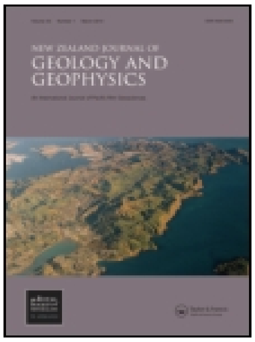

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# Observations of beach gravel transport, Wellington Harbour entrance, New Zealand

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## ABSTRACT

Two small embayments at the entrance to Wellington Harbour, New Zealand, which are thought to have been depleted of sediment by regional tectonic uplift in 1855, have shown a sudden and rapid accumulation of gravel since 1941. A tracer experiment in this locality revealed that pebble-sized sediment moves northwards into the harbour at an average rate of 1·66 km y$^{-1}$.

Further north, inside the harbour, there is a sudden change in the nature of the beach. Towards the entrance, plentiful gravel of fresh appearance occurs, while to the north scarce weathered gravel is present. This sudden change in the nature of the beach is here named a gravel front and it is moving northwards at a rate of approximately 0·42 km y$^{-1}$.

Pebbles are transported during high wave energy events in a zone near low water level. Loss of pebbles offshore and by abrasion is probably small. It appears that gravel is moved alongshore during storms in discrete packages that subsequently coalesce and move landwards to form a berm during normal low wave energy conditions.

It is suggested that the sudden progradation at the harbour entrance and the existence of the mobile gravel front are due to a large influx of gravel to the coast that occurred after landslides were induced by the earthquakes of the 1840's and 1850's, when the base level of Orongorongo River was raised.

KEYWORDS beach pebble tracer experiment, gravel front, waves, shorelines, Wellington Harbour

## INTRODUCTION

Previous studies of gravel beaches in New Zealand have concentrated on aspects of beach texture and morphology and on their relationships with wave and swash parameters, particularly on the mixed sand and gravel beaches of the east coast of the South Island (McLean & Kirk 1969; McLean 1970; Kirk 1971; 1975). Sediment dispersal routes and sediment budgets have also been determined (e.g., Kirk *et al.* 1977; Campbell 1974) but direct observations of longshore gravel transport have not yet been attempted.

In the United Kingdom, as in New Zealand, gravel beaches are relatively widespread, and a variety of tracer techniques have been used to evaluate beach gravel transport. Kidson *et al.* (1958) and Kidson & Carr (1959) used radioactive pebbles to trace the movement of gravel on the beach and nearshore zone of part of the Suffolk coast. They found that significant longshore transport of gravel occurred at a maximum rate of 600 m in 4 weeks. Russell (1960) used repeated injections of fluorescent gravel to quantitatively assess the annual transport of gravel at Rye. Carr (1971) introduced gravel of foreign lithologies to Chesil Beach and by following its movement deduced a rate of transport of 1001 m in 24 weeks. Jolliffe (1964) showed that larger pebbles (of about 8 cm diameter) are transported more rapidly than smaller pebbles (of about 1 cm diameter) under high energy conditions, but that the reverse is true under low energy conditions.

The present paper describes a tracer experiment utilising brick chips of about 2·5 cm diameter, which was conducted on a gravel beach at the entrance to Wellington Harbour.

### *Physical Description*

The study area extends along Wellington Harbour's eastern side (Fig. 1), where the beach face width varies from 10 m near Eastbourne to as much as 30 m on the exposed south-facing coast at the harbour entrance, and where the slope of the beach face varies between 6° and 11°. Granules are the most common grain size constituent, while pebbles and cobbles are found in discrete zones, particularly near the berm crest. Sand occasionally appears on sheltered sections of the beach as thin localised veneers up to 10 cm thick which gradually develop over several days during periods of low wave activity. The gravel is predominantly indurated greywacke and argillite with a minor proportion of spilitic suite lithologies.

### *Wave Climate*

On the south coast of Wellington, waves arrive predominantly from due south (Fig. 2). Waves up to 6·0 m high have been visually recorded at Baring Head, but at Barrett Reef, in the harbour entrance, they are generally less than 3·0 m high and average around 1·5 m. Waves with periods of 9–10 s are most common.

Because most wave fronts arrive fom the south, the predominant direction of longshore drift is to the north. Inside the harbour this northward movement is opposed by longshore transport initiated by short-period northerly waves generated inside the harbour. The opposing drifts are thought to cancel each other at Eastbourne, where a cuspate foreland has built out, indicating a low rate of net littoral transport.

Variations in the orientation of the coastline and in nearshore bathymetry cause the height and angle of

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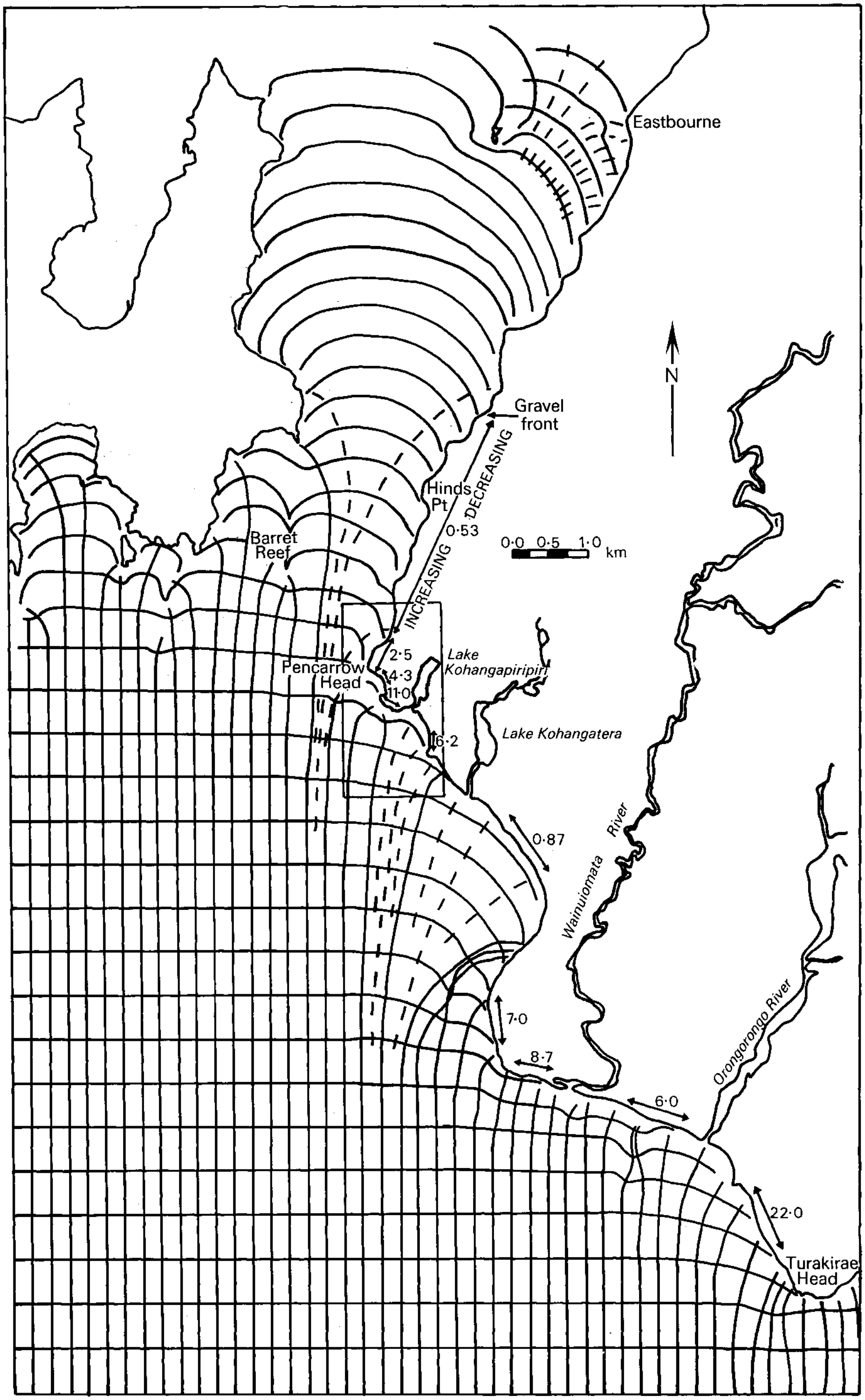

