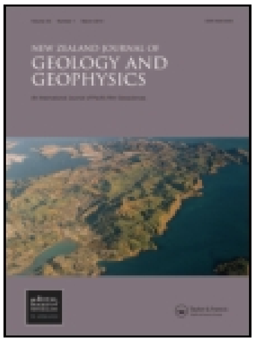

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COASTAL PROCESSES AROUND THE OTAGO PENINSULA

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ABSTRACT

Observations of the wave conditions around the Otago Peninsula were made during the period December 1963 to December 1964. From these observations the influence of sea and swell waves in developing the beaches and spits of this part of the Otago coastline has been assessed. The beaches, including the "southward"-pointing spits of the peninsula, have developed largely in response to a dominant southerly swell of 10–15 sec. period, in spite of intense refraction. North of the peninsula, in an area sheltered from the swell, the dominant waves are produced by the north-easterly sea, which promotes some beach drift from north to south. The energy of dominant waves and the evolution of shoreline curves on a coast of submergence are discussed.

INTRODUCTION

The quartz sands of the Otago beaches have long been attributed to erosion of the schist terrain by the River Clutha and its tributaries (Marshall, 1905). The abundant supply of sediments was thought by Marshall to have been carried northwards by waves and off-shore currents, to be deposited far up the Otago coast. The surface expression of such ocean currents has been described in detail (Brodie, 1960), but virtually nothing is known of their effects at depth. Marshall also noted the sand spits of the Otago coastline, and assumed that they too must have been built up by northerly transport of sedimentary material. Elliott (1958), on the other hand, described the sand spits in some detail and attributed them to longshore or beach drift, moving sediments from "north" to "south". However, the only abundant source of the fine quartz sand is in the south, and if drift is responsible for building up the spits of the Otago coastline, it appears to be a less effective method of sediment transport than the northerly-flowing ocean currents.

The purpose of this paper is to assess the importance of various processes in the construction of the spits around the Otago Peninsula, in the light of recent studies.

OTAGO PENINSULA

From Nugget Point to Moeraki the Otago coastline trends roughly north-east. However, around the Otago Peninsula the trend of the beaches varies from south-south-east through east to north-north-west along about 50 miles of irregularly embayed coastline (Fig. 1).

