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THE SAND BUDGET OF ORIENTAL BAY, WELLINGTON

by K.B. LEWIS,
R.A. PICKRILL and L. CARTER

NEW ZEALAND OCEANOGRAPHIC INSTITUTE
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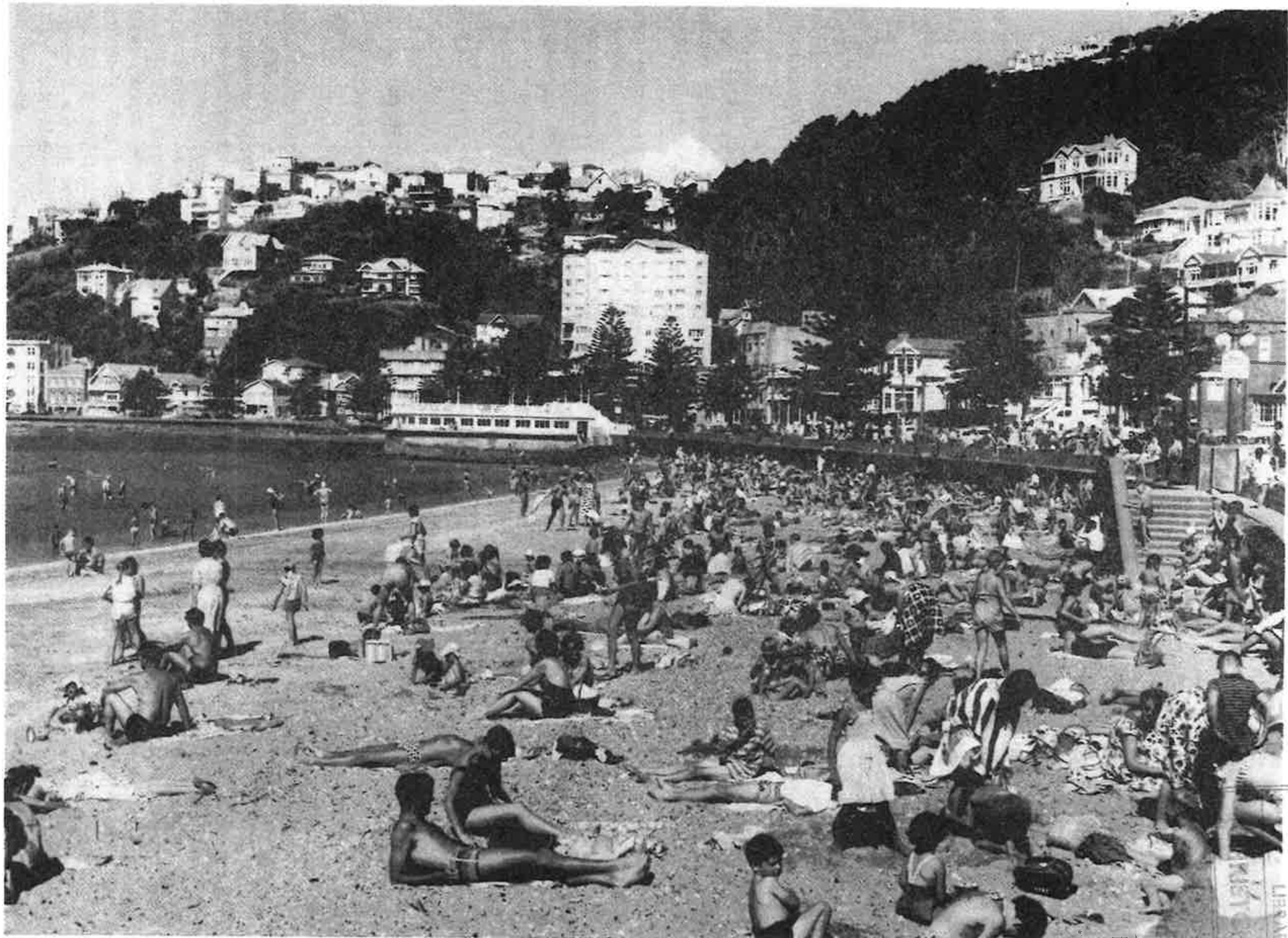
P.O. Box 12-346, Wellington, New Zealand



Frontispiece : Oriental Bay, 1963. Photo : National Publicity Studios (by courtesy of the Alexander Turnbull Library). *(Overleaf)*

THE SAND BUDGET OF ORIENTAL BAY, WELLINGTON

K.B. Lewis, R.A. Pickrill and L. Carter

INTRODUCTION

Oriental Bay is a feature of considerable civic pride to the people of Wellington. Besides the picturesque setting and fine harbour views, it possesses the only sandy beach within walking distance or short bus ride of the capital's main commercial and shopping centre.

A key problem with the beach is its low natural supply of sand. The remedy has been to replenish the beach artificially with sand imported as ships' ballast. The last replenishment was in 1945. Over the last two decades the volume of sand appears to have slowly diminished. Recent inquiries have been made by civic authorities and interested public bodies concerning further additions of sand to restore the recreational value and beauty of the bay.

This paper synthesises available data on the beach and seafloor off Oriental Bay and interprets these data with particular emphasis on sand dispersal and its relationship to the hydraulic regime. An historical perspective was gained through analysis of old records and photographs. The present sedimentary regime was ascertained from surveys carried out in 1977 and 1980.

ORIENTAL BAY

An Historical Perspective

Oriental Bay takes its name from the ship *Oriental* which landed colonists at Wellington on 31st January 1840. It is a north-facing pocket beach sheltered from strong southerly winds by bordering steep hills. At present there are three separate beaches; a central main beach, a western beach, here called Freyberg Beach, and a gravelly, eastern beach, informally called Grass Street Beach (Fig. 1). They are separated from one another by two rocky promontories that are partly covered by an esplanade and a band rotunda. Despite its present air of permanance the foreshore of Oriental Bay has changed many times since the arrival of the *Oriental.*

Changes in the shoreline and beaches over the last century were determined through inspection of records lodged in the Wellington Harbour Board and Wellington City Council and perusal of old newspaper clippings, pamphlets, books and photographs lodged mainly in the Alexander Turnbull Library. Recollections of older inhabitants also proved useful in suggesting lines of investigation which could be verified from one or more of the above archives.

Our earliest photographic record displaying any detail of the beach dates back to the 1880s and 1890s (Figs 2a, b, 3a, b). At that time Grass Street Beach was predominantly gravel with small patches of sand near the low tidal level. The main beach had a covering of sand across and above the intertidal zone. The beaches were backed by a 1–2 m high, locally grass-covered, rock-rubble slope which was probably a modification of the berm uplifted in the 1855 earthquake (Stevens 1974). The early Oriental Parade, above the slope, was an unpaved road, much narrower than present, with a single track railway used for carrying spoil from near Point Jerningham to reclamations at Te Aro (Fig. 3b).

Between 1900 and 1910 the road was progressively widened, mainly at the expense of the beach (Figs 3c, 3d), A series of boat sheds were built (Figs 2c, 3b, c) although these were removed before the First World War (Fig. 3d). The railway (Fig. 3b) was replaced by a tramway (Fig. 3c) thus providing better public access to a beach largely buried beneath road and despoiled by gravel eroded from the rubble revetment.

About this time the Te Aro Baths were built at the present site of the Freyberg Pool. Initially, they seem to have been of open timber construction allowing free flushing and sediment transport by the sea. The present sea wall and band rotunda were built about 1914 with further loss of natural beach (Fig. 3e).

Photographs taken in the 1920s and 1930s (Figs 2d, 2e, 3e, 4a, b, c) show a relatively well developed beach at the Grass Street site and minor but increasing amounts of sand on the main beach. Some local residents recollect experimental sanding of the beaches during or soon after the First World War. On the Grass Street Beach, a cobble substratum was capped by a berm of finer, pebble gravel which extended approximately 20 m either side of the Grass Street steps (Figs 2d, e) and by a sandy beach that extended 20 m east of the rotunda. The berm remained at least until 1935 (Fig. 2e) and possibly longer judging by aerial photographs taken in 1939–1941. In the early 1920s the main beach was covered with sand to 25 m either side of the central steps, with gravel and rock out-

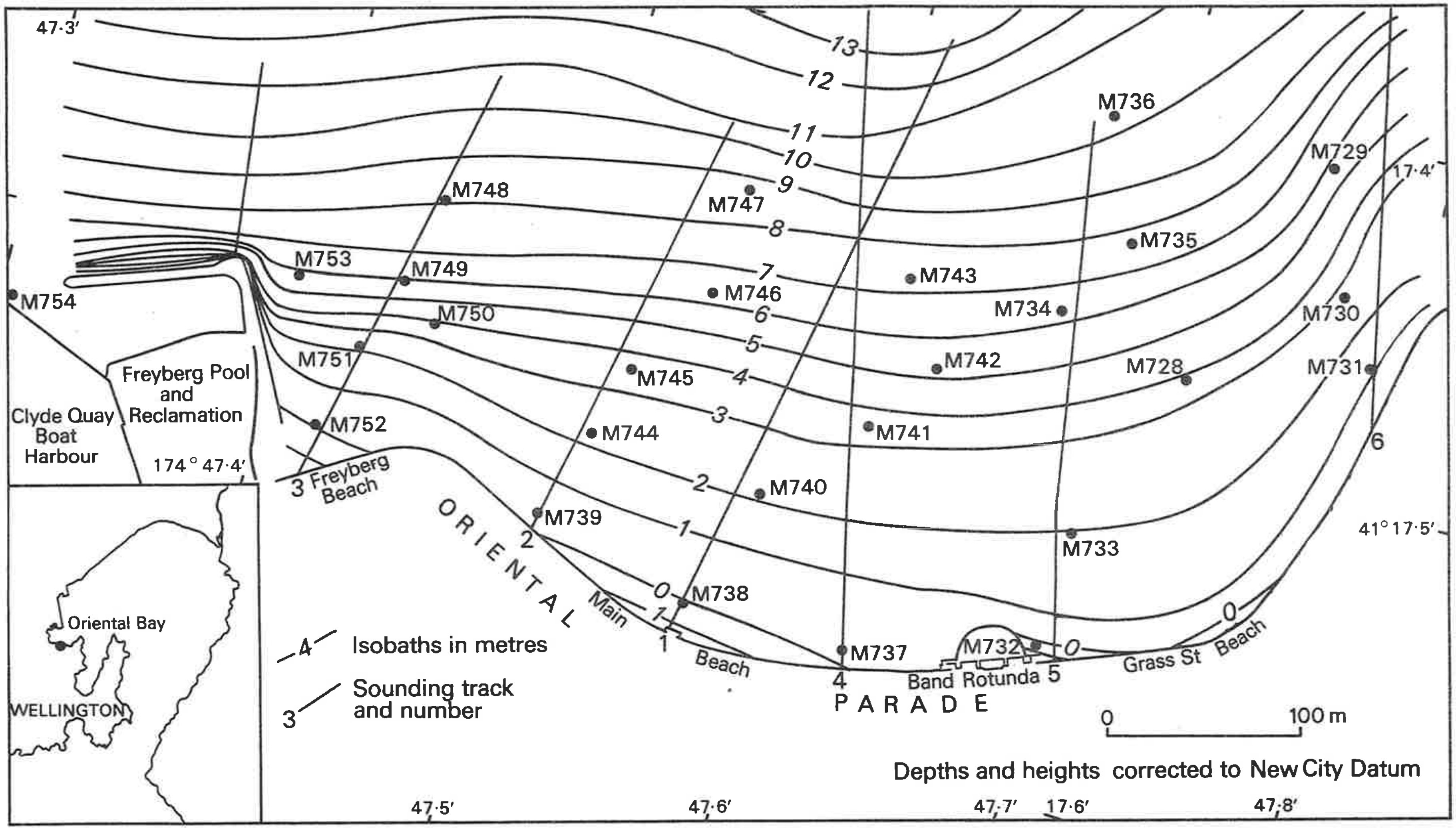


Fig. 1. Locality map and bathymetry corrected to New City Datum, with positions of NZOI sounding tracks and sample stations occupied in March 1980.

cropping beyond the sand (Fig. 4a). In 1929 the sand blanket was more extensive, extending about 10 m closer to the rotunda (Fig. 4b). This change in the beach may reflect either fluctuation in the sand budget or nourishment from some external source, possibly sand moving round from Grass Street Beach. Photographs from the 1930s suggest that the beach sand then was somewhat coarser than at present (Fig. 4d).