Fig. 1—Locality map of the study area. The expected wave refraction pattern for a southerly wave front with a period of 9 s is given, showing every fifth wave crest. Relative values of the longshore component of wave power, which is directly related to the rate of longshore transport, are also shown. Wave refraction was drawn using the method of Johnson *et al.* (1948). Area enclosed by square is enlarged in Fig. 3.

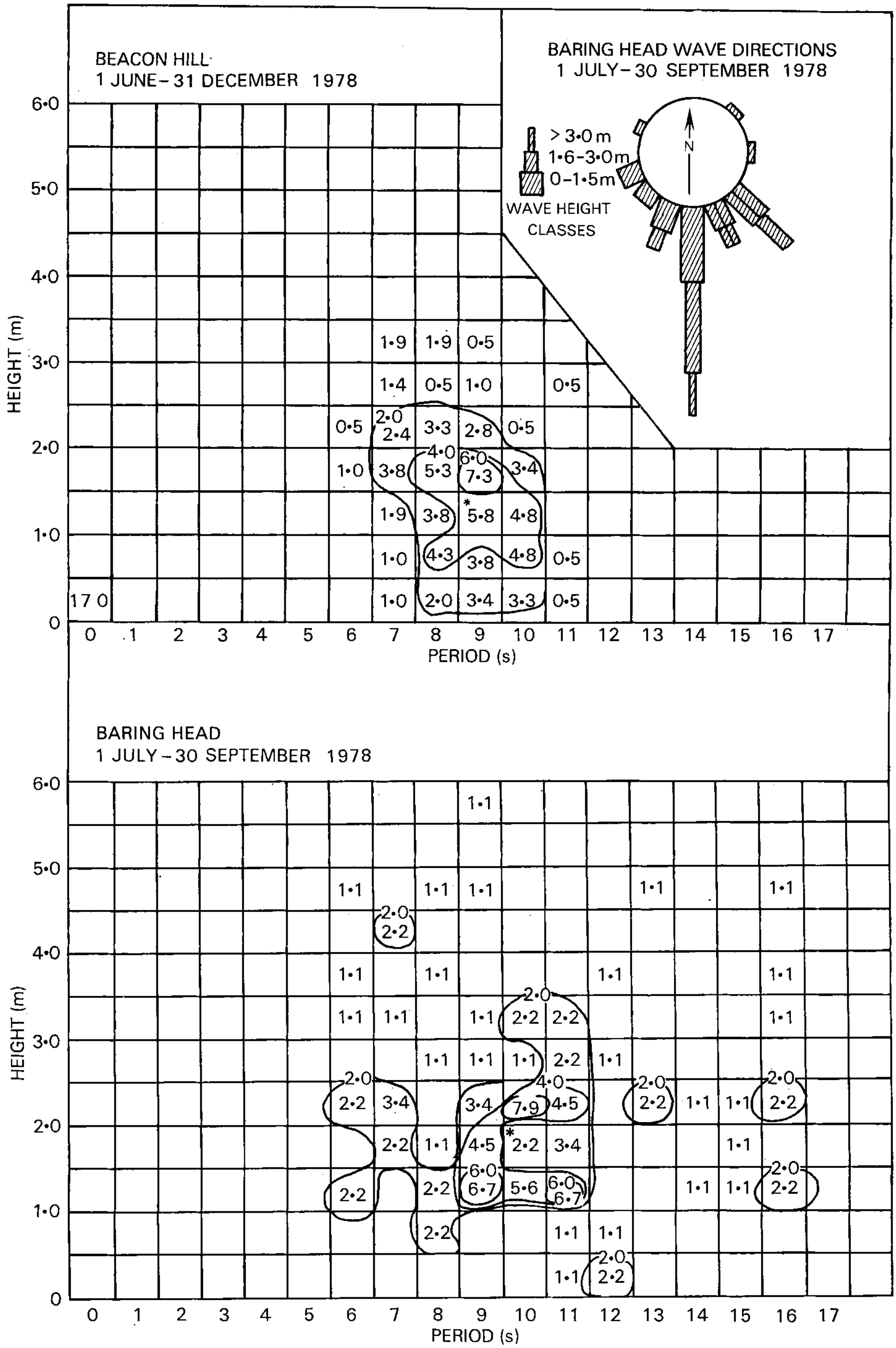

FIG. 2—Summary of visual wave observations from Beacon Hill (Barrett Reef) and Baring Head. Note the predominance of southerly waves. Mean values are marked with an asterisk; contour values are in frequency percent.

incidence of breaking waves to vary alongshore. It is necessary to consider how these differences affect the rate of longshore transport. Accordingly, relative values of the longshore component of wave power (Komar 1976, p. 204), which are directly proportional to the rate of longshore sediment transport, were calculated. The total wave energy flux between each pair of orthogonals on Fig. 1 was assumed to be the same and was arbitrarily assigned a value of 100. The distance between orthogonals at the shoreline was then inversely proportional to the energy flux. Breaker angles were estimated from the orientation of nearshore wave crests.

### *Effects of Regional Uplift on the Coastline*

The Wellington region is undergoing intermittent tectonic uplift that has caused a series of beaches to be raised beyond the reach of the sea and preserved (Stevens 1969; 1974). Disregarding possible abrasion effects, the elevation of these beaches has been the major mechanism for removing gravel from the intertidal zone. Gibb (1975; 1979) measured the quantity of gravel in these deposits and concluded that since 1460 the rate of accumulation has varied between 5000 and 12 000 $m^3 y^{-1}$, averaging 7200 $m^3 y^{-1}$. These sediments are supplied to the beach predominantly by Orongorongo River, but Wainuiomata River is thought to supply an additional small quantity of sand (Matthews in press).