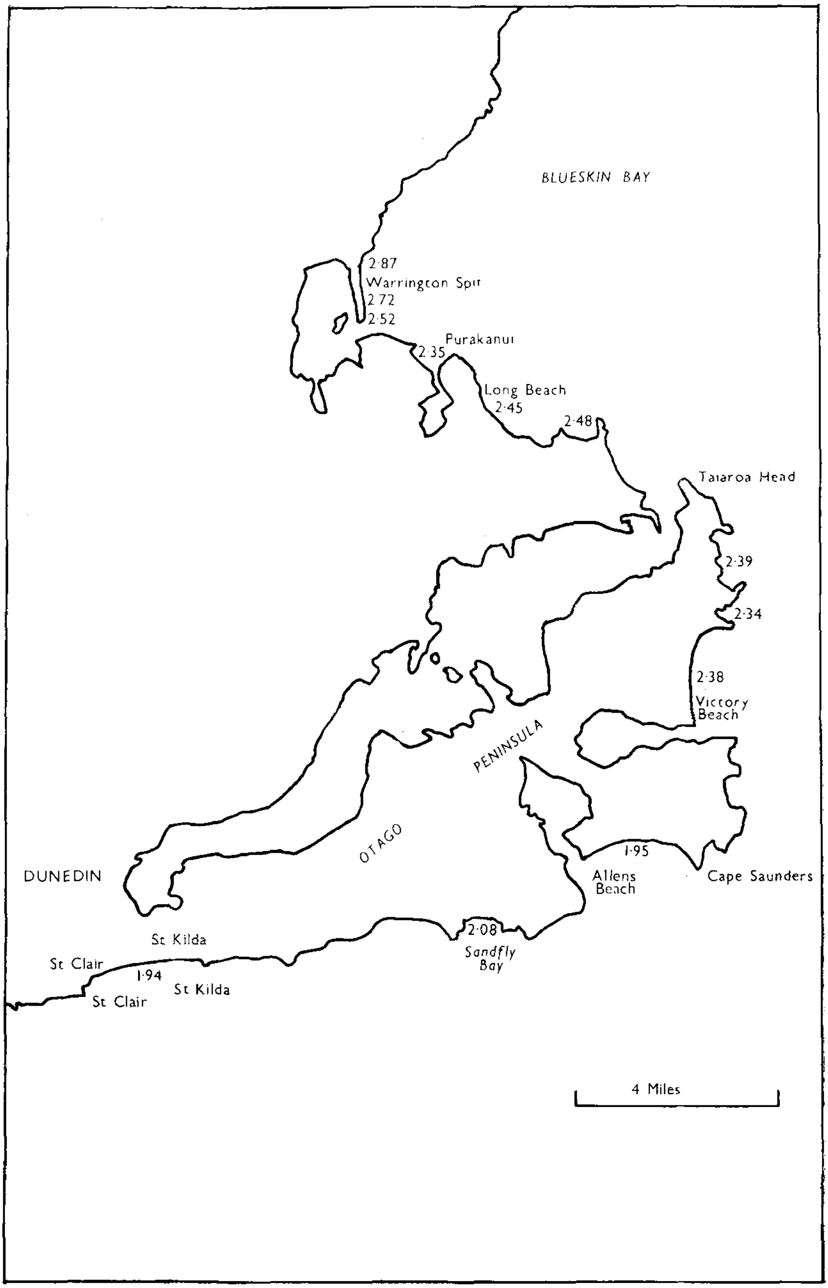

FIG. 1—Locality map of the Otago Peninsula. The figures in brackets indicate the median grain size of the beach sands in terms of the phi scale. (North at top of map.)

The sand has been deposited in every irregularity of the coastline, forming spits enclosing tidal inlets in the larger embayments. The spits are all joined to higher ground at their northern extremity and the tidal channel of each inlet so formed and of the Otago Harbour itself is situated at the right hand end of the spit (looking seaward). The coastal beaches are dominantly concave in plan, except for the south end of Warrington Spit. The beach sands are usually well sorted quartz sands unimodally distributed. However, samples from Sandfly Bay exhibit a strong bimodal distribution reflecting an increase in shell and volcanic rock fragments. A bimodal distribution has also been observed in samples from Allen's Beach.

Observation from the high ground of the peninsula, or from the air, shows that the breakers on most of the Otago coast are normally caused by swell running in from a southerly quarter. The main winds over the peninsula are from the south-west and north-east, the former being the stronger and the latter the more persistent (Elliott, 1958, table 1). During periods when the swell is gentle the effect of these local winds is to raise a slight to moderate sea, this being most noticeable in the area north of the harbour entrance.

THE CONSTRUCTION OF COASTAL LANDFORMS

All processes that effect the transportation of marine sediments can play some part in the construction of coastal landforms. Among them ocean currents, tidal currents, and longshore currents are more important in terms of deposition and erosion of submarine topography, but they can also influence the shape of spits, etc., and the supply of material to a given part of the beach. Excluding the wind only two processes are capable of building up or eroding sand in the beach zone. These are beach drift and the on-shore movement of the waves. Both processes are a function of wave activity. The velocity and duration of the swash and backwash are a function of the volume and period of the waves, and are related to deep-water wave steepness and gradient of the beach profile. There is a limiting steepness above which the backwash flowing to the sea is capable of eroding more material than is brought to the beach by the forward momentum of the swash. From wave tank experiments Saville (1950) has suggested that deposition and the formation of summer beach profiles may take place when the wave steepness of a deep-water wave falls below 0·03.

Beach drift consists of the lateral movement of beach-forming materials by the swash and backwash of successive waves approaching at an angle to the shoreline. Saville's experiments showed that beach drifting was associated with development of a summer beach profile, the optimum range of wave steepness being 0·02 to 0·025. Similar experimental work by Shay and Johnson (*in* King, 1959, p. 145) has shown drifting to be at a maximum when the wave fronts make an angle of 30° to the shoreline. Since these results were derived from experimental models, the values obtained may not be applicable in nature. However, the principle that erosion or deposition is a function of wave steepness remains valid.

It was suggested by Lewis (1938) that in plan the configuration of beaches is a function of the direction of approach of the dominant waves.

