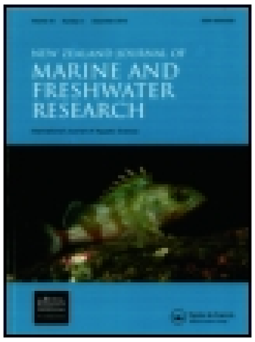

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FACTORS CONTROLLING THE ENTRANCE CROSS-SECTIONAL AREAS OF FOUR INLETS (NOTE)

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Abstract

The frequent occurrence of swell in the entrance to Wellington, Lyttelton, and Akaroa Harbours, coupled with the small littoral drift of sediment on adjacent rocky coastlines, appears to promote development of larger entrances than those associated with tidal control in unconsolidated sediment. In contrast to these three harbours, tidally controlled entrances have either bars or banks that protect them from severe swell and act as bypasses to the littoral drift of sediment.

The entrance to Paterson Inlet lies on a coast with little sediment transport and further protection from sediment influx is provided by islands located at its entrance.

Introduction

The size of entrance cross-sectional areas of coastal inlets is often thought of as being determined by tidal control in entrances rich in unconsolidated sediment or as structurally controlled in entrances with rocky outcrops. For example, in an examination of 20 New Zealand coastal inlets Heath (1975), following Furkert (1947), found that 16 of the inlets fitted the regression equation $\log_{10}$ (spring tidal compartment) $= m \log_{10}$ (entrance cross-sectional area mid tide) $+C$, with a correlation coefficient of 0.96. The error of estimate S_A for the cross-sectional area (A) at the entrance was 0.14, and thus the percentage errors in A which would be the upper limits of the difference from the regression line in 95% of cases was +19%, −16%. The conclusion reached was that the entrances were stable, the cross-sectional areas being determined by the ability of the tidal flow to transport sediment; the maximum tidal speed implied by the regression equation is 1.14 $m.s^{-1}$.

The four inlets not conforming to the tidal control of their entrance cross-sectional areas were Wellington, Lyttelton, and Akaroa Harbours and Paterson Inlet. Each of these have rocky outcrops on their sides and therefore might be thought to be structurally controlled. However, points for all four inlets lie on the deposition side of the cross-sectional tidal compartment curve; the cross-sectional areas (Table 1) for these inlets are 2–10 times larger than those for tidal control as implied by the regression equation for the other 16 inlets. The size of these entrances does not therefore appear to be solely structurally controlled, for the

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TABLE 1—Observed minimum entrance cross-sectional areas and the cross-sectional areas implied by the regression equation [$\log_{10}$ (spring tidal compartment) = 0.98 $\log_{10}$ (entrance cross-sectional area mid tide) + 4.21] for Wellington, Lyttelton, and Akaroa Harbours, and Paterson Inlet.

INLET	OBSERVED AREA ($\times$ 10^4 m^2)	IMPLIED AREA ($\times$ 10^4 m^2)
Wellington Harbour	1.4	0.7
Lyttelton Harbour	3.0	0.5
Akaroa Harbour	4.7	0.6
Paterson Inlet	5.9	1.2

tidal speeds at these entrances are less than at the entrance to those under tidal control, and sediment is found in their entrance floors. The control must therefore depend on interaction between factors such as the hydraulic regime and rate of sediment supply.

A more thorough examination of the hydraulic agents controlling the entrance cross-sectional area of these four inlets appears warranted. The size of the components of water motion in Wellington Harbour have therefore been examined to determine the main control of the entrance cross-sectional area. Based on the example of Wellington, the hydraulic situation at the three other inlets are then also discussed briefly. The general forms of the sediment distribution near the entrance to the inlets with entrances under tidal control and the inlets not conforming to tidal control are then discussed, and reasons for the difference in control are offered.

WELLINGTON HARBOUR

The cross-sectional area at the entrance to Wellington Harbour between Point Dorset and Hinds Point (Fig. 1) of 14.5×10^3 m^2 (Hydrographic Branch 1975) is 2.2 times larger than the 6.5×10^3 m^2 given by the tidal control regression equation. The questions that arise then are: is there deposition taking place in the entrance, is there some mechanism that keeps the entrance at its present size, or is the material in the entrance such that the entrance is stable at its present size?