From 1938 onwards Wellington has been periodically surveyed using vertical aerial photographs, which provide an excellent perspective of the entire beach system at Oriental Bay (Fig. 5). Together with detailed ground photographs and newspaper reports the aerial views document marked changes in the sand budget. In the 1938 and 1941 aerial photos, the sandy part of the main beach was still very restricted with a trend of 106°T and extensive rocky outcrops at either end. The Grass Street Beach was larger than at present with gravel clearly visible in shallow water, and the Freyberg Beach did not exist (Fig. 5a).

On 9 October 1944 the newspaper "Evening Post" reported that 10,000 tons of clean, Bristol Channel sand brought in ships' ballast from England had been donated to the City Council and tipped over the sea wall on to the two beaches on either side of the band rotunda (Grass Street Beach and the main beach). A further 4,000 tons were to follow although much of this went to beaches in Evans Bay. On 27 December 1944 the "Evening Post" reported that the sand had shifted westwards off the Grass Street Beach and the possibility was recognised that the westward drift could continue around the Te Aro Baths at the western end of Oriental Bay. On 24 April 1945 the paper reported that a further 4,000 tons had been divided equally between Oriental Bay and the Te Aro Baths. The reports revelled in Wellington's new asset but pondered how long it would remain.

By September 1945 sand covered much of the gravel platform off Grass Street Beach and appeared to be moving in a broad zone around the rotunda (Fig. 5b). The main beach extended right to the rotunda but sand only partially covered the rocks at the western end. Its trend had changed to 102°T. There was still no beach at the Freyberg site but there appeared to be a sandy shallow terminus inside the Te Aro Baths, which by then had solid concrete foundations that restricted water circulation and sediment movement. By the summer of 1946 most of the sand had moved off Grass Street Beach, partly offshore and partly westwards around the rotunda. Sand has remained on the beach to the present day.

The wartime sanding of the beaches with Bristol Channel sand not only changed the volume of sand available for beach construction, it also changed its grade. The new sand was finer than before (compare Figs 4d and 4e).

The post-war sedimentary history of Oriental Bay has consisted largely of a slow, net westward drift of the Bristol Channel sand.

By 1951 there was still sand below low tide off Grass Street Beach but the rocky platform around the band rotunda was largely clear and sand covered the main beach from the edge of the rocky western promontory to the steps beside the rotunda (Figs 4e, 5c), the trend of the beach being 105°T. There was still no beach development at the Freyberg site although sand appeared to be moving offshore around the end of the old baths.

In the mid-1950s the gravelly subtidal zone off Grass Street Beach was swept free of sand and the main beach probably reached its maximum development (Fig. 5d). Sand extended to both the western rocky promontory and the band rotunda, the alignment of the beach being still 105°T. Sand covered the seafloor in the embayment beside the Te Aro Baths and also appeared to be migrating around the seaward end of the baths.

During the 1960s the westward drift of sand continued. The nearshore area around the band rotunda was swept clear of sand, which built up on the rocky promontory at the western end of the main beach (Fig. 5e). With erosion at the eastern end and build-out at the western end, there seems to have been a minor realignment of the main beach from about 105°T to 109°T. Sand continued to build up in the bay beside the old baths. In 1961 the old open-air baths were filled and the Freyberg swimming pool and car park were built on the reclamation. Although there was a well developed sandy beach at the Freyberg Beach site in 1969 there was almost no sand above high water.

The situation was essentially the same in 1971 but in 1972 the Freyberg reclamation was extended by some 70 m, with 30 m of extra carpark and 40 m of a boulder breakwater that trended westwards to enclose a sheltered "lagoon" originally intended for use by rowing clubs (Fig. 5f). The foundations of the old Te Aro open-air baths extended into water only about 2 m deep and sand moved around them. The new reclamation extended to the 6 m isobath, that is, beyond the depth of sand transport, and acted as a complete barrier or groyne, to the continuing westward longshore movement of sand towards the yacht harbour.

By 1975 the Freyberg Beach was well established (Fig. 5f), being about 15 m wide from the high-water line to the back of the beach. By 1980 it was 22 m. wide with a greater area above high water than the main beach in spite of a small "frontage" to the sea (Fig. 6a). From 1972 to 1980 the high-water mark moved seawards at a rate of more than 2 m per year and there has probably been a similar rate of sediment progradation below water.

The sand that is building out Freyberg Beach appears to derive from the main beach, which has become reduced in width since its heyday in the 1950s and early 1960s (compare frontispiece and Fig. 6b). In particular there appears to have been erosion below low water at the eastern end of the main beach where gravel has been periodically ex-

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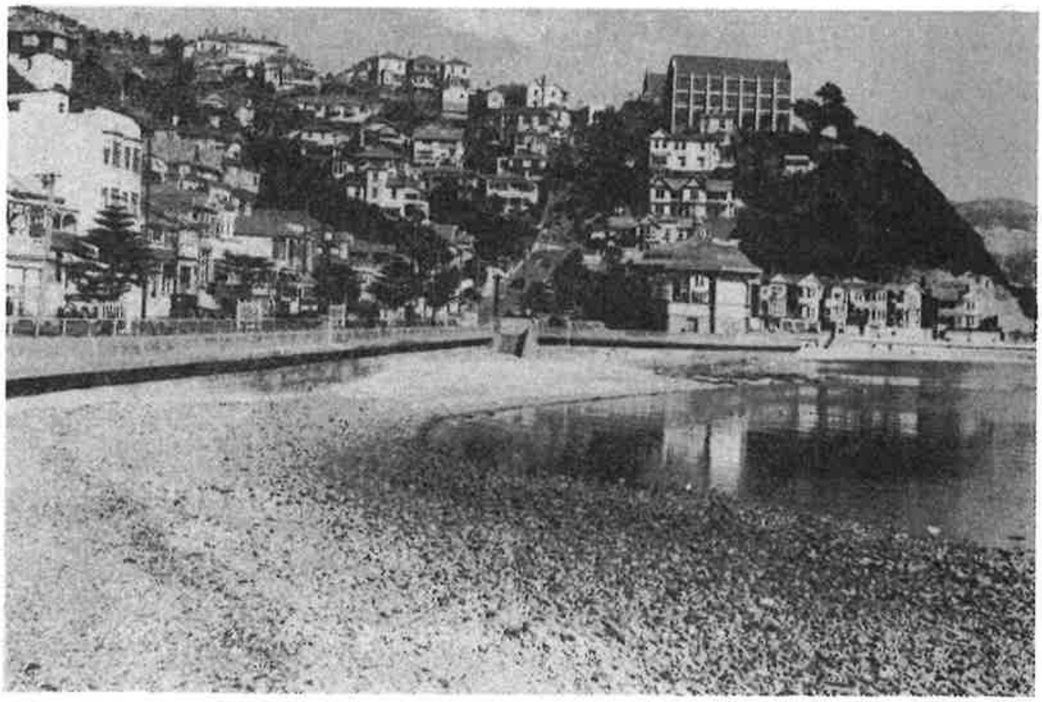

Fig. 2. Early views of Grass Street Beach looking westwards. (All photos by courtesy of the Alexander Turnbull Library.)

(a) 1880s – the beach of rounded cobbles with a sandy beach and the rocky promontory now occupied by the band rotunda. Photo : W.H. Davis.

(b) 1880s – detail of Grass Street Beach near the rocky promontory, showing a tract of sand below the gravelly berm. Photo : W.H. Davis.

(c) 1900 – a view of Oriental Bay showing angular debris, presumably eroded from earlier reclamation, on Grass Street Beach. Photo : C.S. and P. Cording Series.

(d) 1932 – a berm is evident along the base of the sea wall and there is a moderately-sized sandy beach beside the band rotunda. Photo : S.C. Smith Collection.

(e) 1935 – detail of the berm and sand on Grass Street Beach. The sediments on the berm appear to comprise coarse sand and pebble gravel. Photo : Evening Post.

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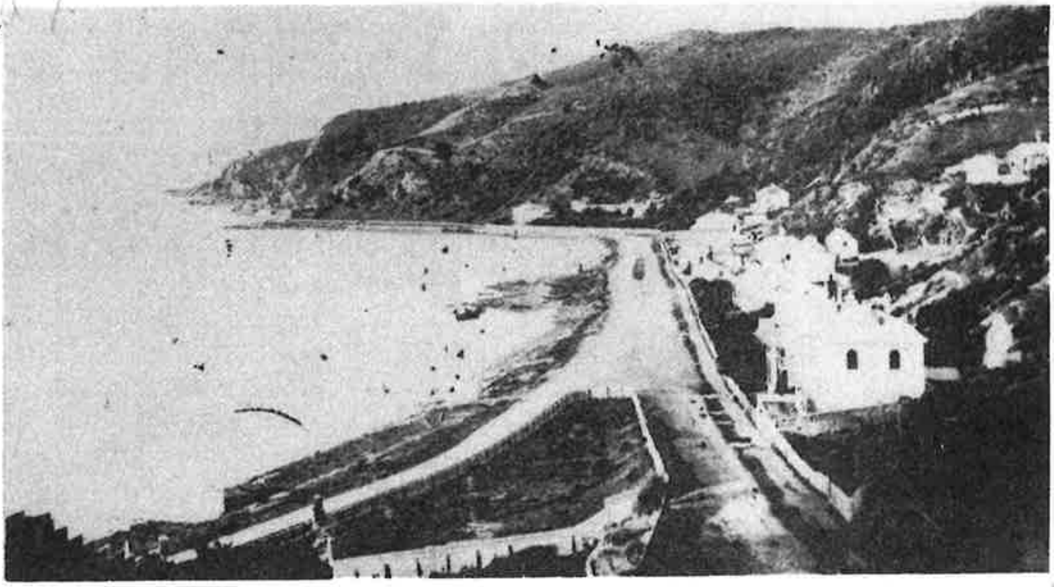

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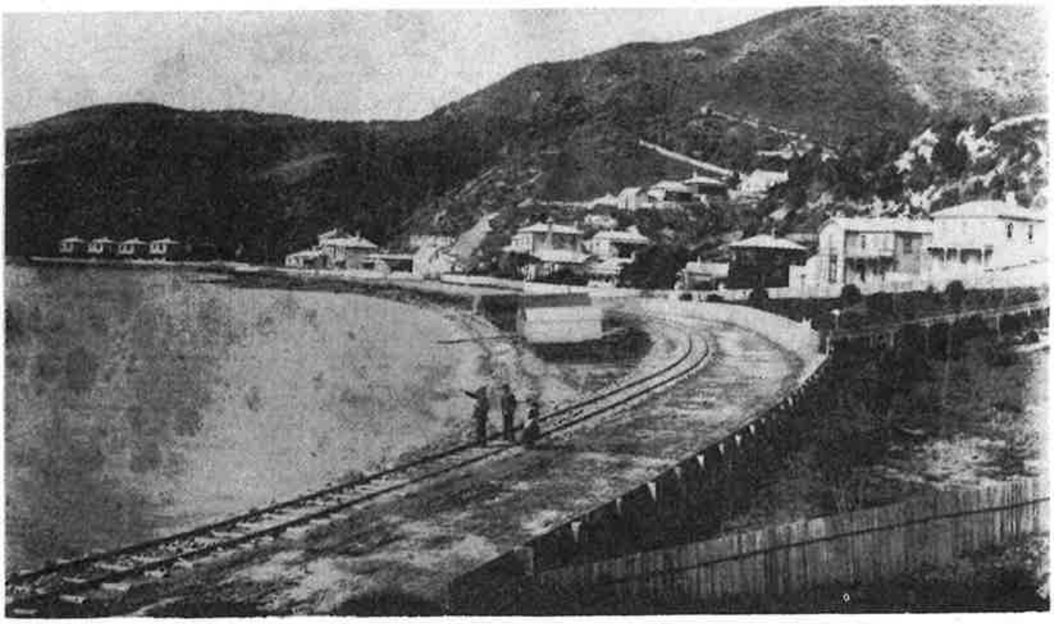

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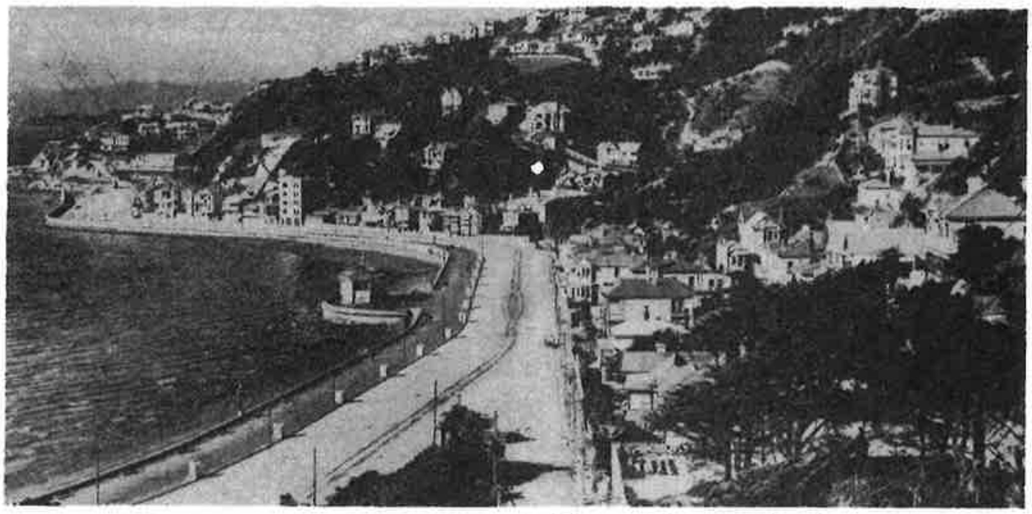

Fig. 3. Early views of the main beach of Oriental Bay looking eastward, showing the development of Oriental Bay Parade and obliteration of the upper beach. (All photos by courtesy of the Alexander Turnbull Library.)