The last uplift occurred in 1855, when beaches along the eastern side of the harbour were raised approximately 2·1 m (Stevens 1974, p. 227). With this in mind, it is interesting to note that two beaches near Pencarrow Head, one at the mouth of Lake Kohangapiripiri (here named Kohangapiripiri Bay) and one south of Pencarrow lighthouse (here named Pencarrow Bay) have prograded since 1941 at a rate much greater than that between 1855 and 1941 (Gibb 1975; Matthews in press.).

About 4 km to the north, on the northern side of Hinds Point, there is a sudden change in the nature of the beach sediments. To the south, small embayments are filled by a series of storm beach ridges which are in the process of being colonised by terrestrial plants. The beach ridges are composed of grey fresh-looking gravel and are thought to have been recently formed. In contrast, the beaches to the north comprise only a thin veneer of brownish weathered-looking gravel and sand resting on rock and boulders. It appears that fresh gravel is being moved into the harbour, transforming the undernourished beaches that formed after the latest tectonic uplift.

Immediately after the series of severe earthquakes in the 1840's and 1850's aggradation of the lower reaches of Orongorongo River was caused by the occurrence of numerous landslides (Gibb 1975). By assuming that the longterm rate of accumulation of beach gravels is equal to the rate of supply, and that the average depth of mobile gravel in the river bed is 1 m, it has been calculated that gravel supplied to the river 3·5 km inland (1/10 of the length of the catchment) would take 100 years to reach the coast. It is therefore possible that the earthquake-induced influx of gravel, probably assisted by the elevation of river base level, took about this long to reach the coast in quantity. Once on the beach it would take in the order of 14 years to reach the harbour entrance (see below).

Thus the sudden increase in the rate of aggradation of Kohangapiripiri and Pencarrow Bays since 1941, and the presence of a northwards-moving gravel front downdrift at Hinds Point in 1978, may be related to the arrival of an earthquake-induced pulse of gravel.

## PEBBLE TRACER EXPERIMENT

A tracer experiment was conducted with the aim of investigating the mechanism and speed of longshore transport of pebbles on the exposed coast. Brick tracer was placed so that it would move towards Kohangapiripiri and Pencarrow Bays (Fig. 3), with the aim of determining if significant quantities of sediment were still accumulating. This was of practical interest because of the recent blockage of a sewage outfall located on the eastern side of Kohangapiripiri Bay.

### *Tracer Material*

After assessing all possible materials, it was decided to use chipped, double-baked brick roofing tiles. This material has a density of 2·4 $g\,cm^{-3}$ and ranges from 8 to 45 mm intermediate diameter, with a mean grain size of 25·2 mm ($-4{\cdot}6\,\phi$). Using the empirical settling velocity equation of Gibbs *et al.* (1971), it was found that greywacke pebbles (which have a density of 2·7 $g\,cm^{-3}$) of 17·2 mm diameter ($-4{\cdot}1\,\phi$) would fall, assuming sphericity, at the same velocity as brick chips of 25·2 mm diameter. As well as the density difference there was also a rounding difference. The brick chips were very angular when first introduced to the beach, whereas the natural beach pebbles were moderately to well rounded. However, both the brick chips and natural pebbles were roughly equant so that the mean shape was similar.

It was observed that the newly introduced brick chips tended to be sorted into zones where natural pebbles of similar size were also segregated, indicating that the brick chips are representative of the natural pebbles.

### *Procedure*

On 19 July 1978 a front-end loader was used to place approximately 20 $m^3$ of brick chips in a strip across the beach face at the southern end of Kohangapiripiri Bay (Fig. 3). For each of six days after placement, the area was visited during low tide. The concentration of brick chips at each point in a sample grid with a maximum spacing of 30 m was determined by counting the number visible on the surface of the beach in a measured area. The median b-axes of at least 50 chips were measured at selected stations. Sample positions were fixed alongshore by reference to stakes driven into the backshore at 30 m intervals. Position across the beach was determined by reference to the strand line, which is marked by an accumulation of fine floatable debris deposited by the highest waves at high tide.

After the first week of detailed observation (20–25 July 1978) the movement of tracer material was assessed at approximately weekly, and then monthly, intervals by counting the number of chips visible in a metre-wide strip of beach normal to the shoreline. Distinction was made between chips above and below the strand line.

The sampling methods used are thought to give significant results because of the large initial input of tracer material comprising 1·5 million grains. By comparison, Carr's (1971) experiments involved the use of between 1000 and 17 000 grains. In the present investigation, metre-wide strips were searched every 50 m so that on average 1/50 of the tracer population, 30 000 grains, was monitored.

*Results*

1. 20–25 July. During the first few days of the experiment high wave energy conditions prevailed (Fig. 4).

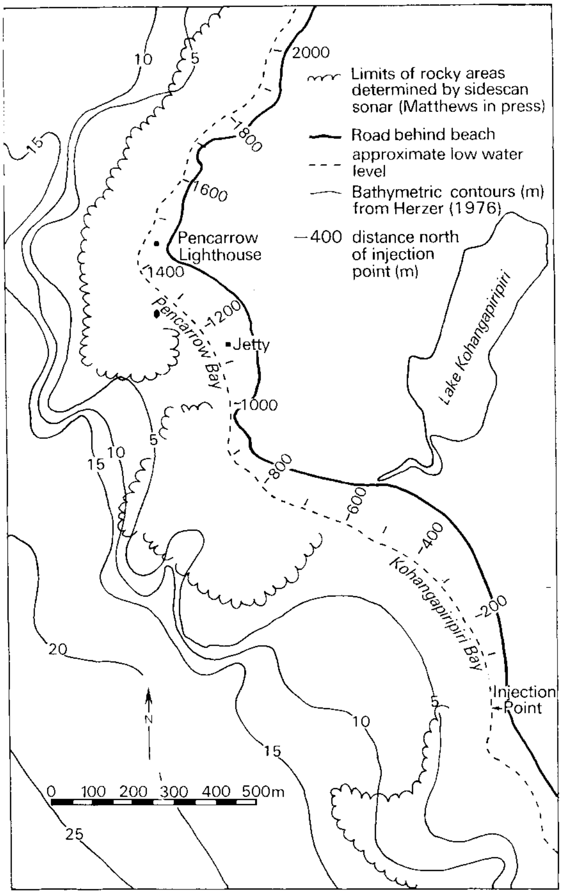

FIG. 3—Locality of the beach tracer experiment showing distances (m) northwards of the injection point. The nearshore bathymetry (m) from Herzer (1976) is also shown.

The beach slope was lowered and tracer pebbles were drawn to the bottom of the beach and pushed to the top, above the reach of normal waves, where they were stranded (Fig. 5). During this separation there was a general drift to the north, particularly on the lower part of the beach. After the first two days and under the influence of normal, lower energy waves, this longshore movement ceased. Instead, tracer pebbles from the bottom of the beach were pushed landwards to form a berm at the highest reach of normal waves. The size measurements revealed that coarser pebbles were generally concentrated high on the beach. There were no significant size trends alongshore (Fig. 6).