He considered the dominant waves to be the biggest storm waves, and their size and direction of approach to be a function of prevailing winds and the distance of greatest "fetch". The curvature of bays between adjacent headlands was taken as an indication of protection of parts of the beach from waves from different directions. This concept does not apply to coasts fronting the opea sea, where the dominant waves may be a function of swell generated some thousands of miles away. However, the diagrams drawn by Lewis and later by Jennings (1955) show how their interpretation was a preliminary step in the understanding of wave refraction. Davies (1960) has shown that on Australian beaches the shoreline curves are developed in response to a dominant swell of 14 sec. period generated in the Southern Ocean. Swell of this order, originating in the Southern Ocean has also been recorded on the Californian coast (Weigel and Kimberley, 1950). It is not unreasonable therefore to conclude with Davies that this swell is probably an important factor in building up shoreline curves in the Southern Hemisphere. The distinction between the dominant waves of Lewis and Jennings and the dominant swell of Davies is largely that the former is of short wave length and unrefracted, probably a result of local winds, whereas the latter is refracted by a shallow bottom and travels a path that is by no means straight.

PREVIOUS WORK

Dealing with the Otago coastline from the Clutha River to Oamaru, Elliott (1958) tabulated wind strength, direction, and frequency for Taiaroa Head and Waikouaiti and discussed the effects of these winds upon the form of the breakers. The data show that the strongest winds are from the south-west, operating for some 20%–25% of the total frequency, and the most prevalent are from the north-east, although they are generally lighter than the south-westerlies. She concluded that the anomalous nature of the spits around the Otago Peninsula is a result of longshore drift caused by the swell modified by north-east winds, whereas on the Canterbury coast modification by strong south-west winds causes drift to the north.

Elliott suggests that wave height is increased by south-west winds and decreased by north-east winds, and that under extreme conditions south-west winds increase and north-east decrease the period of swell. She records a wave period of 10·5–13 sec associated with wave heights before breaking of 1–3 ft and 6–8 ft for north-east and south-west weather respectively. These values would give a maximum deep-water wave steepness of ·005 a value far below Saville's experimental data.

OBSERVATIONS ON THE LOCAL BEACHES

During the period December 1963 to December 1964 daily observations of the period and direction of both sea and swell were made from Taiaroa Head lighthouse. Daily observations of the swell were made from Cape Saunders lighthouse during the same period. Additional observations of wave period and wave height were made at St Clair and St Kilda for a three-week period during January and for four weeks during June. The data from Taiaroa Head were accompanied by a wind report and gave a clear indication of the conditions of generation of the sea in Blueskin Bay.

The direction of swell approach at Taiaroa Head is persistently affected by refraction around the Otago Peninsula, and for this reason observations of swell from Cape Saunders lighthouse are more valid with respect to open-sea conditions. At Cape Saunders (Fig. 2) swell ran from the south on 57% and from the south-east on 26% of the occasions observed. Both Taiaroa Head and the Cape Saunders lighthouse are situated high above sea level and are thus unsuitable for observation of wave heights. Visual estimates of wave height were therefore made during summer and winter conditions on the St Clair and St Kilda beaches. The breakers on these beaches are less affected by wave refraction than those further north.

The method of observing wave height consisted of sighting across the crest of the waves to the horizon, and using a graduated pole to measure the height of this line above the approximate still-water level inside the breaker zone. Estimating wave period involved timing a group of 10 wave crests past a recognisable point (rock, buoy, or cluster of seaweed) and determining the average. More reliable data could be obtained from wave-recording apparatus, but installation and maintenance of such equipment was considered unwarranted for the present study.