(a) 1880s - showing small gravelly, rocky promontories and a sandy beach. A coastal road has been formed on the pre-1855 earthquake berm and shore platform. Photo : W.H. Davis.

(b) 1900 - showing the small sandy main beach. The coastal road has been widened with crushed rock carried from east of Oriental Bay to the reclamations at Te Aro. The despoiling of the beach and proliferation of boat sheds suggest that the beach was considered to be of little aesthetic value. Photo : M Connally, Lowe Collection.

(c) 1905 - the road and the railway have been replaced by a tramway and widened to accommodate a footpath. With improved access and development of housing Oriental Bay was incorporated into the City. Photo : Muir-Moodie.

(d) Ca. 1910 - the boat sheds have been removed and the sandy beach obliterated by widening the coastal road. The main beach has been covered by gravel derived from erosion of the spoil used to widen the road. There still appears to be some sand on Grass Street Beach. Photo : S.C. Smith Collection.

(e) 1920 - the mainly gravelly beach is bordered by the completed road, promenade, rotunda and sea-wall. Lamp-posts have been moved seawards from their earlier position. The berm on Grass Street Beach is clearly shown. There appears to be some sand on the main beach close to the central steps.

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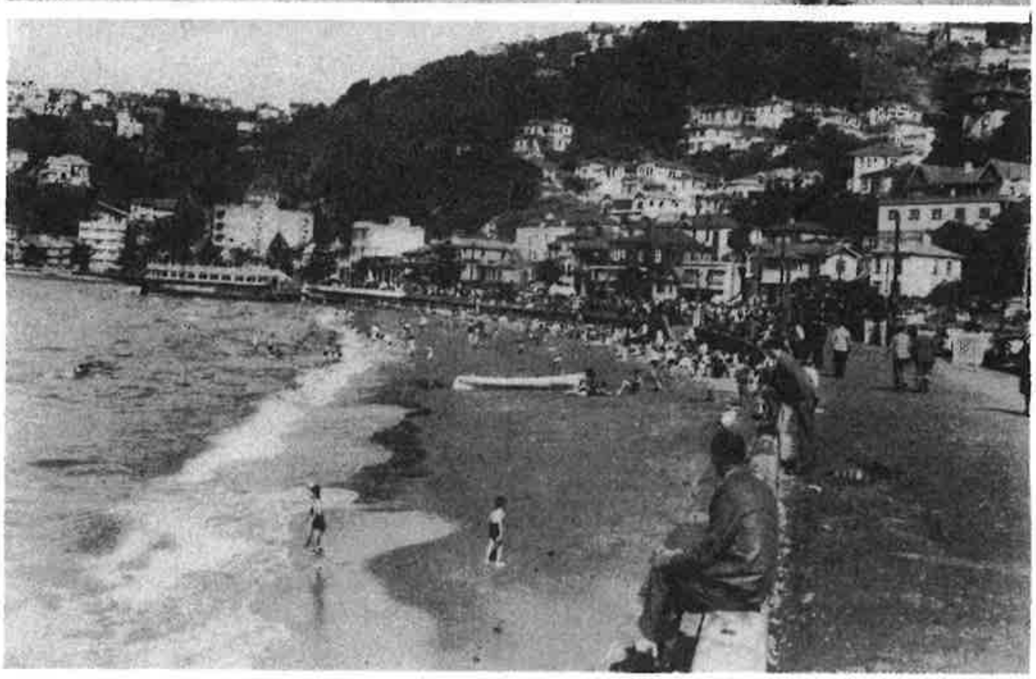


Fig. 4. **Post-First World War evolution of the main beach at Oriental Bay.** (All photos by courtesy of the Alexander Turnbull Library.)

(a) 1920 – showing the beach of gravel and sand. The sand extended approximately 25 m either side of the steps.

(b) 1929 – the sand has moved closer to the rotunda judging by its position relative to the multi-headed lamp-posts on the parapet. Sand could have moved on to the main beach from offshore and from Grass Street Beach. Photo : S.C. Smith Collection.

(c) 1931 – at the western end of the main beach the sand has extended an estimated 50 m west of the steps. Photo : S.C. Smith Collection.

(d) 1939 – the beach has become more extensive and higher up the steps than before and appears to have been steeper and coarser than at present.

(e) 1949 – five years after replenishment, fine sand has covered the entire beach between the band rotunda and western promontory. Photo : S.C. Smith Collection.

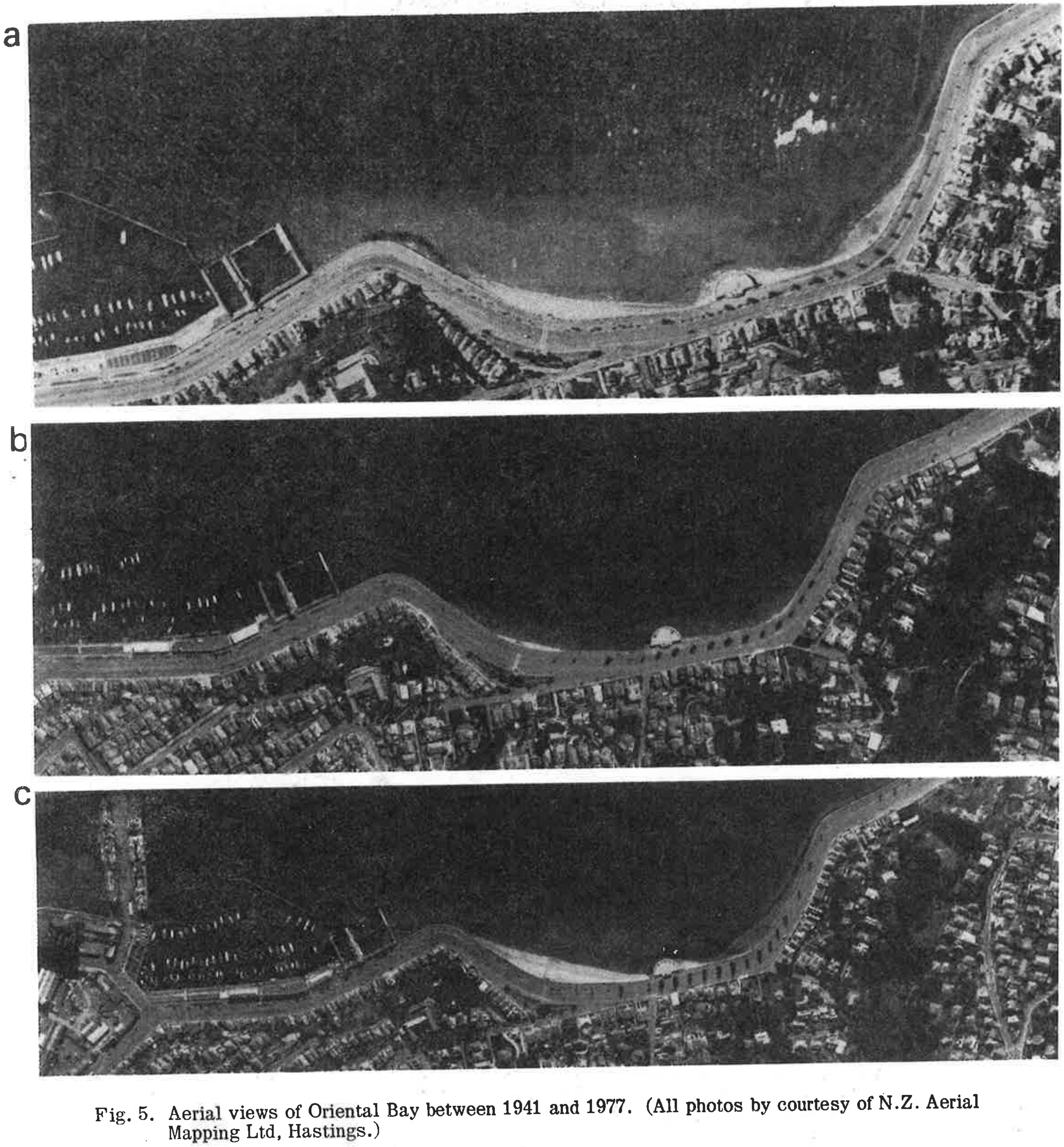
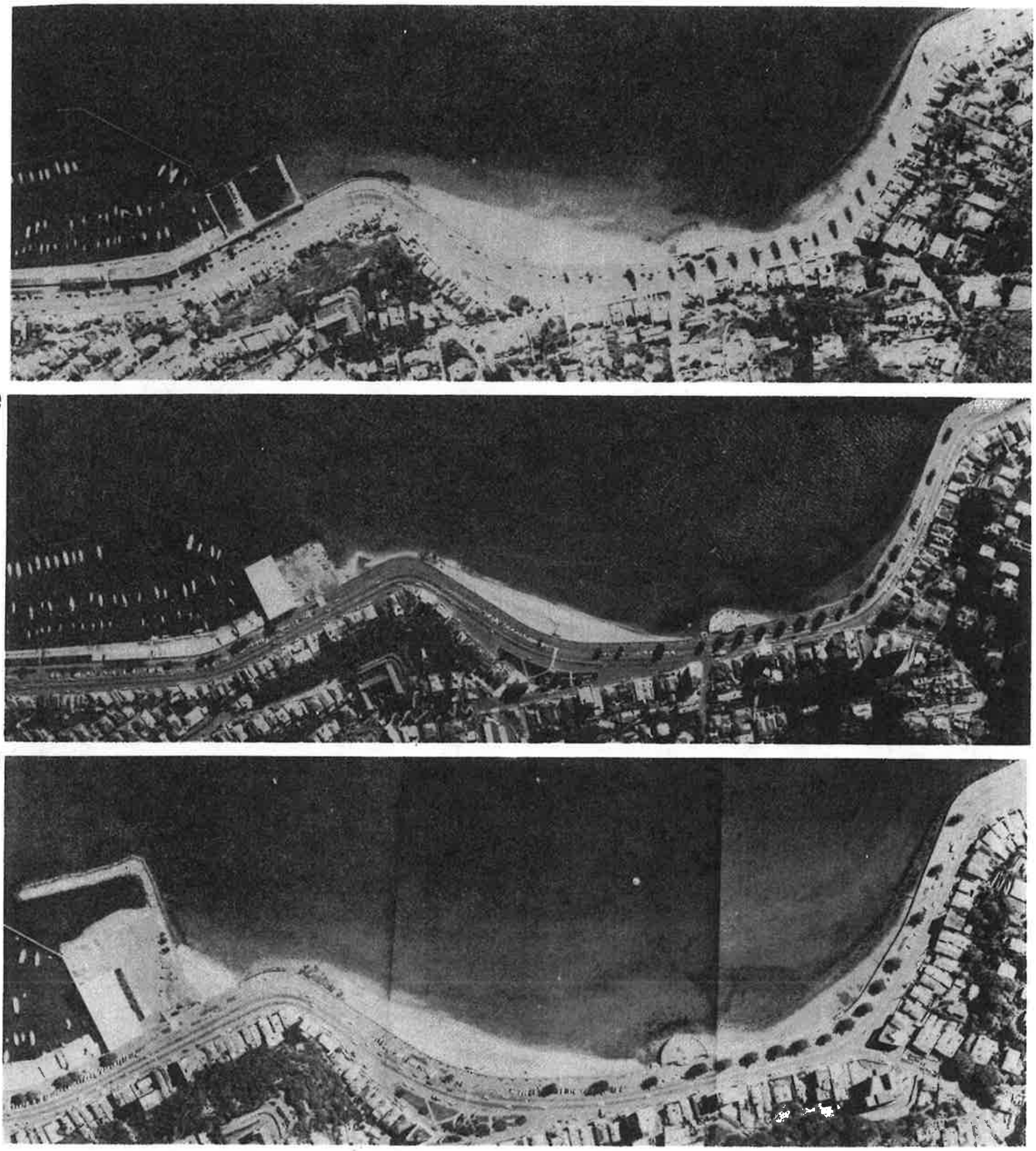


Fig. 5. Aerial views of Oriental Bay between 1941 and 1977. (All photos by courtesy of N.Z. Aerial Mapping Ltd, Hastings.)