TIDAL SPEEDS

The maximum tidal speed for a uniform sinusoidal flow through the 14.5×10^3 m^2 needed to fit the Wellington Harbour tidal compartment of 88×10^6 m^3 is 0.45 $m \cdot s^{-1}$. Current drogue measurements in the entrance (Figs 1, 2) have peak values near 0.5 $m \cdot s^{-1}$, and this is supported by the current measurements shown on the bathymetric chart of Wellington Harbour (Hydrographic Branch 1975). The agreement between these measurements and the speed implied by continuity indicate that in the narrowest part of the entrance channel the flow is essentially uniform across the cross-section and is substantially slower than the

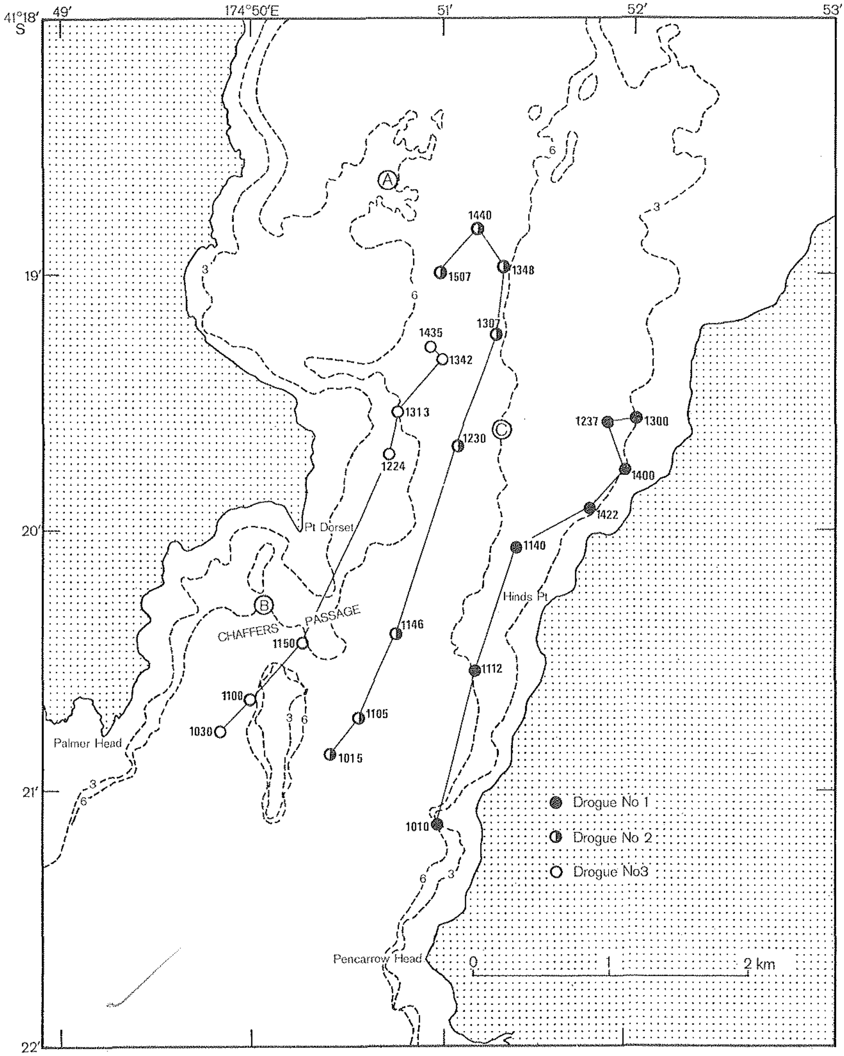

FIG. 1—Tracks and timed positions of three parachute drogues, all at 5 m, in the entrance to Wellington Harbour, 3 October 1975. The encircled letters A–C indicate the areas of deposition mentioned in the text: isobaths in fathoms (1 fathom = 1.83 m).