2. 3 August–17 November. Tracer pebbles were moved gradually northwards (Fig. 7). It is inferred from observations during the first week of the experiment that the northward transport occurred below the strand line and that coarse pebbles were thrown above the normal strand line during storms. This could account for the slower northward shift in mean tracer position above the strand line.

The general northward transport was accompanied by some apparent southward shifts. Northerly waves of sufficient magnitude to cause significant longshore gravel transport do not occur on this south-facing coast. It therefore seems unlikely that there could be significant southerly movement of gravel in either Kohangapiripiri or Pencarrow Bays. On the other hand, tracer pebbles could have been buried by sand veneers a few centimetres thick, which have been observed to develop in localised areas during calm periods. These veneers would have covered the coarser beach sediments and thus have affected the visible distribution of tracer pebbles. Conversely, during stormy periods the beach was flattened, and mobile sediments, including the brick chips, moved largely seawards and out of sight. This could have caused the generally low counts that were observed on Day 41 during a waning storm. By Day 42 a berm had been built and there were higher counts reflecting a shift in mean position that would actually have occurred two days earlier, during the storm. Evidence for such a process is provided by differences in recovery rates associated with storm and post-storm profiles (Fig. 8). The mean recovery rate for post-storm berm profiles was 2·39% compared with 1·53% for flattened storm profiles. Using the Student's *t*-test this difference was found to be highly significant.

Thus the apparent southward shifts may have been caused by these sorts of textural changes in the beach surface. In addition, the visible distribution of tracer pebbles above the normal strand line near the injection point was reduced by a 5–10-cm-thick cover of coarse gravel and debris that was observed to gradually accumulate there after successive storms (Fig. 7).

Recovery rates, although slightly higher at first, were essentially constant over the period of observation, varying between about 1·5 and 2·5%, depending on the prevalent wave conditions. These low rates can be attributed to vertical mixing with the natural beach sediments. At one site brick chips were found approximately 50 cm below the beach surface. The constancy of recovery rates suggests that loss of tracer material

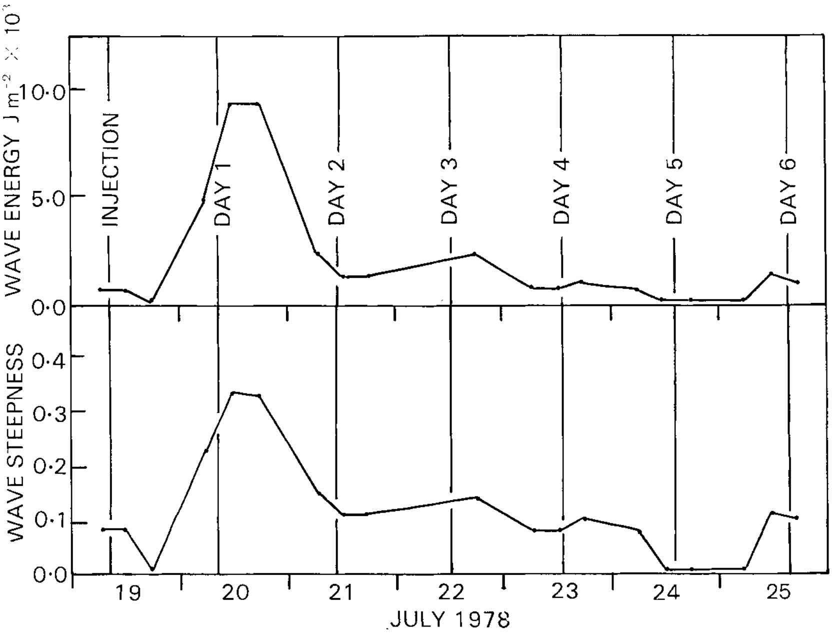

FIG. 4—Variation in wave energy and steepness during the first week of the pebble tracer experiment. These parameters were calculated from visual wave observations at Barrett Reef, made by the Wellington Harbour Board from Beacon Hill.

to the subtidal zone and by crushing and abrasion is small. However, it is conceivable that steady erosion of tracer-rich beach material near the injection point may have created a constant supply of tracer into the beach system. This would counter losses due to attrition and offshore transport (see below).

### *Mechanism of Transport*

During the first week of observation longshore transport occurred predominantly near low water level during high energy conditions while coarse pebbles were thrown above the normal strand line. In the calm conditions that followed, landwards movement resulting in berm construction occurred. On Days 2 and 6 isolated patches of tracer pebbles were observed at the northern limit of the tracer distribution. These patches suggest that beach gravel does not move alongshore coherently, but as small slugs which are somehow separated from the main gravel body and moved rapidly alongshore. Effective transport appears to occur by the "leapfrogging" of small gravel slugs rather than by movement of separate grains or by movement en masse (Fig. 9). There is no morphological evidence of such slugs; when returning to the beach face they are welded smoothly onto the berm. Judging by the tracer distribution (Fig. 5) the slugs are small, in the order of 1–10 m$^3$, and on the open coast may move distances in the order of 10–50 m while they are in existence, which would be less than one day.

This theory is supported by repeated observations, even several months after initiation of the experiment, of tracer pebbles occurring in small groups of 3–10 grains within a few square metres, at a distance of several hundred metres from the injection point. This segregation is not thought to have occurred by selective sorting because the surrounding barren area was usually of the same texture as the area in which the tracer grains occurred. Similar clustering is apparent in the observations of Carr (1971) and Kidson & Carr (1961) but was not discussed by them. The movement of gravel in slugs could possibly be caused by short term variations in wave energy related to wave interference patterns.

### *Rate of Transport*

The rate of movement northwards on the exposed south-facing coast was found using the relationship between time and mean tracer position (Fig. 10). Using the equation so derived it was calculated that in 365 days the mean tracer position would move 1·66 km.

Wave energy is known to be significantly and positively related to the strength of southerly winds at Wellington Airport (Matthews in press.). Southerly winds of Beaufort Force 5 correspond on average to a wave energy of $6 \cdot 5 \times 10^3$ J m$^{-2}$ (see Fig. 4). Such energies are typical of storms on this coast. Accordingly, the frequency of occurrence of southerly winds $\geqslant$ Force 5 may be considered proportional to the frequency of occurrence of storm events causing longshore transport on this coast. Over the last 18 years such winds were recorded on an average of 51·5 days per year.

During the year of observation there were 51 days with southerly winds $\geqslant$ Force 5 so it may be concluded that 1·66 km y$^{-1}$ approximates the average rate of pebble transport below the strand line on this section of coast. The maximum transport over this period was 3·80 km, over twice the mean distance of transport.

As discussed earlier, the brick chip represents beach gravel of approximately $-4 \cdot 1\ \phi$ (17·2 mm diameter).

