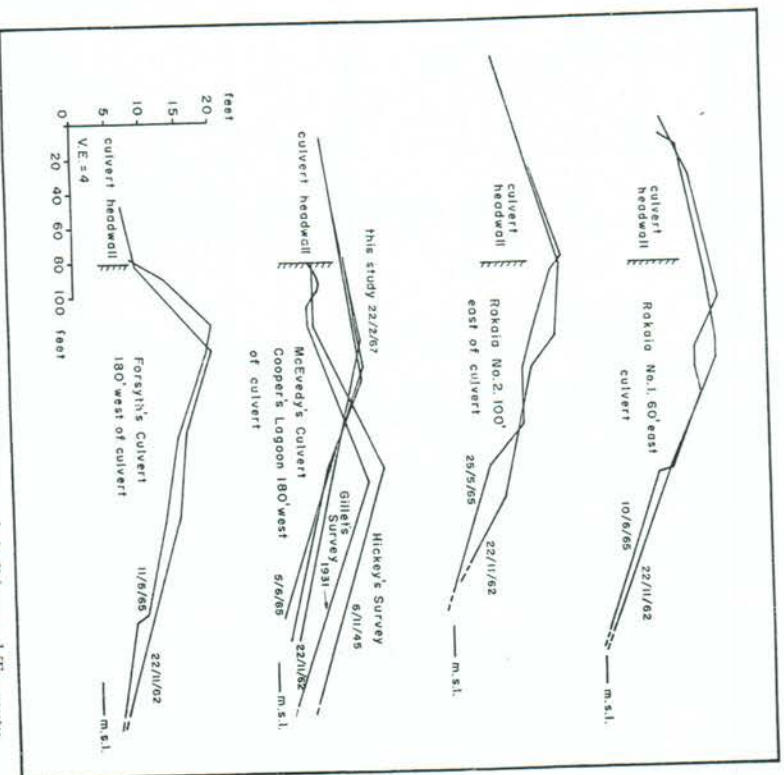


Fig. 5. Long term changes in beach profiles between the Rakai River and Taumutu

of old surveys dating to 1860 reveals erosion rates of up to three feet per year along much of the Canterbury Bight.¹⁴ Figure 5 indicates that there is a marked tendency for the beach to become wider and flatter as erosion proceeds. Coastal residents of long standing also report a trend toward finer grain sizes near Timaru.

¹⁴ Data from North Canterbury Catchment Board drawings Nos. L. 125 and Gch. 4846, and from the Black Map Series housed in the Lands and Survey Dept. Christchurch, especially maps Nos. BM115, BM71, BM43 and Timaru 1 and 2.

TABLE 1
RATES OF EROSION BETWEEN TAUMUTU AND THE RAKAI RIVER

Profile location North to South	1931-45 ft/yr	1945-62 ft/yr	1962-65 ft/yr	1965-67* ft/yr
NZMS 1. S. 93 725163 180 feet west of Forsyth's Culvert	—	—	3.2	—
NZMS 1. S. 93 703151 180 feet west of McEvedy's Culvert (profile 7)	0.15	3.0	1.67	5.0
NZMS 1. S. 93 692154 100 feet east of Rakai No. 2 Culvert	—	—	Nil*	—
NZMS 1. S. 93 674142 100 feet east of Rakai No. 1 Culvert	—	—	3.2	—

Accel./Decel. 1931-45 to 1945-62 1945-62 to 1962-65
at profile 7 + 0.178 ft/yr² - 0.133 ft/yr²
1962-65 to 1965-67
+ 1.332 ft/yr²

*Data gathered during this investigation

**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

Table 1 shows the rates of erosion at the four culverts and a measure of the acceleration or deceleration of erosion at profile 7 has been calculated according to Bruun.¹⁵ Even though the data are few it is clear that considerable fluctuation in the rate of coastal recession occurs.

¹⁵ P. Bruun: 'Coast Erosion and the Development of Beach Profiles', U.S. Army Beach Erosion Board Tech. Memo No. 44, 1954, pp. 1-79. On p. 22 the rate of acceleration or deceleration of erosion is given by $\frac{x+y}{2(V_2 - V_1)}$ ft/yr² where V_1 equals the rate in one period of x years, and V_2 the rate in the next period of y years. Acceleration is indicated by a positive sign and deceleration by a negative value of the ratio.

Between 1931 and 1965 the rate has accelerated and decelerated at least once, and now appears to be accelerating again. Though it is probable that similar fluctuations occur at other points along the coast it is important to note that the calculations are valid within the limits of survey error for profile 7 only.