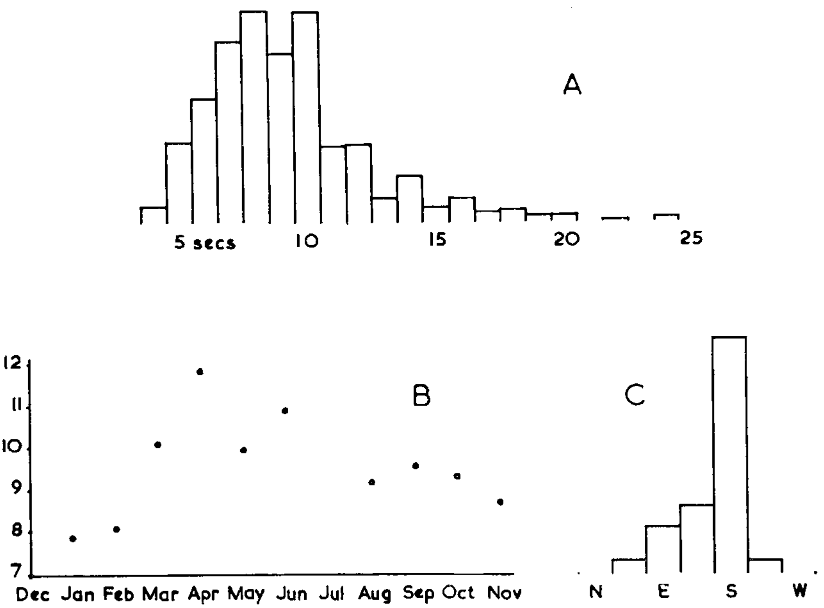

FIG. 2—A. Variation of swell period observed at Taiaroa Head during the period December 1963 to December 1964. Observations made twice daily.

B. Graph showing the monthly fluctuations of the average swell period (in seconds) during 1963–64.

C. Variation of swell direction observed at Cape Saunders during 1963–64. Observations made once daily. The approach of swell from the south-east indicates refraction of swell with a period greater than 10 seconds (see Fig. 4).

INFLUENCE OF SWELL ON THE OTAGO COAST

Swell Period and Wave Height

Although the prevalent swell is from the south, occasionally a secondary swell may run in from the north-east or east, probably as a result of local storms off the coast. The swell period observed varies considerably from 4 to 25 sec (Fig. 2), but 81% of the observatons lie between 6 and 12 sec. These values for swell period are lower than might be expected. It is interesting that the average period at St Clair and St Kilda, Cape Saunders, and Taiaroa Head decreases in the order of 12, 10, 8·5. No explanation of this variation is available. The shorter-period swell is usually associated with local weather, as for example south-west gales in Foveaux Strait, whereas the more usual period of the swell on open beaches is from 9 to 16 sec. The deep-water wave height (calculated from observed breaker height) varies from 1·5 to 9·5 ft, giving breakers of 3–11 ft on beaches fronting the southern swell. The average wave height increases from 3 to 4 ft from summer to winter.

On-shore Movement of Waves

Because of the effects of refraction, the swell from the south runs on to the coast almost at right angles, i.e., with the wave fronts parallel to the shoreline. The occasional though prominent development of beach cusps on St Kilda beach demonstrates the parallel approach of these waves. Refraction diagrams have been drawn for waves of 10 and 15 sec period coming from all points from north-east to south-west. The diagram drawn for swell from the south fit remarkably closely to the configuration of the local shore lines (Figs. 3 and 4). This perfection of fit around the Otago Peninsula suggests that the "anomalous" development of the local spits is related to the acute refraction undergone by the swell. Bascom (1954), working on the Pacific coast of North America, has shown that where a beach is built up across the mouth of a stream, the outlet is situated in the most sheltered position on that stretch of coast, which is where the dominant swell has undergone the greatest amount of refraction. The extreme attenuation of the wave front results in a minimum value for the wave energy at this point, so that the spit or beach berm constructed by it is most easily broached there by the river or tidal channel. Consideration of the wave diagram for 15 sec southerly swell off the Otago coast (Fig. 4) shows that the outlets of all the lagoons on the east of the peninsula are situated in the position of greatest refraction. The refraction diagram drawn for waves of a 10 sec period coming from the south (Fig. 3) does not show such a good fit for the beaches of the peninsula, thus suggesting a predominant value of the wave period between 10 and 15 sec.

Beach Drift

Off the coast the north-east and south-west winds must blow more or less with or against the southerly swell. The influence of the north-east winds on the swell is probably slight, but it seems likely that the reinforc-