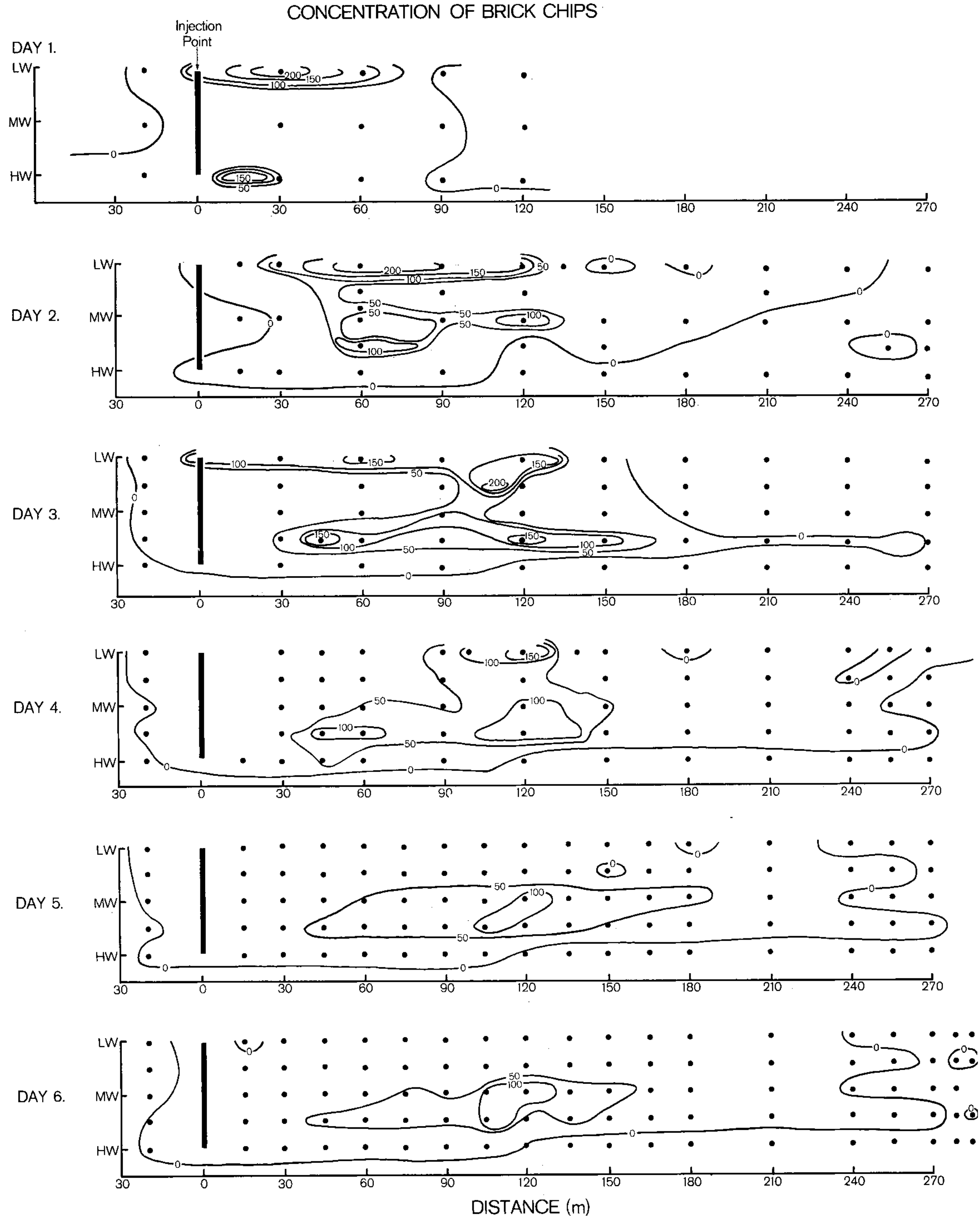

FIG. 5—Distribution of brick chips during 20–25 July. Concentrations are in number per m², north is to the right. High water level shown on this figure corresponds to the strand line that formed under the influence of storm waves and tide on the first day. The normal reach of waves at high tide is somewhat seawards of this level.

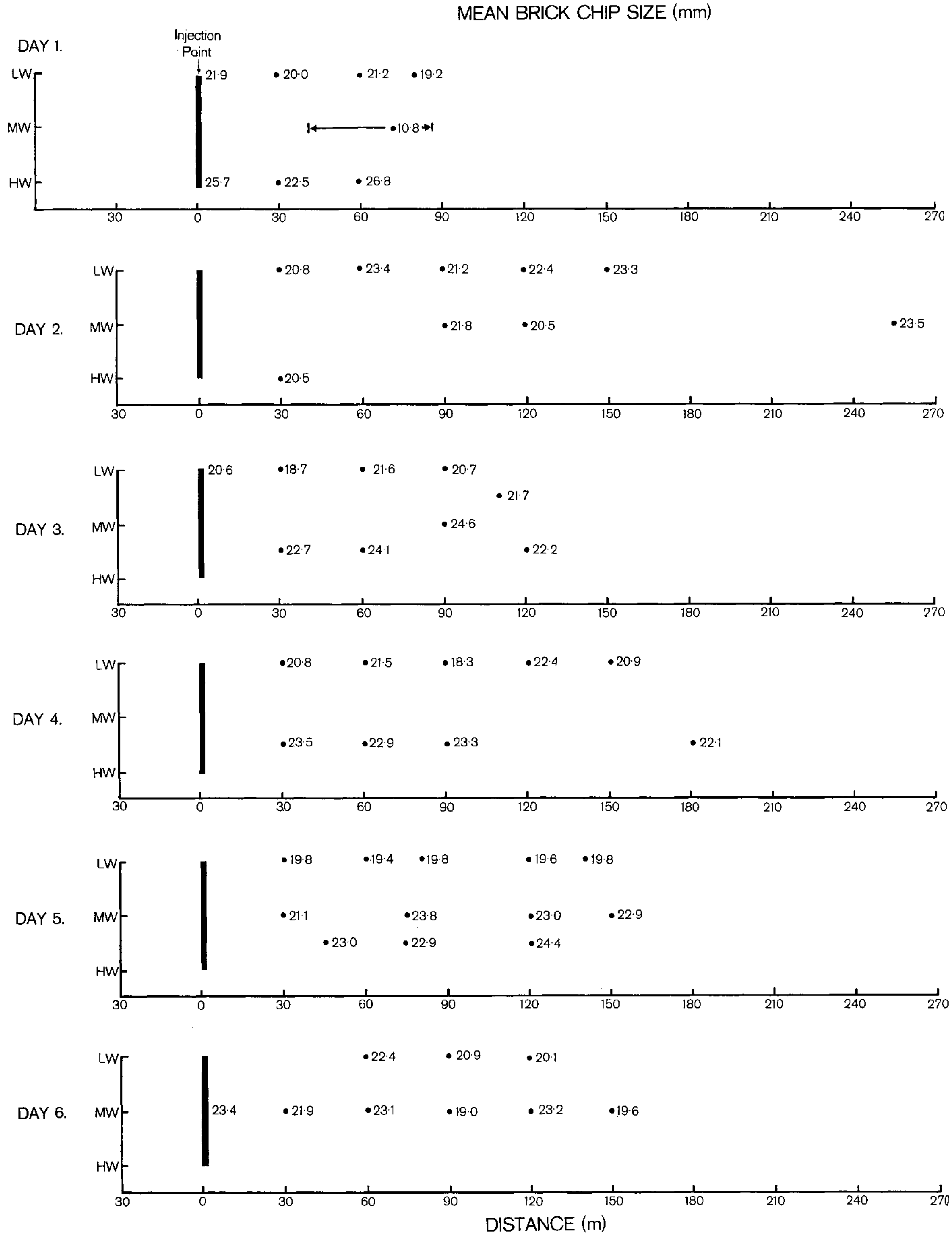

FIG. 6—Variation in mean brick chip size during 20–25 July. Layout is the same as in Fig. 5.