It is thus clear that the beach profiles of the Canterbury Bight are similar in type to those described by Bruun as being 'undernourished'. They are best described as being at a subequilibrium stage of development. This is because they are in short term erosional equilibrium with both the prevailing southeasterly swells and with southerly storm waves. Fluctuations around this form have been shown to be minor but over a period of decades these small amplitude envelope curves are shifting landward as the cliffed coast erodes.

There is therefore an important distinction to be made between the short term equilibrium *form* of the profiles (which is a complex function of the prevailing, or most frequent swell and of storm waves); and the *position* of the profiles relative to set of fixed co-ordinates (which is entirely a function of the incidence and severity of storm wave action). Warnke has observed this situation on a sand beach at Alligator Spit, Texas, where periodic hurricane surges are responsible for the erosion of a beach which under prevailing wave action assumes an equilibrium configuration.¹⁶ In the case of the Canterbury Bight the recognition of a subequilibrium stage of profile development raises important questions of sediment supply to the littoral zone, and of its subsequent movements both along and across the shore. These are answered to some degree by a consideration of the beach plan-form characteristics.

THE DISTRIBUTION OF EROSION IN PLAN

Incomplete refraction of waves in bays leads to the generation of longshore currents which may move sediment in one or more directions along the coast. A combination of updrift erosion and downdrift deposition leads to shoreline concavity, equilibrium being attained when the two phases are balanced, so that there is only sufficient energy available to move the materials supplied. This concept has been utilised in several attempts to formulate a satisfactory theory of equilibrium plan shapes of beaches.

One such attempt has defined the equilibrium configuration in relation to a circular arc and a recent study has employed this model in an examination of 86 beaches on the east coast of the South Island, including the Canterbury Bight.¹⁷ Hoyle and King set four conditions

for the theoretical 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. (This condition is satisfied if the ratio of the beach chord, C , to the maximum perpendicular, P , is equal to 15.0. See Fig. 6). The third condition is that the slope of the beach must be in equilibrium; and the fourth, the orientation of the beach must be aligned consistent with the prevailing wave direction.

On prograding beaches plan shape is often irregular or convex seaward (as on deltas). On retrograding beaches plan form tends to be more regular but is either too curved, or more usually too flat relative

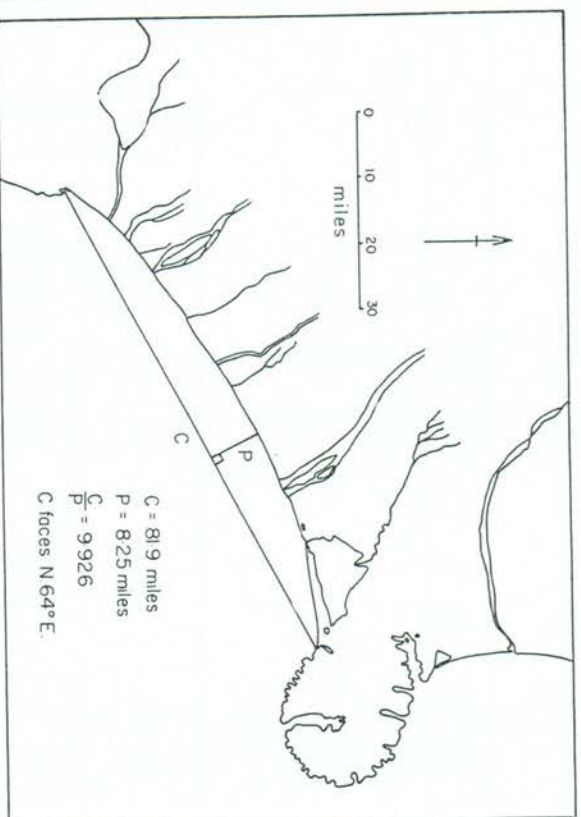


Fig. 6. Plan shape characteristics of the Canterbury Bight

to equilibrium requirements. It can be seen from Figure 6 that the Canterbury Bight is of the latter type. It has long been suggested that a persistent drift of shingle from the south has built Kaitorete Spit and tied off Banks Peninsula from the south.¹⁸ The materials involved in this movement were thought to have been derived from the rivers to the south and from erosion of the alluvial cliffs along the centre of the bight.

Analysis of old surveys shows that there has been little change in the beach between Taumutu and Banks Peninsula since at least 1860.

¹⁶ D. A. Warnke: 'Conditions of Beach Retrogression in a Low Energy Environment', *Zeitschrift für Geomorphologie*, N.S. Vol. 11, 1967, pp. 47-61.

¹⁷ J. W. Hoyle & G. T. King: 'Origin and Stability of Beaches', *Proc. 6th Coastal Engineering Conf.*, 1958, pp. 281-301; R. F. McLean: 'Plan Shape and Orientation of Beaches Along the East Coast, South Island', *N.Z. Geogr.*, Vol. 23, 1967, pp. 16-22.