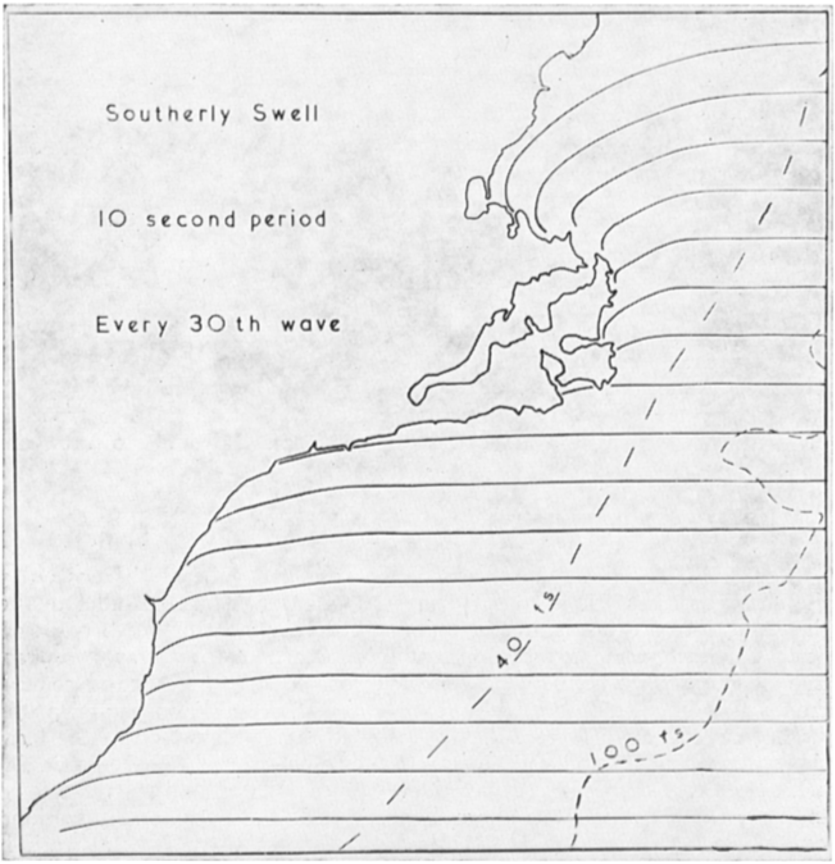

FIG. 3—Refraction diagram for a southerly swell of 10 sec period. The 40 and 100 fathom contours indicate the depth at which refraction commences for waves of 10 and 15 sec periods respectively.

ing effect of the south-west gales may not only increase wave height as suggested by Elliott but also, by decreasing rather than increasing the wave period, may influence the direction of approach of the swell in nearshore regions. If this occurs to the extent that the effects of refraction on the long-period waves is partly overcome, the residual longshore component could be translated to the beach zone. This would explain the south to north migration of coarse sand and gravel mentioned by Elliott for the Canterbury coast and for isolated localities around Dunedin. Areas where this is likely to occur are those in which the "fit" for the refracted swell is initially not perfect, for example the coastline between Quoin Point and Taieri Mouth some 15 miles south of Dunedin. The increased energy of these storm waves can be seen from the coarser sands they bring on to local beaches. Coarser and more rounded than normal beach sand, and strongly stained with hematite, these sands must be derived from the Taratu Formation of Cretaceous age which crops out sporadically along the coast to the south between Kaitangata and Brighton—and possibly on the sea floor (Marshall, 1931).

From the above it appears unlikely that the ocean swell could cause extensive beach drift round the Otago peninsula, although it is important as the source of the breakers on most of the beaches. On the north side of the peninsula the refraction is incomplete. Attenuation of the wave fronts during refraction around the Otago Peninsula (Fig. 4) decreases the effectiveness of the southerly swell so that on certain beaches the surf is very flat. It is here that the prevalent north-east winds play an important part, and the angle of wave approach is often related to local weather.