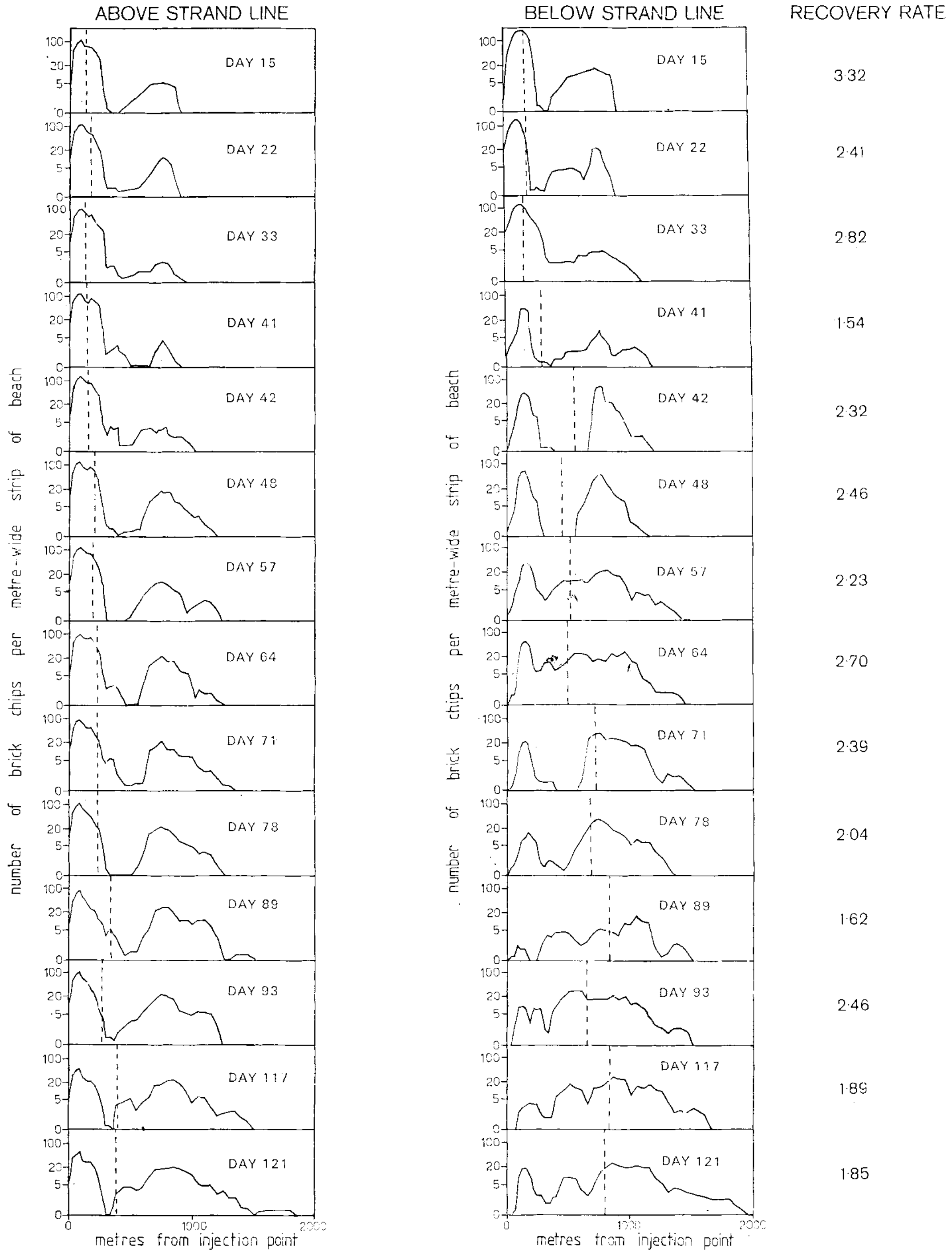

FIG. 7—Distribution of tracer material between 3 August and 17 November 1978. Recorded values were smoothed using a 3-point running mean and plotted using a probability scale with an arbitrarily defined zero so that the significance of low counts would not be lost. Mean tracer positions are indicated by dashed lines. The relationship of tracer positions to the coastline can be determined by reference to Fig. 3.

The relative rates of transport of the finer, granule and sand size sediment are not known.

### *Rounding*

During the first week of the experiment samples of between 50 and 150 brick chips were collected from the area of maximum concentration below the strand line. Subsequently, similar samples were collected during each survey from the active beach 750 m north-west of the injection point. These samples were subjected to visual rounding analysis using the scale of Krumbein (1941a).

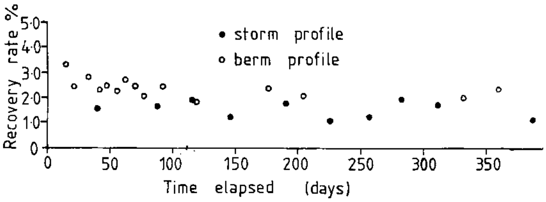

FIG. 8—Tracer recovery rates over the entire period of observation, calculated to include tracer pebbles both above and below the strand line.

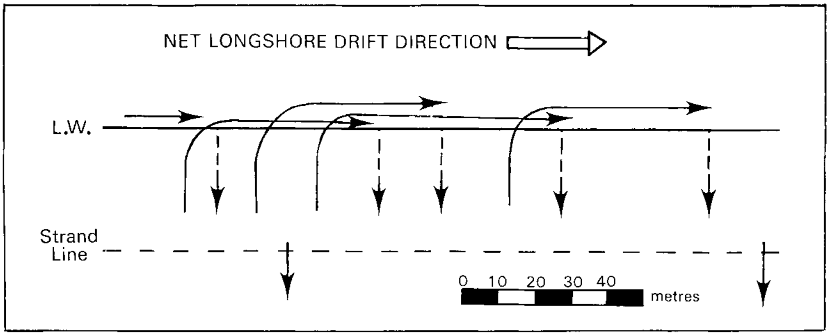

FIG. 9—Schematic representation of the mechanism of transport suggested for pebbles at Pencarrow. Movement during storm and post-storm conditions is indicated by solid and dotted lines respectively.