(a) January 1941 : before replenishment by Bristol Channel sand; beach trend 106°T.

(b) September 1945 : immediately after replenishment. Note the sand cover offshore from Grass Street Beach; trend of main beach 102°T.

(c) May 1951 : six years after the replenishment programme; sand has remained offshore, east of the rotunda. The main beach has prograded and trends 105°T.



(d) **April 1954 : the main beach at maximum development, with gravel off Grass Street Beach.**

(e) September 1969 : showing a change of trend of the main beach to 109°T and the beginning of growth of Freyberg Beach; some sand occurs beyond the band rotunda.

(f) February 1977 : showing development of Freyberg Beach beside the extended Freyberg reclamation.

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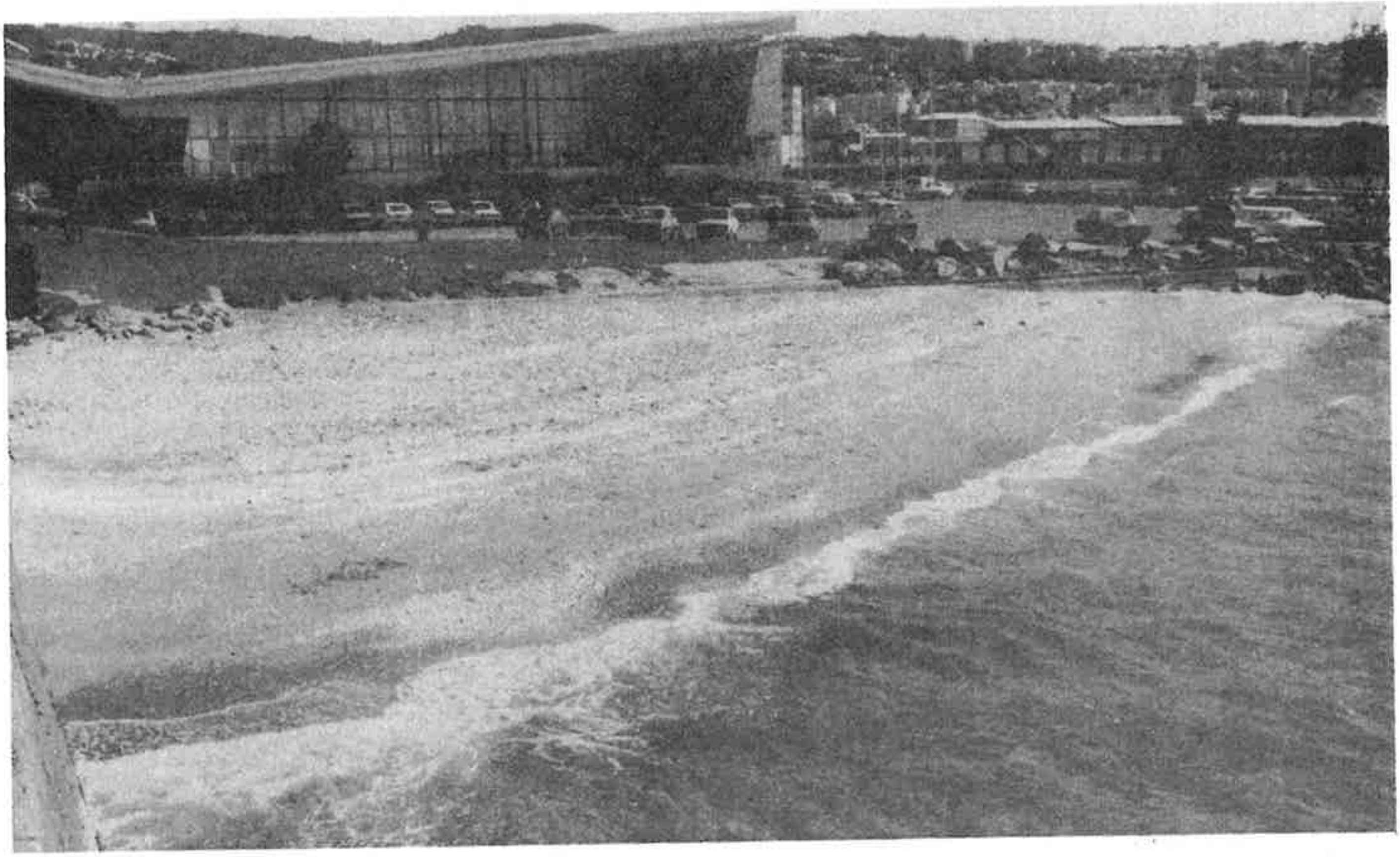

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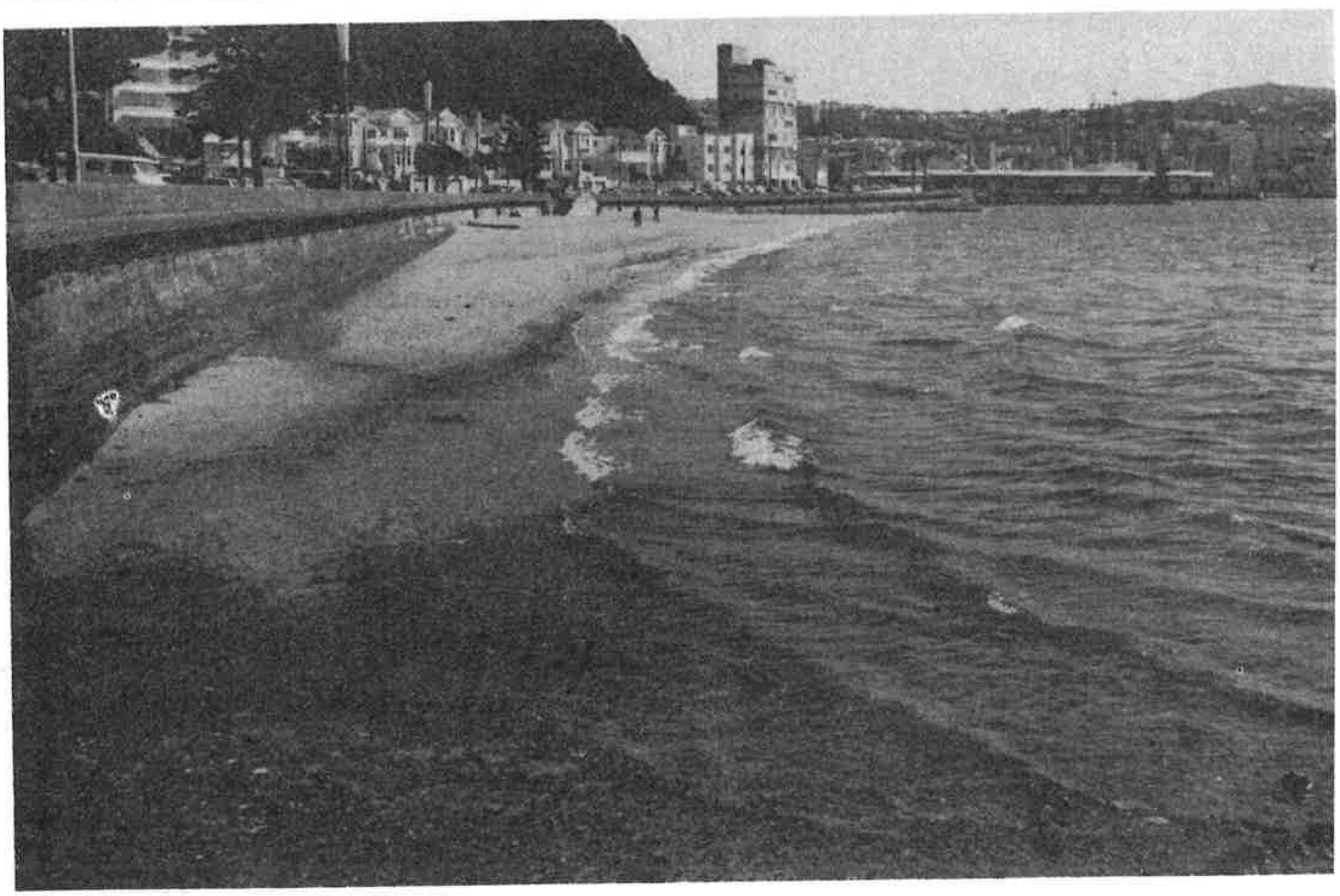

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Fig. 6. (a) Freyberg Beach; (b) the main beach (*facing page*) and (c) Grass Street Beach in September 1980.

Photos : Science Information Division, DSIR.

posed in 1971, 1975 and in 1980. In addition there are reports that divers laying cables from the band rotunda to the Carter Fountain in 1973 found a lag deposit of old bottles that remained as sand was transported from the site. The sand seaward of the band rotunda may be part of the fill that was removed rapidly from Grass Street Beach in 1945. There is no obvious plentiful source of sediment to the Oriental Bay beaches, which now, since elimination of loss to the west, form an almost closed system. The only addition of beach material is from comminuted shells and, possibly, from sand generated east of Grass Street Beach.

SURVEYS

A general indication of the bathymetry in Oriental Bay is available in hydrographic charts of Lambton Harbour (Hydrographic Office 1975). These are corrected to a hydrographic datum.

In 1977, the seafloor off Oriental Bay was surveyed with a Klein side-scan sonar (model 400) towed from the 6 m long NZOI survey boat *Taraiti*. The instrument is essentially a "sideways-looking" echo sounder which produces the submarine equivalent of an