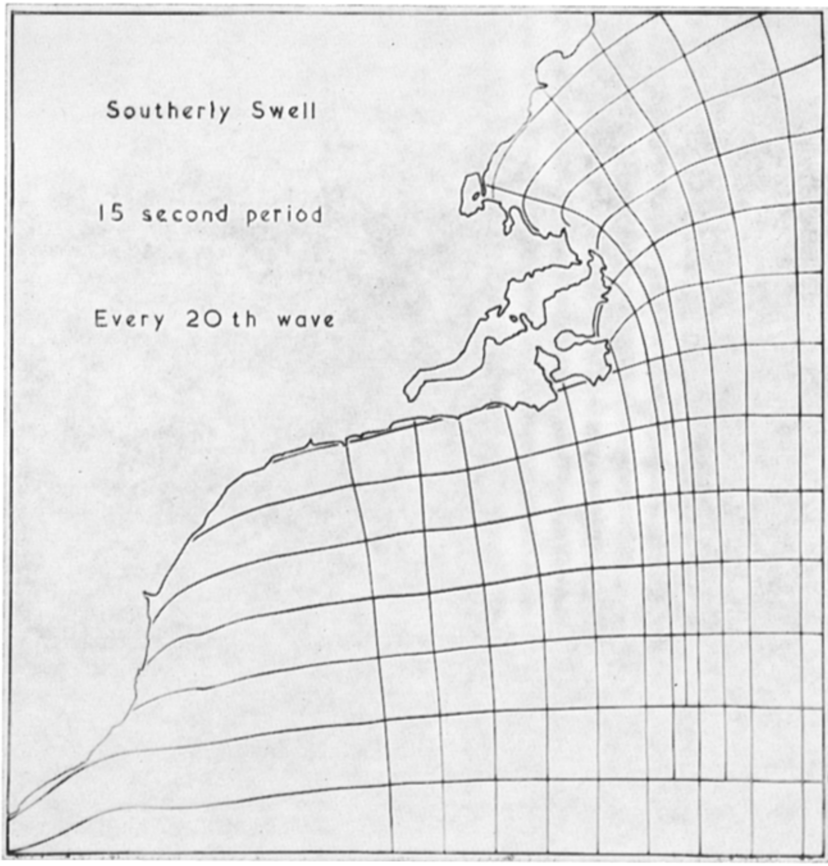

FIG. 4—Refraction diagram for a southerly swell of 15 sec period. Orthogonals, equally spaced in deep water, indicate the amount of attenuation undergone by the wave fronts during refraction. Such attenuation is accompanied by a decrease in wave height.

INFLUENCE OF SEA NORTH OF THE OTAGO PENINSULA

On the beaches betweeen Taiaroa Head and Warrington Spit the breakers are often a product of local north to north-east winds, and their characteristics are much more variable than the ocean swell. Observations from Taiaroa Head indicate a slight to moderate north-east sea running in Blueskin Bay some 37% of the time. The observed period is usually in the order of 2–6 sec. Longer periods for the sea are seldom observed even in winds of 20 knots or more. With an average wind velocity of 10–16 knots and a possible fetch varying from 20 to 170 miles the waves might have a height of up to 5 ft (see deep-water wave forecasting curves of Bretschneider, 1952). These short wavelength waves are only slightly refracted by the bottom topography and thus tend to run into the shore more obliquely than the longer wavelength swell. Refraction diagrams and observations from aerial photographs show the wave fronts making an angle as high as 30°–40° to the shore, particularly at the south end of Warrington Spit. The steepness values for these north-east-generated wind waves also appear to fall well within the range of Saville's (1950) experimental results. For example, to fall within the optimum range for beach drift a wave of 6 sec period should have a wave height from 2·7–4·6 ft, a wave of 5 sec period from 2·0–3·2 ft. However, drift experiments carried out during September 1964 on Warrington Spit were unsuccessful, presumably because conditions for the longshore movement of sand were not attained at the time. Some 500 lb of coloured sand initially obtained from the beach was deposited near the high-tide mark. At the following low tides no trace of the sand was found. Nevertheless a north to south longshore component can be traced in the movement of coarse shell debris on this beach during north-easterly weather.

It seems likely that the north-east sea plays a significant part in the distribution of sand on the northern beaches and may also cause limited longshore drift along Warrington beach during north-easterly weather.

Application of Bascom's rule to waves of 5 sec period running in from the north-east can explain the central position of the stream outlet at Long Beach. In terms of the swell the situation of this stream is anomalous, for the greatest refraction of the swell would be at the eastern end of the beach. However, as can be seen from the refraction diagrams, when the waves approach a concave beach at right angles to the trend of the shore, the greatest refraction will occur in the middle of the beach. It is possible that refraction of the north-east waves also influences the situation of Purakanui Inlet and the inlet at the south end of Warrington Spit.