The analysis revealed a rapid initial rounding followed by a more gradual increase in roundness (Fig. 11). This trend is very similar to the results of laboratory experiments described by Krumbein (1941b). After 205 days the brick chips were still not as rounded as greywacke pebbles of similar size collected at the same locality, even though brick would be expected to abrade more readily than the indurated greywacke naturally present. This, combined with the evidence provided by the constancy of recovery rates, indicates that abrasion and attrition take years rather than months to cause significant loss of the pebble-sized sediment. However, granule-sized grains may be destroyed much more rapidly particularly as they are mixed with pebbles (Marshall 1927).

### *Discussion*

The suggested mode of gravel transport can be used to interpret some features apparent in the longer-term part of the experiment. Initially, the highest tracer concentrations were observed immediately north of the injection point. Above the strand line, the area of high concentration did not shift northwards as it was beyond the reach of normal waves, but was gradually covered by storm-deposited debris. Below the strand line, the area of high concentration moved slightly north and decreased in concentration. This can be attributed to gradual "erosion" of the tracer-rich beach material near the injection point as successive slugs were formed and moved north.

An interesting feature is the persistent lack of tracer pebbles about 500 m north of the injection point, in the centre of Kohangapiripiri Bay (Fig. 3). Tracer material appears to bypass the beach face and is presumably transported north below low water level. The visible absence of brick chips must be due to the inability of waves to move the pebbles landward during calm conditions. This could be caused by wave refraction effects (see Fig. 1) or to differences in the way the incident waves break. Either side of Kohangapiripiri Bay there are reefs upon which spilling breakers form. In the centre of the bay the waves build up rapidly on the steep bottom and form plunging breakers. Assuming similar wave parameters, a plunging breaker creates more swash than a spilling breaker because it breaks in a narrower surf zone. The higher backwash velocities that result may account for the lack of landward pebble movement in the centre of Kohangapiripiri Bay. In any case, the bypassing of tracer pebbles indicates that Kohangapiripiri Bay is

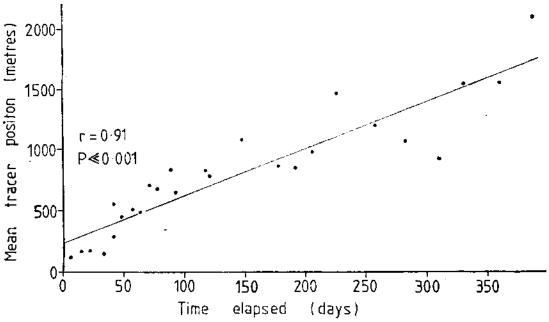

FIG. 10—Average rate of transport of brick chips below the strand line for entire period of observation.

FIG. 11—Rounding of brick chips. After 205 days the tracer pebbles were not as rounded as natural greywacke pebbles of similar size.

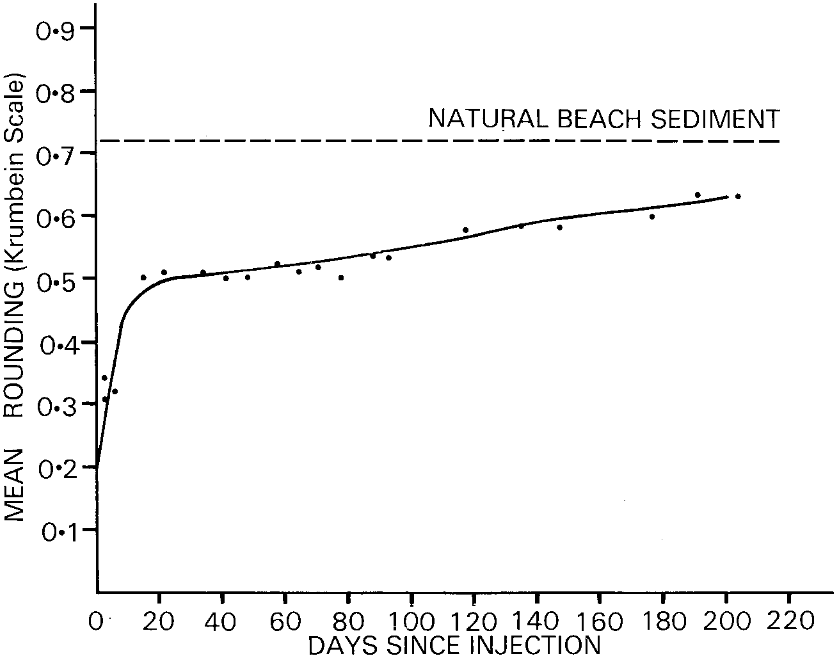

FIG. 12—View north shows a gravel front (outlined) at Hinds Point on 20 October 1978. Reference peg is at lower right.

not acting as an efficient gravel trap, at least in the intertidal zone. The small, and perhaps temporary, accumulations that formed above the strand line are probably not significant. As tracer pebbles did not accumulate in Pencarrow Bay, it is likely that the two bays are no longer prograding significantly.

Due to the complexity of the natural beach system, along which morphology, texture, and exposure to wave action vary rapidly, the distribution of tracer was irregular. This means that beach tracer experiments should be monitored in at least two dimensions, and that point sampling is not adequate to describe the movement of littoral sediments.

Longshore transport of beach gravel is dependent on the occurrence of high energy events. It is known that on this coast stormy conditions are on average twice as common in mid winter as in summer (Matthews in press), so that some seasonality in the rate of longshore transport could be expected. In addition, the occurrence of storms varies from year to year by a factor approaching two, so that interannual variation in the rate of transport should also be significant.

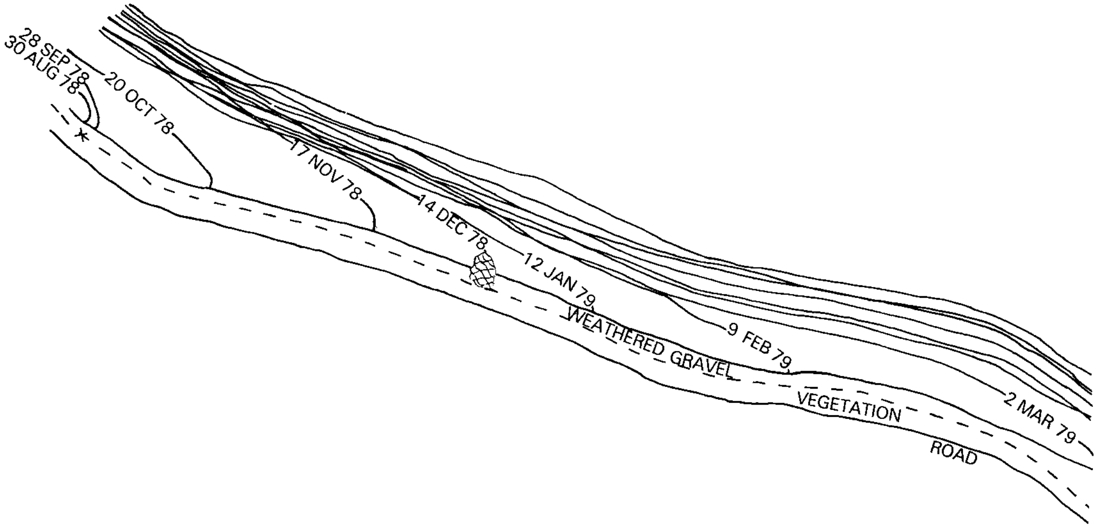

FIG. 13—Change in position of the gravel front at approximately monthly intervals. Note the sudden increase in beach width after 20 October 1978, and the decrease in movement after 15 June 1979.