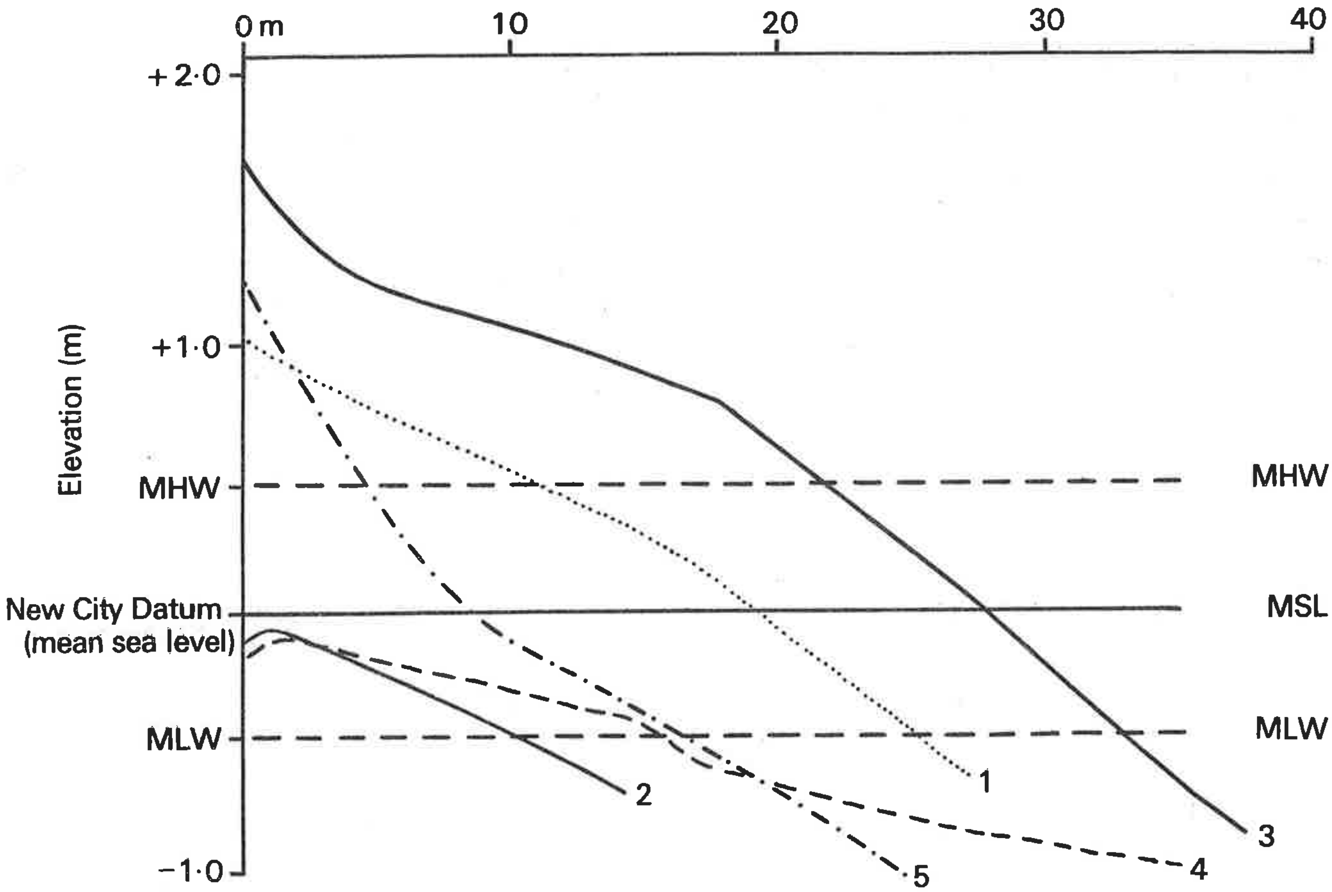


Fig. 7. Profiles of the main beach (1, 2, 4), Freyberg Beach (3) and Grass Street Beach (5). Depth is relative to the New City Datum versus the distance from the sea wall. Positions are shown in Fig. 1.

aerial photograph - a sonograph. Interpretation of sonographs yields data on seafloor morphology and, to a lesser extent, water depth and sediment type. The last two aspects generally require substantiation, which was the object of the second survey in February 1980 when a series of beach surveys and echo-sounding traverses were made in conjunction with collection of bottom sediment samples (Fig. 1). The soundings were corrected to New City Datum and contoured, together with soundings supplied by the Wellington Harbour Board, at 1 m intervals. The sediment samples, including five samples collected by divers in 1979, were texturally analysed for gravel, sand and mud, with sand being sieved at 0.5ϕ intervals. Textural parameters were computed according to Folk (1968).

Beach Morphology

In the centre of the main beach, sand extends 1.0 m high above mean sea level (Profile 1, Fig. 7). It is about 25 m wide from mean low water to the sea-wall in front of the central steps narrowing to about 11 m wide at mean high water. The ends of the beach are exposed only at low water (Profiles 2, 4; Fig. 7). At each end of the beach there is a 1 m wide, 0.1 m deep, scour zone against the sea wall maintained by the turbulence associated with the reflection and refraction of waves against the wall. The beach is steepest (3.7°) in the centre and gentlest (2.4° and 1.5°) at the extremities.

Freyberg Beach (Profile 3, Fig. 7) reaches 1.6 m high above mean sea level and is the widest (from front to back) of the three beaches at all stages of the tide, ranging from 22 m wide at mean high water to 33 m wide at mean low water. At the time of the survey the beach had a convex accretionary profile with a berm 0.9 m above mean sea level. The gradient, 3.8°, is similar to that of the main beach.

Grass Street Beach (Profile 5, Fig. 7) is predominantly gravel with a steep (8.2°) gravel berm, up to 1.3 m above mean sea level, in the re-entrant between the rotunda and the sea-wall. The beach is narrow, ranging from 5 m at mean high water to 16 m at mean low water. The berm grades on to the less steep (3.2°) shore platform below mean sea level. There is also a small cobble-pebble beach in front of the Grass Street steps.

A gravel-strewn shore platform borders the eastern side of Oriental Bay and abuts against the sea-wall. It ranges from 5 m to 30 m wide and is bordered by a well defined scarp at its seaward edge.

Offshore Physiography

Echo-sounding profiles consistently show a flat, shallow terrace on the upper part of a broad, arcuate, submarine slope off Oriental Bay (Fig. 1). The terrace extends seaward from the toe of the beach into water 3–4 m deep. Correlations between profiles, side-scan sonographs (Fig. 8) and sediment samples (Fig. 9) indicate that the terrace is the morphological expression of the nearshore sand prism.

On steep limnic and oceanic shorelines exposed to short fetches a distinctive terrace profile develops (Pickrill 1978, in press). Typically, a gently sloping, nearshore terrace increases in width and depth as exposure to wave energy increases. Sandy sediments fine down the terrace. The outer edge of the terrace is marked by an abrupt change in sediment texture and gradient, with sandy muds on a steep offshore slope. The terrace profile develops as an equilibrium form in response to wave climate, with the shelf-break forming in relatively deep water in response to infrequent high energy events.

In Oriental Bay a similar terrace morphology and sediment distribution have formed. Gravelly sands fine seaward, changing to muddy sand across the terrace edge. The edge has formed in 3.5-4.5 m of water, the same depth as on terraces exposed to similar fetches elsewhere (Pickrill, in press). This depth is inferred to be the limiting depth of sediment transport under storm waves. Thus Oriental Bay has probably developed an equilibrium profile form in response to the wave climate.

The side-scan sonographs, used in conjunction with the aerial photographs, indicate two slightly anomalous parts of the terrace. Beyond the rotunda there is a nearly flat sandy area, at a depth of 0.5-2.0 m, with indications of gravel around its periphery. Comparison of aerial photographs (Fig. 5) suggests that the area of sand has contracted over the last decade revealing part of an underlying, gravel-strewn, rocky platform. At the western end of the system the terrace has a relatively steep seaward face and sharp contact with the muddy offshore slope, which gives the impression that it developed more recently than the rest of the terrace. Beyond the toe of the terrace, at a depth ranging from 6-7 m, the muddy seafloor shows evidence of anchor drag marks. It slopes away at about 3° to the floor of the Lambton Harbour Basin at 14 m depth.

Surface Sediments

Sediments collected from Oriental Bay show a clear separation between the sands and gravels of the beach-nearshore zone and the muddy sands of the slope and harbour floor (Fig. 9a).

In general, beach and nearshore sediments become finer towards the west. Off Grass Street Beach the shore platform is armoured by lithic pebbles and cobbles. Off the main beach the wide sand prism consists of shell-gravelly sands. Off Freyberg Beach the sediment grades seawards from moderately sorted to well sorted sand. The westward change from very poorly sorted pebble gravel to well sorted fine sand is illustrated by plots of mean grain size and inclusive standard deviation (Fig. 9b).

As a rule sediments become finer and better sorted as they are transported away from their source (Pettijohn and Ridge 1932; Sunamura and Horikawa 1972), while coarse gravel with interstitial sand is left behind as a "lag deposit" and fine sand is moved easily along the bottom to a "sediment sink". In the case of Oriental Bay, the gravel of Grass Street Beach seems to represent the lag deposit and the new sharply defined terrace by the Freyberg reclamation seems to be the present "sediment sink". Before the 1972 extension, the sand moved westward around the end of the baths towards the yacht harbour.

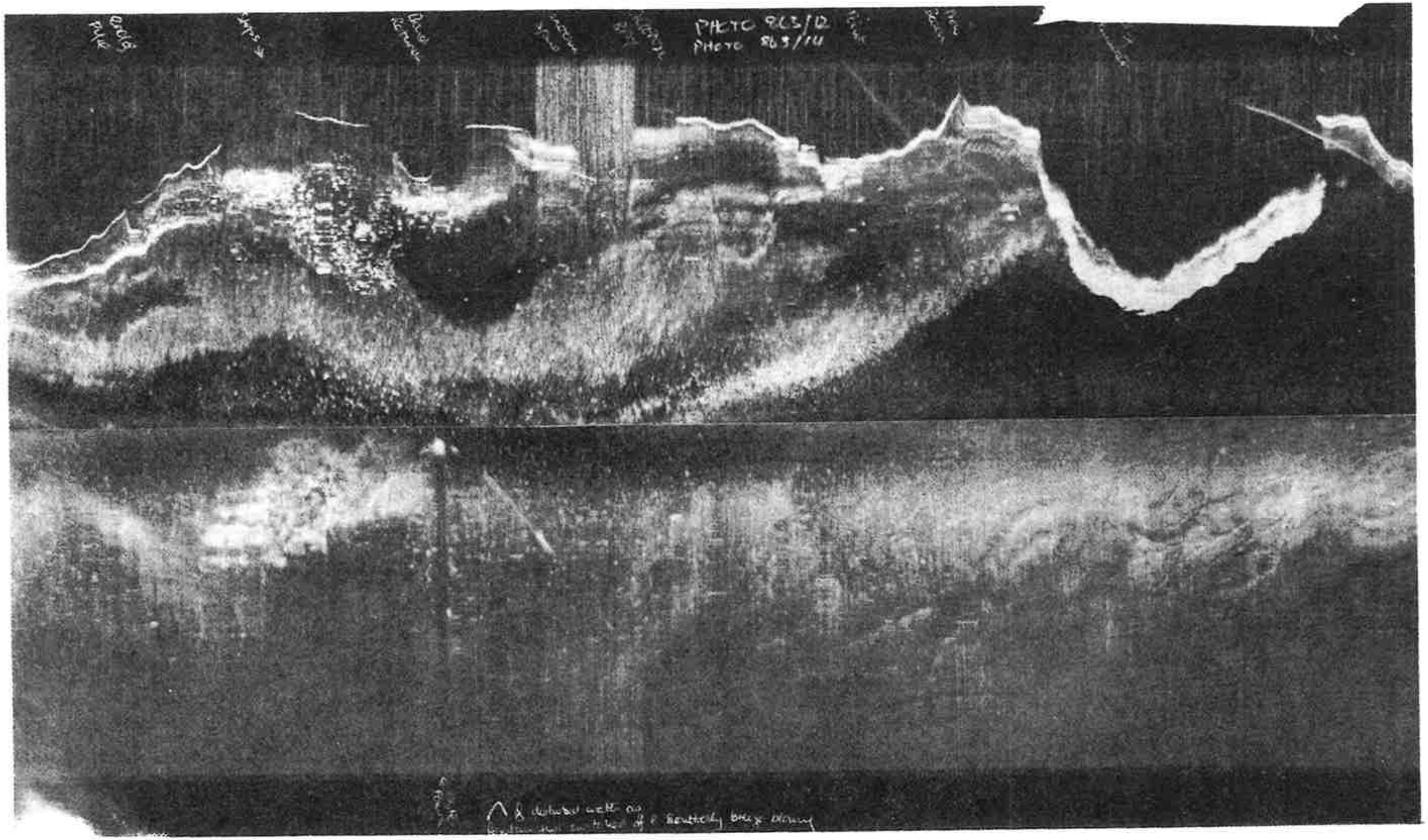
Samples also contain several distinct sediment modes (most common grain size) which appear to represent differences in sediment supply and response to water movements.

On the nearshore "sand prism" terrace there is commonly a pebble mode ranging from -2.3ϕ to -4.4ϕ (5 mm to 20 mm). In the east it is predominantly of original greywacke fragments supplemented by debris presumably dumped during construction of the sea-wall. In the west it is predominantly shells of the local bivalve *Paphies australis* (pipi) which now appears to be a major source of new sediment to the beach.

In many of the samples taken on, and just offshore from, the main beach and Grass Street Beach there is a minor mode centred on very coarse sand. It is commonly about -0.5ϕ (1.5 mm) in size but ranges from 0.9ϕ (0.6 mm = coarse sand) to -1.5ϕ (2.8 mm = granule) in size. On the evidence from old photographs, this mode may represent the sediment that was there before the Bristol Channel sand. The very coarse sand fraction contains, however, significant amounts of comminuted shell debris, part of which could have been generated since the Bristol Channel sand was dumped.

The principle sediment type in Oriental Bay's sand prism is represented by a medium sand mode. This is likely to be the Bristol Channel sand. The mode is commonly centred on 1.8ϕ (0.3 mm) but becomes finer on the outer, probably newer, part of the sand prism off the Freyberg Beach. On the outer part of the prism adjacent to the Freyberg reclamation it decreases to $2.3\ \phi$ (0.2 mm = fine sand).