WAVE ENERGY IN THE BREAKER ZONE

This raises a question as to the nature of the dominant wave. From the viewpoint of this study the dominant wave is that which has most influence in buiding up the present beach, in plan and profile. Dominance is therefore dependent on wave energy, which is a function of wavelength and height. The height of a wave breaking in shallow water is related to its deep-water height both through refraction and through the shallowing of the water. Thus, as a result of refraction, the energy of breakers from a given wave train will vary on different beaches. It is theoretically possible to calculate this energy for different beaches using the deep-water height and length of the waves and a coefficient derived from the spacing of orthogonals drawn on a refraction diagram (Arthur, Munk, and Isaacs, 1952) (Fig. 4). However, when the angle through which the waves are refracted exceeds 45°, the observed wave heights are found to be greater than those calculated using the refraction coefficient, presumably because of some diffraction of energy along the crest of the wave (U.S. Navy, H.O. *234*).

Because of the uncertainty of this error, and the very irregular coastline around the Otago Peninsula, and because of the practical difficulties of measuring deep-water wave height, it is simplest to calculate wave energy in the beach zone. Assuming that the breakers on all beaches are derived from a given wave train, wave energy is related to the breaker heights observed simultaneously on different beaches. Wave length in the breaker zone can be determined from the observed wave period and breaker height using published tables (H.O. *234*, Plate III). Fig. 5 illustrates the relation between the energy and height of breakers formed by waves of a given period.

The most common period of breakers on the northern beaches, as a result of north-east winds in excess of 7 knots, is in the order of 2–6 sec. However, during a calm sea a southerly swell of 9–16 sec arrives on these beaches. Although the longer-period waves always have a greater energy for a given height, the effects of refraction must be taken into account. Simultaneous observations of breaker height have been made at St Kilda and Long Beach during periods of calm. These indicate that refraction has reduced the waves at Long Beach to a fifth of their original height. For example, swell forming 5 ft breakers at St Kilda only forms breakers of 1 ft at Long Beach. Thus once a north-easterly sea is established, the energy of the breakers formed by it can readily exceed that of breakers formed by the swell. In north-east winds of 16 knots the breakers at Long Beach have been in the order of 3 ft high while breakers 5 ft high were observed at St. Kilda. However, on the beaches south of Taiaroa Head, where refraction is less marked, the north-east seas remain less powerful than the swell. This interplay between sea and swell in forming breakers on the northern beaches can be seen in the accompanying aerial photographs (Figs. 6 and 7). From the energy relations mentioned above the balance between the two may well be controlled by a seasonal variation in the period of the swell (Figs. 2 and 5).

Evidence of the variation of wave energy along the crest of the refracted waves can also be found in the variation of grain size of sand samples taken from beaches around the peninsula. All samples were taken from a point near the centre of the beach roughly 5½ ft below high-tide level. These precautions were considered necessary to eliminate the local effects of refraction within the beach itself. The median values of the size frequency distributions have been plotted on Fig. 1 in terms of the phi scale. Thus higher-energy waves are associated with coarser sands—expressed as numerically smaller values on the phi scale. Because of the abrupt change in trend of the beaches north and south of Cape Saunders there is no obvious gradation in grain size due to refraction of the swell. However, around Blueskin Bay the effect of the refracted sea is clearly seen. The finest sands occur at the north end of Warrington Beach, the size increasing to a maximum at Purakanui and decreasing slightly towards the harbour mouth. This suggests that the north-easterly set may be dominant over the refracted swell on all the northern beaches, including the whole of Warrington Beach.