¹⁸ Speight: 'The Lake Ellesmere Spit', *Trans. N.Z. Inst.*, Vol. 61, 1930, pp. 147-69; *idem*: 'An Eroded Coastline', *Trans. Roy. Soc. N.Z.*, Vol. 78, 1950, pp. 3-13.

However, from Taumutu to the mouth of the Rangitata River erosion is, and has been, at a maximum of two to three feet per year. The end of the road at the Rakai Mouth settlement has been moved about a chain since the first days of habitation and an old well now lies in the lagoon fronting the present shore.¹⁹ A road along the cliff top connecting the settlement with Taumutu has been removed and the same has happened south of the Hinds River where a road has had to be moved back over a chain.²⁰ The four culverts previously discussed were installed to drain the seaward land between the Rakai Mouth and Taumutu. Old surveys show that formerly this land was drained by a stream flowing parallel with the coast, between the beach deposit and the cliff, and emptying into the northern end of the Rakai Mouth lagoon. At present the former channel is almost filled with shingle thrown landward by the retreating beach.

From the Rangitata River to Timaru the rate of erosion has been much slower, of the order of 0.5 feet per year. Coastal changes near Timaru relate mainly to the cessation of longshore drift of shingle from south of the city after the construction of the harbour breakwater.²¹

With reference to the theoretical equilibrium conditions of Hoyle and King Figure 6 demonstrates that the first is satisfied by the headlands to the north (Banks Peninsula) and south of the beach (the Timaru lava flows). In the case of the second the C/p index for the bight is 9.926, near, but not equilibrium curvature. It is interesting to note that the curve of the shoreline is too flat in the central region, relative to equilibrium requirements. It is in this area that erosion is most vigorous at present. On the other hand, in the north, the beach has been stable for at least the last century, suggesting some form of equilibrium in this area. It is probable therefore that there is only a low order of net longshore transport to the north under present conditions. In turn such a conclusion raises questions concerning the disposal of cliff debris and the role of the rivers in sediment supply to the coast. There is little evidence to suggest a large supply of materials larger than sand size from the rivers under present conditions. Pebble sizes appear to be either moved offshore to a depth beyond shoreward return by waves, or deposited in the river channels before reaching the coast. The latter is the more probable of these alternatives. The erosional nature of the beach profiles and other considerations relating to the effects of erosion on sorting, sphericity and roundness of the beach materials suggest that cliff debris is moved offshore for the most part rather than alongshore.

Further south, nearer Timaru, coastal adjustment is nearly, but not

yet completed. Here it is difficult to distinguish long term natural changes in the beach from those initiated by human disruption of the littoral system.

With regard to the third condition, it has already been demonstrated that the beach profiles are at a subequilibrium stage of development, with low erosional slopes that undergo only minor fluctuations in form and volume. Condition four is satisfied since the chord of the beach faces N.64°E., very close to the observed approach direction of the prevailing southeasterly swells. The stable northern section of the beach faces the southerly storm waves.

It is thus clear that a subequilibrium stage of coastal development is suggested by plan form characteristics as well as by analysis of variations in the beach profiles.

CONCLUSION

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 to 15 feet higher than now some 5000 years ago. During subsequent time coastal sedimentation in the north of the Canterbury Bight has reached and passed a maximum, as evidenced by the large volume of materials in Kaioore Spit. This adjustment appears to be completed as far south as Taumutu.

Present coastal erosion has been shown to be most intense in the central area between Taumutu and the Rangitata River. Further to the south erosion proceeds more slowly and, over the last century, is at least partially due to the cessation of littoral drift of gravels from south of Timaru. On the other hand from the stability of the beach in the north it seems probable that net longshore transport into this sector from the south is small but sufficient to maintain the present position of the shoreline.

Surprisingly, in view of the high energy waves received there is little short term change in beach volume. The shore appears to have reached a subequilibrium stage of development in both plan and profile. It has been shown that the transverse profiles are well adjusted to the prevailing southeasterly swells and to the dominant storm waves. Consequently, beach profile envelope curves are of small amplitude even where coastal erosion is slowest. 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. Continued coastal erosion will result in further changes in plan and profile morphology, though a stable equilibrium may never be attained.

¹⁹ Speight: 'An Eroded Coastline', *Trans. Roy. Soc. N.Z.*, Vol. 78, 1950, pp. 11-12.

²⁰ Speight: 'An Eroded Coastline', *Trans. Roy. Soc. N.Z.*, Vol. 78, 1950, pp. 11-12.

²¹ C. E. Hassall: *A Short History of the Port of Timaru 1852-1955*, Timaru, 1955, pp. 51-52 and