The sand fraction in the muddy sand beyond the sand prism has a distinct fine to very fine sand mode that is limited in size between 2.7ϕ (0.15 mm) and 3.0ϕ (0.12 mm). The origin of this mode is uncertain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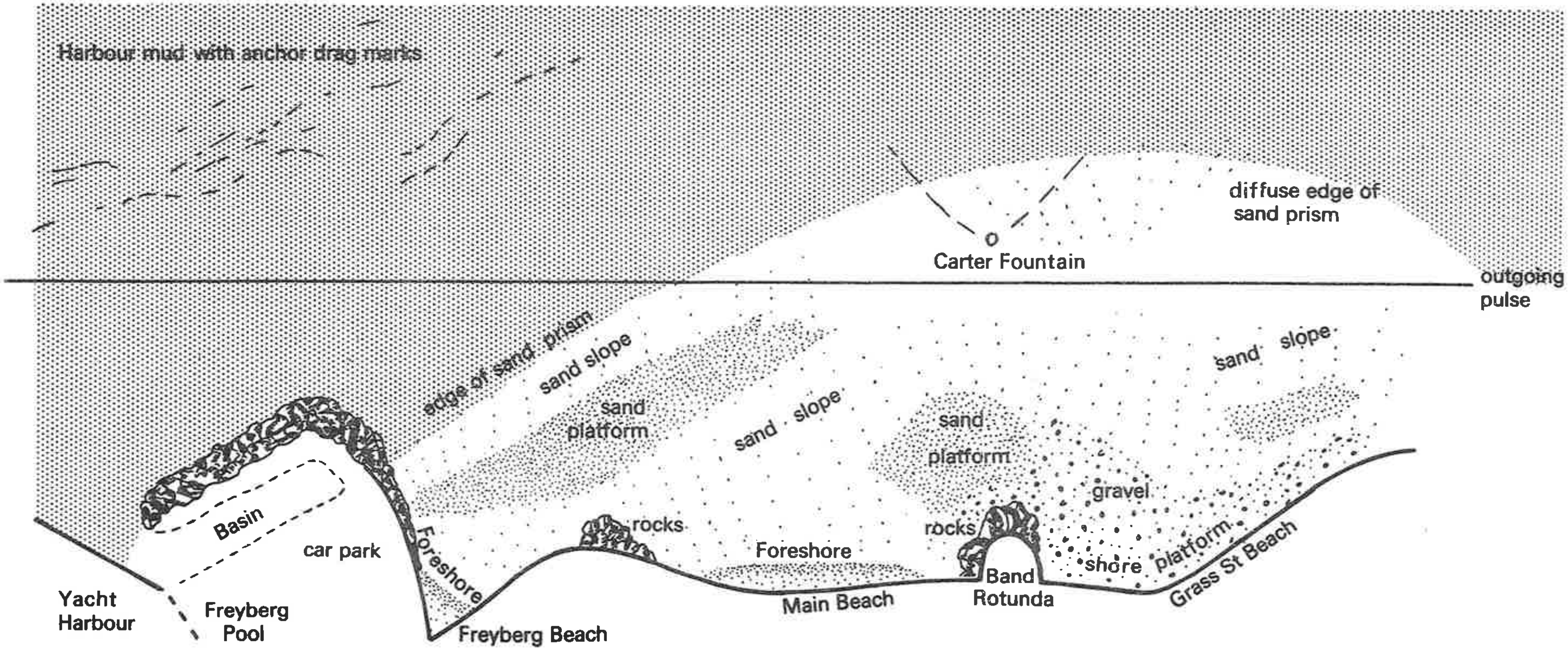

Fig. 8. Side-scan sonograph and interpretation. Distortion is produced by the meandering of the towed, side-scan "fish" at very slow speed. Note the reflective edge of the shore platform in the east; the non-reflective platform of shelly sand beyond the band rotunda; and the non-reflective top, strongly reflective slope, and sharp boundary with mud, of the sand prism beside the Freyberg reclamation which projects well beyond the sand prism.

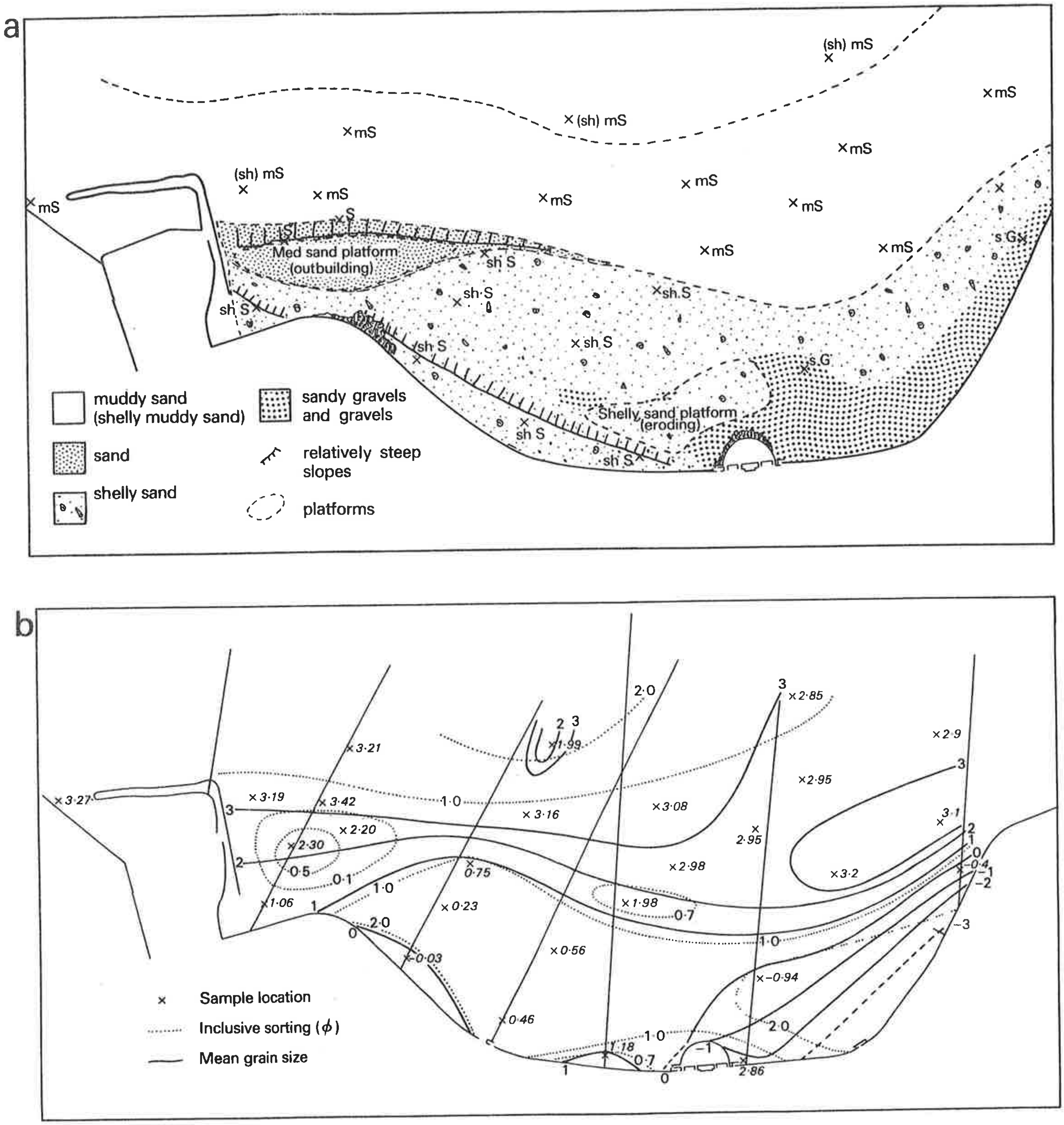

Fig. 9. (a) Distribution of the main sediment types, based on analyses of samples from the locations shown and the boundaries portrayed in the side-scan sonographs.

(b) Distribution of graphic mean grain size and sorting. Units are phi (ϕ) values, i.e., $-\log_2$ diameter.

but it possibly represents sediment winnowed from the Bristol Channel sand, having been moved seaward in turbulent suspension during northerly storms.

Carbonate analyses were made of 16 samples of sand and mud to ascertain their biogenic (shell) component. The mean concentration is 9.2% by weight with a deviation of 4.37. Highest concentrations (12-18%) are confined to the main beach and immediately offshore around the entire bay. Beyond a depth of 2 m carbonate values drop to 4-6%.

HYDRAULIC REGIME

Tidal Regime

Tides in Wellington Harbour are semi-diurnal with a range of 1.0 m at mean spring tides and 1.0 m at mean neap tides (Marine Division 1978). The Wellington Harbour Board has measured the linear flow 1 m above the floor of the Lambton Harbour at 41°17.185'S, 174°46.815'SE. The current meter record is discussed by Heath (1977) who quotes the flow under calm weather conditions, i.e., predominantly tidal, as less than 0.015 m s^{-1}.

Waves

In the absence of wave records for Oriental Bay, we have relied upon an empirical evaluation of the wave climate from wind records using forecasting techniques developed by the U.S. Army Coastal Engineering Research Center (1973). In restricted fetch conditions, wave generation is a direct product of the local wind field. The size of the waves and their potential to move sediment are controlled by the length of the exposed fetch and the strength and duration of the wind.

Hourly wind records from Pipitea Wharf, directly opposite Oriental Bay, are available for February 1974 to January 1976. Wind strengths and directions are summarised in Fig. 10. Wind directions are bimodal, reflecting the north-south orographic effect of Cook Strait. Easterlies and westerlies are rare. Oriental Bay is sheltered from southerly winds by Mount Victoria but, during strong southerlies, winds eddying over and around the hill can generate small waves moving along the main beach to the east. Oriental Bay is fully exposed, however, to northerlies from 305° round to 50°, the prevailing wind being from slightly west of north. Northerly winds blow for 41.6% of the time. Moderate northerlies, over 37 km h^{-1} (20 knots), have been recorded for 12.4% of the time, and strong northerlies, over 56 km h^{-1} (30 knots), for 0.7% of the time.

Significant wave height and period are forecast for the four onshore wind directions affecting the bay (Fig. 10). Percentage exceedence wave height and period curves are presented in Fig. 11. The highest and longest waves come from the direction where the fetch is longest, that is. from the direction of Korokoro to the east of north. Here, wave heights and periods exceed 0.8 m and 3.5 s less than 0.1% of the time, and waves 0.6 m and 3.0 s less than 1%.

Theoretical Effects of Waves

From the forecasted wave climate it is possible to predict the movement of sediment during wave action. On entering shallow water waves feel bottom when the orbital wave motion impinges on the seabed. Sediment starts to move on the seabed when the speed of the orbital flow exceeds the threshold speed required to move sediment of a specific size and density.

Near-bed orbital speeds have been calculated for the range of wave conditions and water depths in Oriental Bay using the following formulae from Komar (1976) :

$$U_m = \frac{\pi H}{T \sin h\ (2\pi h/L)}$$

where T is the wave period, H is the wave height, h is the water depth, and L the wave length.

In deep water

$$\left(\frac{h}{L} > 0.25\right), \qquad L_0 = \frac{g T^2}{2\pi}$$

and in intermediate water

$$\left(\frac{h}{L} < 0.25\right), \qquad L_1 = L_0 \left[\tan h \left(\frac{2\pi h}{L_0}\right)\right]^{0.5}$$

Near-bed orbital speeds have been plotted against depth as a group of exceedence curves for Oriental Bay at low water spring tides and at mean sea level (Fig. 11).

The bottom sediment samples have also been plotted on this figure in terms of water depth and critical erosion speed required to initiate sediment movement. Critical erosion speeds have been calculated using the technique developed by Komar and Miller (1975) where the threshold for grain diameters smaller than about 1.0ϕ (0.5 mm) is defined by :

$$V_{crit} = \frac{\rho\, U_m^2}{(\rho_s - \rho)\, gD} = 0.21 \left(\frac{d_0}{D}\right)^{0.5}$$

where U_m and d_0 are respectively the near-bottom threshold speed and orbital diameter, ρ is the density of water and ρ_s and D are respectively the density and diameter of the sediment grains. For grain diameters larger than 1.0ϕ (0.5 mm) the threshold is defined by :

$$V_{crit} = \frac{\rho\, U_m^2}{(\rho_s - \rho)\, gD} = 0.46\,\pi \left(\frac{d_0}{D}\right)^{0.25}$$

where the sediment density is assumed to be 2.65 and wave period 2.5 s. Critical erosion speeds have been plotted for the mean grain size and 5th and 95th percentiles.