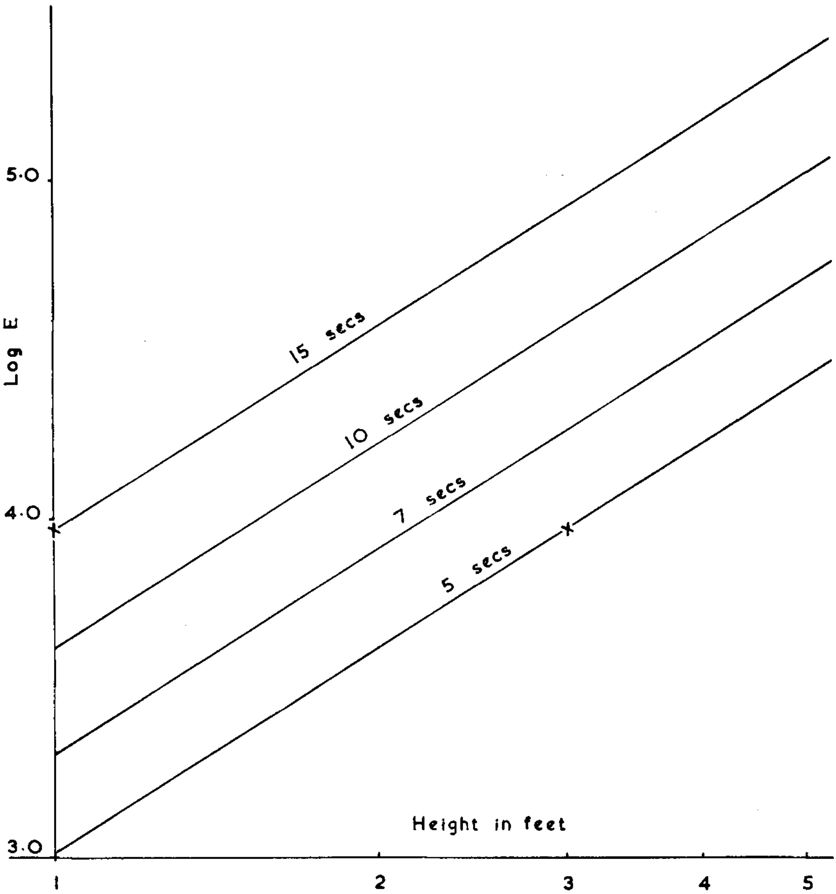

FIG. 5—Graph showing the relation between energy (E) per unit length of wave front, and height, for waves of different period. Energy is calculated from the equation $E = \frac{1}{8} WLH^2$ where W is the weight of 1 cub. ft of sea water and L and H are the wave length and wave height respectively (Biglow and Edmondson, 1947). The two crosses indicate the probable energy relationship of sea and swell referred to in the text.

Photo by permission of the Department of Lands and Survey

FIG. 6—Interplay of north-easterly sea and refracted southerly swell off the mouth of Otago Harbour. Scale approximately 25 chains to an inch. (North in the photo is to the left above, the mole extending north-east.)

Photo by permission of the Department of Lands and Survey

FIG. 7—The influence of sea and swell in forming breakers on Warrington Spit can be seen from the spacing between breakers in the surf zone. Scale approximately 25 chains to an inch.

DISCUSSION

Development of a shoreline curve is a gradual process accompanied by changes in the bottom topography of the off-shore zone. If one considers the initial bottom topography of a coast of submergence it is clear that wave refraction would be incomplete, probably resulting in beach drift and the build-up of recurved spits extending part of the way across the bays. At this early stage in the formation of the spits around the Otago Peninsula the south-west swell probably played an important role in promoting beach drift from south to north. However, once the spits had been extended further across the bays the bottom topography would be considerably changed and refraction would be more complete. The spits would then be built up by the on-shore movement of sand by wave fronts approaching parallel to the submarine contours. Once fully established as a bay-mouth bar each spit would be broached at the most protected end—where refraction was then greatest.

This sequence illustrates the distinctive difference between spits built as a result of beach drift and those resulting from the on-shore movement of material. During the initial build-up by longshore drift a recurved spit would be developed, convex on the seaward side of a single (or narrow) line of dunes enclosing the lagoon. As a result of the landward movement of sand outside the breaker zone the bay would silt up on the seaward side of the spit, establishing equilibrium between the refracted waves and the bottom contours. This stage can clearly be seen at the south end of Warrington Spit, where a submarine bar is developed at the entrance to the lagoon in equilibrium with the north-east wind waves (Fig. 7). Where a spit has been built up as a result of the on-shore movement of sand it can be recognised by the seaward concavity of the shoreline. The tip of the spit at the most protected end of the bay is not markedly recurved, showing the lack of longshore drift. Both Allen's Beach and Victory Beach exhibit this form of spit.

CONCLUSION

It is clear that while refraction of the swell has been the principal factor in development of the beaches, it is not the only one. The importance of longshore drift promoted by south-west swell during storms should not be ignored, as it is probably responsible for building up the gravel spits of the Canterbury coastline, and for the northerly dispersion of coarse sand and gravel mentioned by Elliott (1958). North-easterly seas play an important part in the distribution of sand on the beaches around Blueskin Bay, both by on-shore movement of the waves and in promoting beach drift along Warrington Spit.

ACKNOWLEDGMENTS

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