Gibb (1979) has suggested that the rate of supply of gravel to this coast may vary by a factor of eight. The sudden progradation of Kohangapiripiri and Pencarrow Bays and the existence of the gravel front suggest that large fluctuations in supply rate do occur on this coast.

## MOVEMENT OF THE GRAVEL FRONT

### *Procedure*

At Hinds Point, about 4 km north of Pencarrow Head, there is a sudden change in the nature of the beach sediments that has already been described as a gravel front. In August 1978 a peg was driven into the backshore to mark its position. On subsequent visits the relationship of the gravel front to this peg was measured (Figs 12, 13, 14).

### *Results*

After the first month, during which there was very little movement, there was a regular northward shift of 20–30 m per month. A sudden increase in the width of the beach which occurred between Day 51 (October 20) and Day 69 (November 17) may be related to the occurrence of high wave energy conditions on October 21.

At Hinds Point the rate of northwards transport decreases, probably because of the gradual decrease in southerly wave energy (Fig. 1) and possibly also because of the effect of short-period northerly waves generated inside the harbour. Because of the energy gradient, the storm intensity required to move gravel northwards will be greater further inside the harbour, so that transport will occur more intermittently than on the open coast. In addition, the wave direction is more critical than on the open coast, and all waves except those arriving from a very small range of directions will be strongly refracted. This, as well as the length of the intersurvey period, may explain why movement of the front does not appear to be closely related to peaks of wave energy.

After April 1979 the front became more diffuse, apparently in response to a change in orientation of the coastline (Fig. 13), which reduced the angle of wave incidence. This has caused a reduction in the rate of transport, particularly after June 1979.

By using the rate equation (Fig. 14) it has been calculated that the front would move 0·42 km in 365 days. As the occurrence of strong southerly winds during this period was very close to the average, 0·42 km y$^{-1}$ can be taken as the average annual rate of movement. Gibb (1979) has also followed the movement of this front. He deduced an average rate of 0·33 km y$^{-1}$ between 1974 and 1977, supporting the rate derived from the present study. From measurements of the disposition of the gravel front it has been deduced that movement at this rate corresponds to a total transport in the order of 6600 m$^3$ y$^{-1}$.

### *Discussion*

The rates of movement of the gravel front and the pebble tracer are not strictly comparable because movement of the gravel front represents transport of the entire beach whereas movement of the brick chips represents the transport of pebbles only. However, the existence of the mobile gravel front is consistent with the mechanism of gravel transport outlined earlier, although transport is more intermittent than on the open coast. Movement of gravel slugs may be considered analogous to the movement of a conveyor belt along which articles are repeatedly placed at irregular intervals. The conveyor belt ends when and where waves are not sufficiently powerful to move gravel in large quantities.

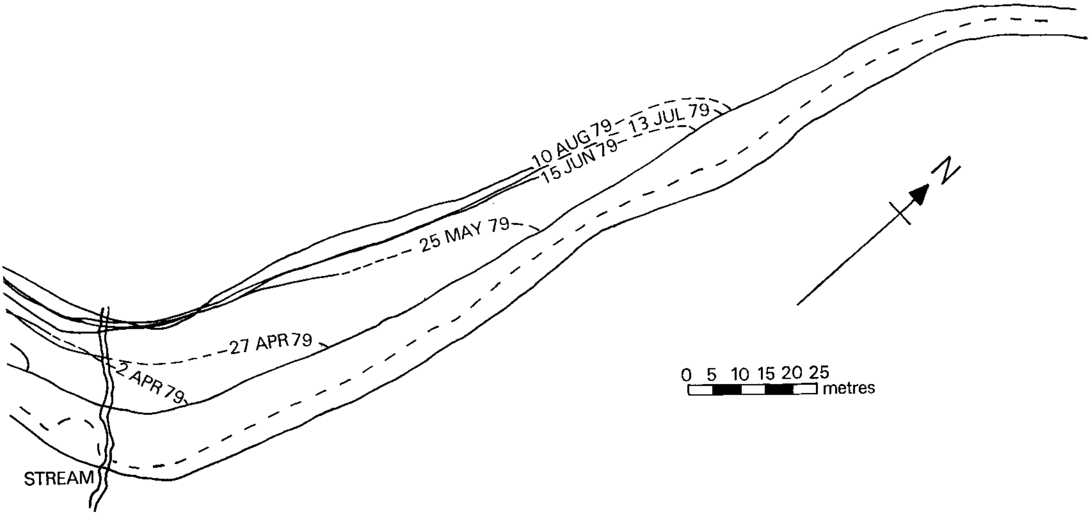

FIG. 13—*(continued)*

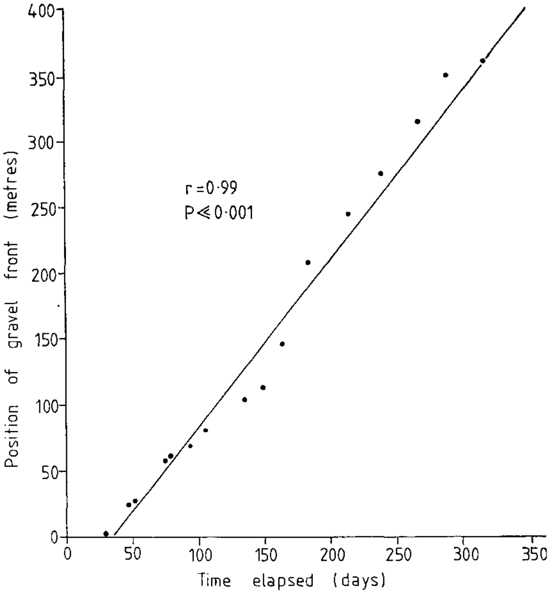

FIG. 14—Rate of movement of the gravel front.

## CONCLUSIONS

1. Pebbles at Pencarrow Head are moved northwards below the strand line at 1·66 km $y^{-1}$. At Hinds Point, inside the harbour, the entire beach is moving north at about 0·42 km $y^{-1}$. These rates are probably average values and may vary by a factor of two from season to season or year to year. Variations in the rate of supply of beach materials may cause larger fluctuations still.

2. Bypassing of tracer grains indicates that Kohangapiripiri and Pencarrow Bays are no longer efficient gravel traps.

3. The constancy of recovery rates and the relatively slow rate of rounding of brick chips suggest that longshore transfer of pebbles is accomplished with minimal losses due to abrasion and seawards transport.

4. It is suggested that pebbles at Pencarrow are transported in small slugs that form during conditions of high wave energy and are moved alongshore near low water level. At the same time coarse pebbles are preferentially selected and pushed above the normal strand line, where they may remain for several months or longer. During normal low-energy wave conditions the slugs of gravel move landwards, losing their identity, to form a berm.

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