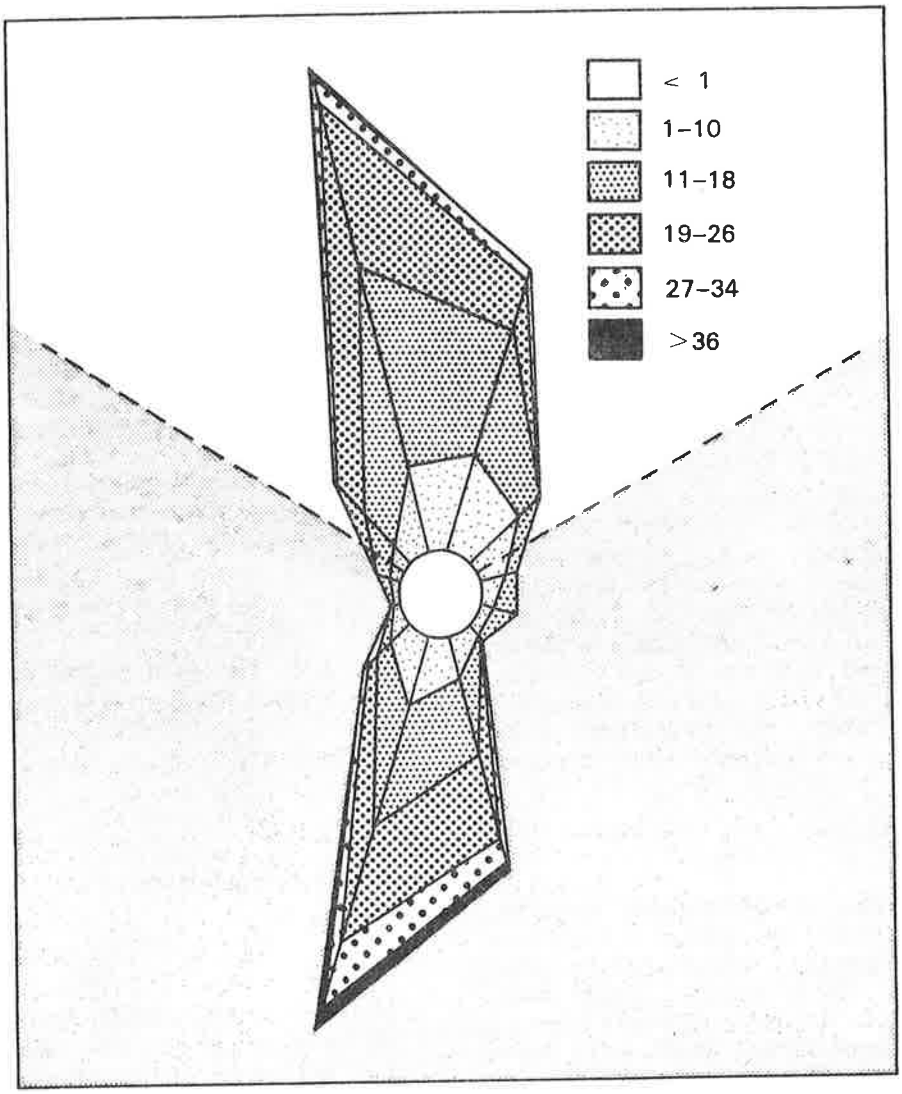

Fig. 10. Hourly wind strengths and directions at Pipitea Wharf between February 1974 and January 1976. Oriental Bay is largely protected by bordering hills from winds in the stippled segment. In southerly conditions, however, winds may sweep around the hills surrounding Lambton Harbour and enter Oriental Bay from the northwest. (Data from the N.Z. Meteorological Service.)

A comparison of the near-bed orbital speed and the critical erosion velocities enables some prediction of the likelihood and frequency of sediment movement. During periods of calm weather and frequent low energy waves, i.e., conditions prevailing for 76% of the time, critical erosion speeds exceed near-bed orbital speeds and bottom sediments remain undisturbed. Only in the breaking-wave zone, in less than 0.4 m of water, are sediments moved off the bed.

During less frequent, higher energy events (i.e., those occurring less than 16% of the time) the critical erosion speed for the mean grain size of the nearshore sediments is exceeded out to 4.5 m depth. Over all of the nearshore terrace therefore, there is a potential for the infrequent movement of most of the sediment (Fig.12, bracket A).

On the seaward facing slope, at depths of 4.5 m to 7.5 m, orbital speeds exceed only the critical erosion speed of the fine fraction of the sediments (Fig. 12, bracket B). In these depths extremely high energy; low frequency events, occurring less than 1% of the time, are required to initiate sediment movement. The potential for sediment transport is very small, the bulk of the sediment remaining immobile.

On the lower slope and harbour floor, at depths of more than 7.5 m, critical erosion speeds are not exceeded (Fig. 12, bracket C). All sizes of sediment lie beneath the maximum depth of disturbance by waves. The potential for sediment transport by waves is nil.

Interpretations from Fig. 12 must be treated with caution; the wave climate has been forecast from meteorological records, and the near-bed orbital speeds and critical erosion speeds are empirically derived. No direct field evidence has been collected to verify these results. These interpretations are, however, in agreement with the sediment distribution patterns. The terrace is mantled by moderate to well sorted sand which suggests frequent movement. The terrace face has a muddy sand mantle indicative of less frequent movement, and the harbour floor is covered by mud which is typical of "quiet" water environments.

The effect of linear currents on sediment transport is minimal although it may gain some significance during meteorological disturbances. During calm weather the tide-dominated flow is far too slow (< 0.015 m s^{-1}) to move fine sand which responds to current speeds in the order of 0.35 m s^{-1}. During gales and storms, however, wind shear instigates flows which, from the Lambton Harbour record, achieve 0.1 m s^{-1} (Heath 1977). While still too low to instigate sediment movement, the wind-induced flow will influence transport of sediment suspended by the waves which invariably accompany these winds. The pattern of these wind-induced flows is unknown.

Frequency of Storms

Changes in beach morphology may occasionally be correlated with frequency of storms. The changes in frequency of gales between 1930 and 1970, however, reveal only minor long-term changes with the period 1940-1950 having fewer gales than preceding or ensuing decades (Fig. 13).

CONCLUSIONS ON SEDIMENT ORIGINS AND DISPERSAL

Sand Sources

The beach sand of Oriental Bay is now virtually in a closed system. There is little natural supply and almost no natural loss.

The supply of sand has always been limited. Before European settlement some mantling of the shore platform was probably achieved by feeble coastal erosion during northerly storms and by subaerial erosion of the hills. There is also a small (average of 9.2%) biogenic component from molluscs living in the sediment and on the adjacent rocks.

In the 1855 earthquake the berm would have been uplifted by perhaps 1.5 m to form dry land (Stevens 1974) which was soon armoured with spoil from east of Oriental Bay to form a coastal road and railway line. For a while the old beach and armouring constituted a source of coarse sediment to a new beach which was predominantly gravel. About 1914 this supply of sediment stopped with the construction of a sea-wall preventing further coastal erosion. About the same time ducting of storm water presumably reduced the input from subaerial erosion. Oriental Bay had a small beach of coarse sand during the years following the First World War but since there was no obvious source of this sand, it had been either artificially introduced, or weathered and sorted from available material within the zone affected by waves.

The replenishment programme of 1944 created sandy beaches on either side of the band rotunda. The sand at Grass Street Beach was short-lived. Within a year it had been removed leaving the original gravel-covered shore platform. Because the eastern shore platform rises abruptly from the harbour floor any sand that had moved directly offshore could not have returned and would have been irretrievably lost to the beach system. It seems, however, that most of the sand moved westward, the central core of the sand body remaining for many years on the shore platform north and northwest of the rotunda. This reservoir proved to be a blessing. Since World War II its volume may have fluctuated in response to different weather conditions, but overall it has slowly released sand to the main beach, helping to stabilise it. The main beach has remained stable even while losing sand for 25 years to the west around the Te Aro Baths/Freyberg Pool reclamation.

Since the 1972 extension to the Freyberg reclamation the sand of Oriental Bay has become contained within an almost completely closed system with

(i) very little addition of sediment, except for quantities of shell debris and, possibly, sand from the east, and

(ii) very little loss except for that removed during storms and strong winds and by subsequent cleaning operations by the Wellington City Council.

Sediment moving westward has formed the Freyberg Beach and has also built the sand prism seaward of this beach upwards and outwards into relatively deep water.

Littoral Drift

In general, beaches develop plan shapes with their centres normal to the predominant wave direction (e.g., Schalk 1938). At Grass Street Beach the dominant waves strike the shore obliquely, setting up littoral drift towards the band rotunda. Much of the foreshore, therefore, is denuded of sand leaving only a small beach, normal to the predominant waves, trapped in the re-entrant against the band rotunda, and an immobile, gravel-lag pavement on the shore platform. Any sand that formed on, reached, or was dumped on Grass Street Beach moved rapidly westwards towards the main beach. It seems possible that much of the sand dumped there in 1944 accumulated off the band rotunda. During infrequent northerly storms, waves may drive sand from this offshore reservoir to the main beach.

Destruction of the gravel berm in front of the Grass Street steps occurred sometime during the 1940s. This was a period of fewer than normal gales so that its disappearance cannot be correlated with increased wave activity. It may be that during the 1944-45 re-

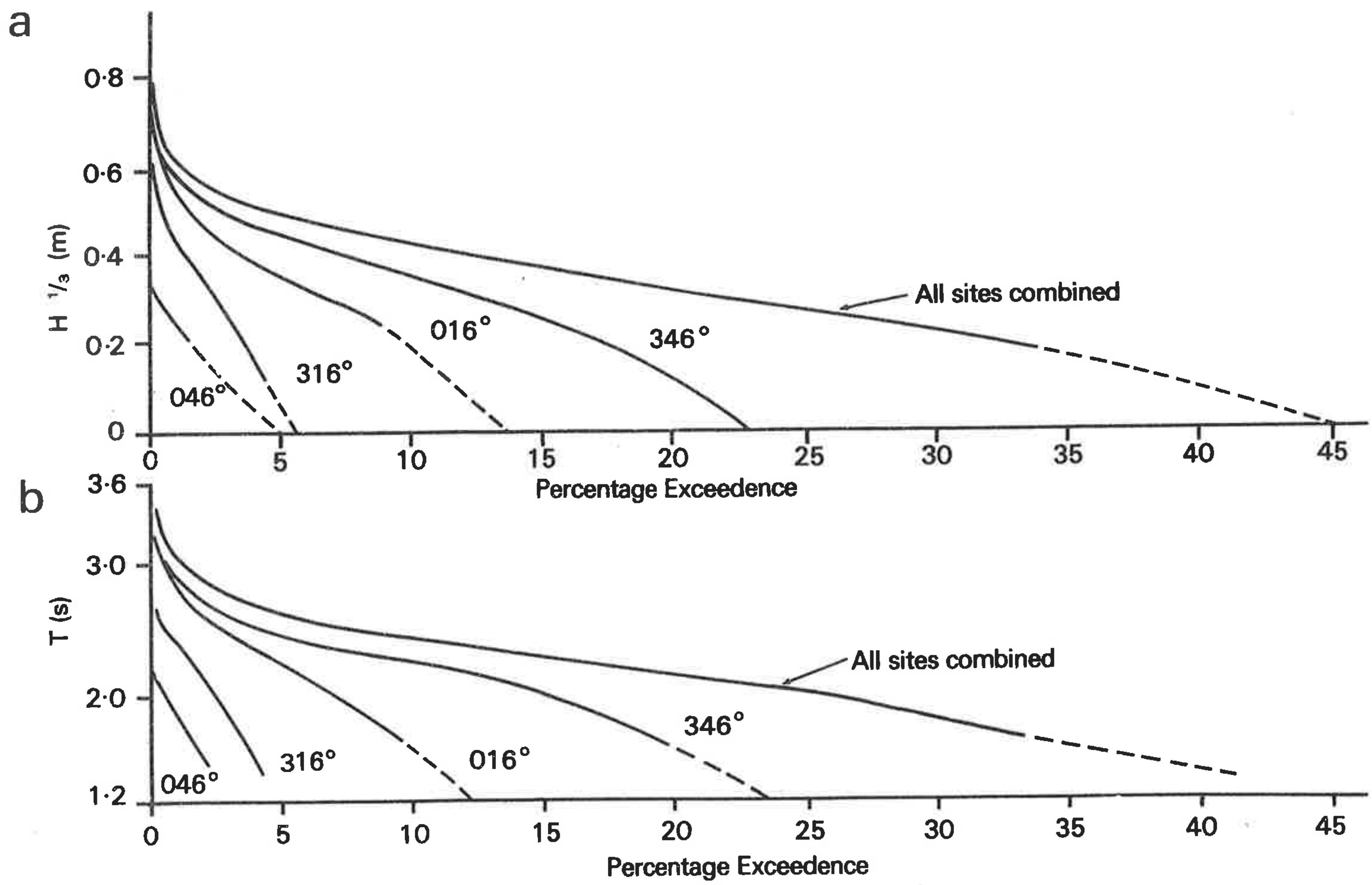

Fig. 11. Percentage exceedence-forecasted significant wave heights (a) and wave periods (b) for the onshore winds in Oriental Bay.

plenishment the berm was artificially levelled as the dumped sand was spread over the beach.

The rapid growth of the Freyberg Beach indicates that westward littoral drift continues as far as the Freyberg reclamation. Since its extension in 1972 this reclamation has projected beyond the nearshore sand prism and the depth to which waves can transport sandy sediment. It has, therefore, proved to be a barrier to further westward littoral drift.

The growth of Freyberg Beach and the subtle re-alignment of the main beach are the result of slow littoral drift from an easterly source. There appears to be a weak counter drift produced by NNW winds and by eddies of strong SSW winds. There is a possibility that the counter drift has been progressively reduced over the years as the construction of large buildings and the growth of wharf reclamations around Lambton Harbour have reduced the fetch of waves generated by winds with a westerly component.

A crude estimate of the rate of littoral drift can be made from the growth rate of Freyberg Beach since 1972. Out to the beach base at 0.5 m below New City Datum it is estimated that 700 m^3 of sand, an average of 90 $m^3 y^{-1}$, has been added to the beach. The amount that has been added to the sub-tidal part of the sand prism is unknown but it is probably at least as much again.

Future Beach Nourishment

If, at any time in the future, sand of appropriate grain-size becomes available for beach nourishment then Oriental Bay's recreational potential could benefit from the addition of this material to the present beach system.

There is a well established relationship between the grade of sediment and the beach-nearshore slope, with coarser sediment being stable on steeper slopes (U.S. Army Coastal Engineering Research Center 1973). The type of sand that is appropriate for nourishing a particular site will depend to a large extent on the nearshore submarine slope. Coarse sand (> 0.5 mm diameter) is most appropriate where the nearshore

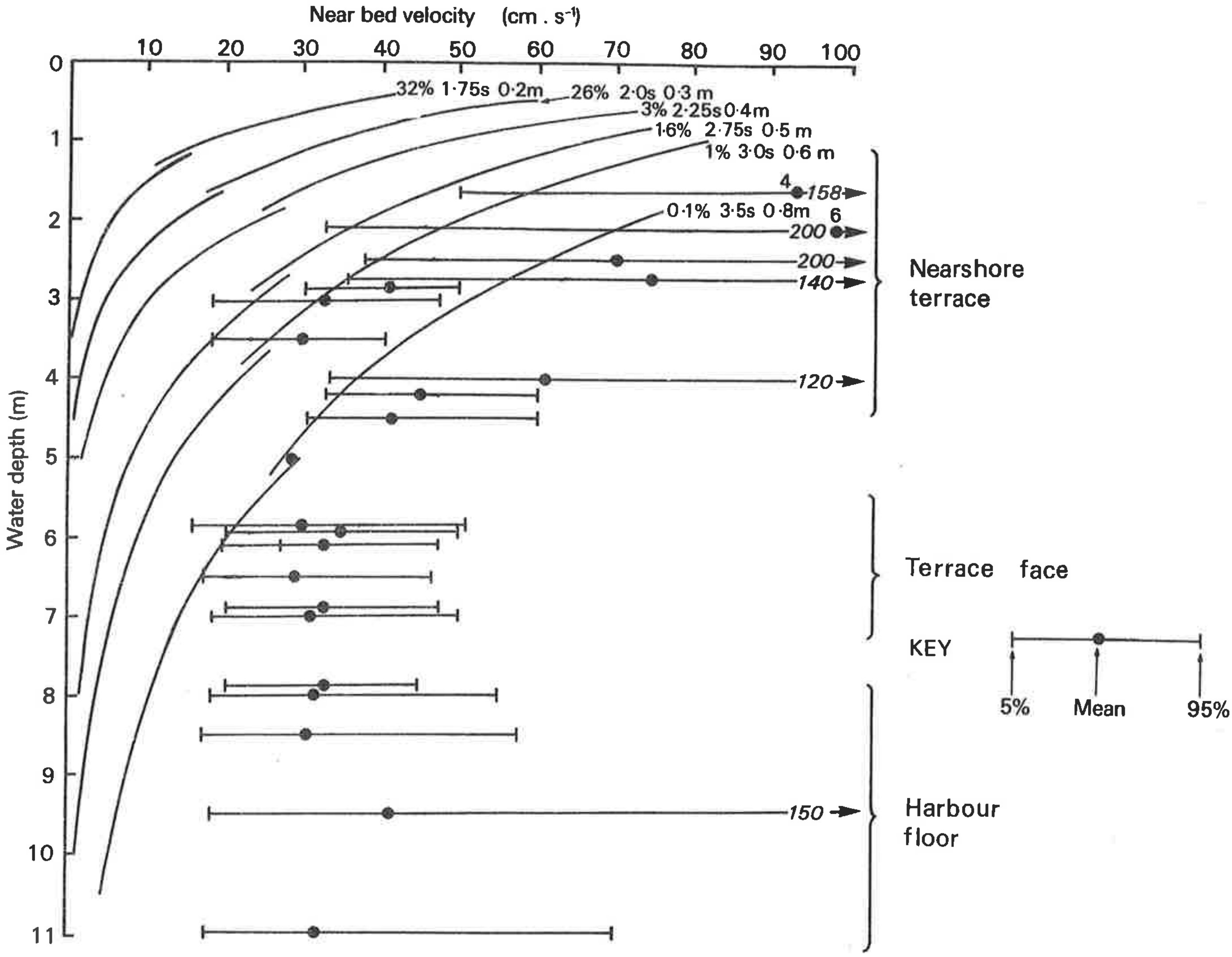

Fig. 12. Near-bed orbital velocities against depth-forecasted waves of different frequencies and sizes at mean sea level. Bars denote the velocity range over which 90% of the sediment sample from that depth is stirred. Thus 0.5 m high waves (occurring 1.6% of the time) will stir sediments down to 4 m. 0.8 m high waves (0.1% of the time) will stir to ca. 7 m, beyond which sediments are not moved at all.

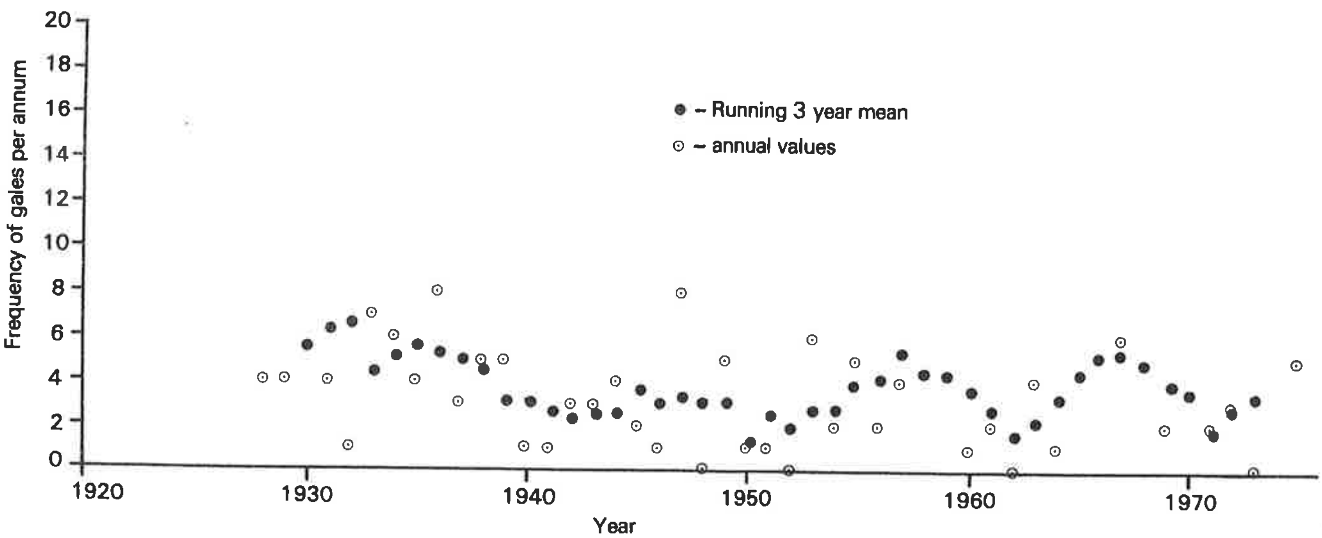

Fig. 13. Frequency of gales per annum (running three-year average) between 1928 and 1975. (Data from the N.Z. Meteorological Service.)

profile is steep (e.g., off many of the beaches around the northern and western sides of Miramar Peninsula) since the sand itself maintains a relatively steep profile and it is not all swept offshore as fast as fine sand would be. Fine sand (< 0.25 mm diameter) is most appropriate where the offshore profile is gentle (e.g., Scorching Bay, Hataitai Beach) since it will build parallel with the existing gentle beach slope.

A supply containing a high proportion of medium sand (0.25 - 0.50 mm diameter) would be most appropriate for Oriental Bay since it would tend to prograde the stable beach profile produced by the existing prism of medium to fine sand. Coarse sand fill would tend to remain on the foreshore and produce a steeper beach. It would also probably be considered less desirable (it doesn't make such good sand castles, S. Carter pers. comm.). Fine and very fine sand would tend to migrate offshore to build a nearshore slope that would be flatter than before. In this case, a smaller proportion of the fill would be available to build out the foreshore and increase the recreational area of the beach.

The nearest source to Oriental Bay of large quantities of sand is the harbour entrance although the thicknesses of the layers are unknown. The sand in the main shipping channel is generally finer than at Oriental Bay with a principle mode in the fine sand grade (about 0.12 - 0.15 mm diameter) rather than in the medium sand grade (about 0.25 - 0.30 mm diameter) (van der Linden 1967; Carter 1977). Thus, considerable losses of material would be expected in the early stages of emplacement as the offshore platform developed a new, flatter, equilibrium profile. At present there is no proven method of computing the quantities of particular grades of sand required to prograde a beach in a given wave and current environment by a required amount. Where representative core samples of proposed borrow material are available, however, some rough estimates can be made of required volumes (U.S. Army Coastal Engineering Research Center 1973). The predictions might be improved by tracer studies of marked borrow material.

It is clear that the medium fraction of any sand deposited in Oriental Bay will tend to migrate westwards and to build out the Freyberg Beach until it has a continuous plan profile with the main beach. At that stage the Freyberg Beach would have prograded about 20 m seaward of its present position and there would be continuous access between Freyberg Beach and the main beach at low tide. Further replenishment would prograde the main beach and Freyberg Beach together until the toe of the sand prism extended beyond the end of the rubble mole that protrudes seawards from the Freyberg reclamation. This might occur after a further 10 - 20 m of progradation but the position of the sand prism along this mole should be periodically monitored in order to forestall any leakage.

Grass Street Beach is, at present, a boulder-strewn shore platform of little recreational or aesthetic value. Mobile sand deposited on it moves westward under the influence of littoral drift to the main beach and Freyberg Beach. It could be sanded in its present form to provide a recreational beach with a limited life and to provide an updrift source of sediment to feed gradually the main and Freyberg Beaches. This may be desirable if the borrow sand contains an appreciable proportion of gravel since wave action would naturally sort the material, supplying sand to the other beaches and leaving the gravel behind at the Grass Street site.

If more permanent sanding of this site is considered desirable then a groyne, built nor'-nor'-eastwards from the band rotunda, should be investigated as a means of reducing longshore drift. The groyne should not extend beyond the 2 m depth contour otherwise there is the risk of sand escaping around the groyne to the harbour floor instead of the main beach. A beach retained by such a groyne would be broadly parallel to the existing beach and might extend as far eastward as the Grass Street steps. Sanding of the whole platform would require a more complex retention scheme.

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