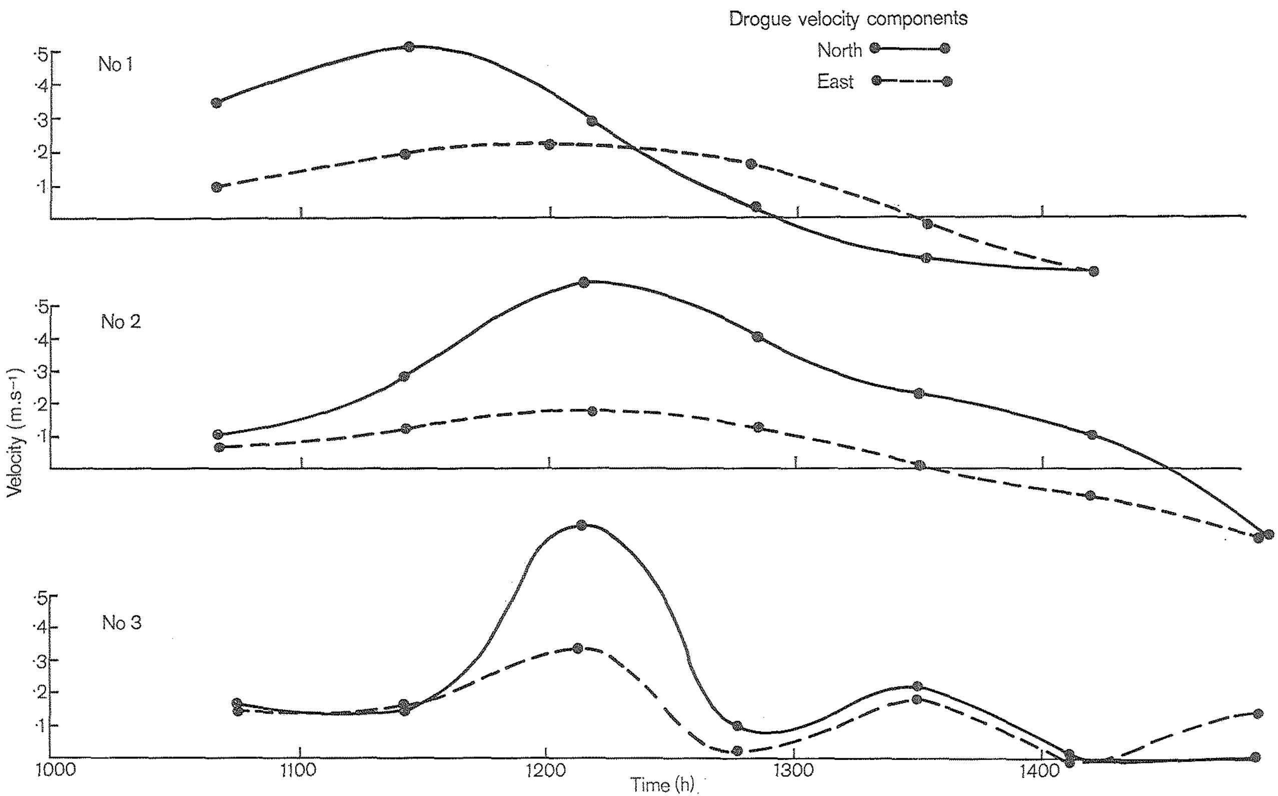

FIG. 2—Components of velocity positive to the north and east for three parachute drogues at 5 m in the entrance to Wellington Harbour, 3 October 1975 (predicted high water 1429 h; tracks shown in Fig. 1).

$1.14\ m{\cdot}s^{-1}$ implied by the regression equation for the 16 inlets with tidally controlled cross-sectional areas. As the entrance widens out into the harbour these measurements (Fig. 1) and those of Brodie (1958) suggest there is a return flow along the Eastbourne coast immediately before high tide.

Van der Linden (1966) found gravel in the entrance to Wellington Harbour in 1964–65 but this was covered by medium fine sand in 1974–75 (Carter, in press). Divers inspecting the bottom have frequently found waves of 1 m amplitude in the gravelly sediment. Observations made with remote sensing instruments, which measure the current velocity, wave height, and take photographs of the sea floor (Carter *et al.* 1976), indicate there is movement of the sediment in Chaffers Passage (Fig. 1). Clearly, then, although the tidal speed is slower than that implied as necessary for a tidally controlled cross-sectional area, the sediment is not stationary in the entrance.

DEPOSITION

Carter (in press) indicates that there is a net sediment transport northwards into the harbour. Comparison of bathymetric maps of three surveys made in 1849, 1903, and 1950 (Carter, in press) revealed that, after taking account of the 1855 earthquake, there has been a larger net deposition immediately inside and outside the entrance to Wellington Harbour (of the order of 3.6 m at positions A and B, Fig. 1) than in the narrowest part of the entrance itself (of the order of 0.2 m at position C, Fig. 1). This situation, with a general northwards sediment transport and minimum deposition at the narrowest part of the entrance, indicates that most of the sediment is swept either into or out of the entrance. The sediment transport through the entrance is a potential sediment supply for net deposition if the hydraulic regime is suitable.

The entrance cross-section does not then appear to be controlled solely by the tidal flow. Nor does it appear to be progressing rapidly towards a state of tidal control, and we should therefore look for some other transport mechanism.

WATER MOTIONS INDUCED BY METEOROLOGICAL DISTURBANCES

An extreme example of a meteorological disturbance affecting Wellington Harbour was that of 10 April 1968, the storm in which the inter-island ferry t.e.v. *Wahine* foundered in the entrance to Wellington Harbour. The observed and predicted tide on 10 April, with barometric pressure, wind speed, and difference between the observed and predicted tide for most of 10 April are shown in Fig. 3.

The increase in non-tidal water level is clearly influenced more by the wind or through a resonant coupling between the ocean and atmosphere (see, e.g., Proudman 1953, p. 295) than directly by isostatic adjustment to barometric pressure. For example, the rise in non-tidal water level from 0315 h to 1000 h on 10 April was 1.75 ft ($=$ 53.34 cm) whereas the decrease in atmospheric pressure was only 10 mb ($\approx$ 9.9 cm). The mean

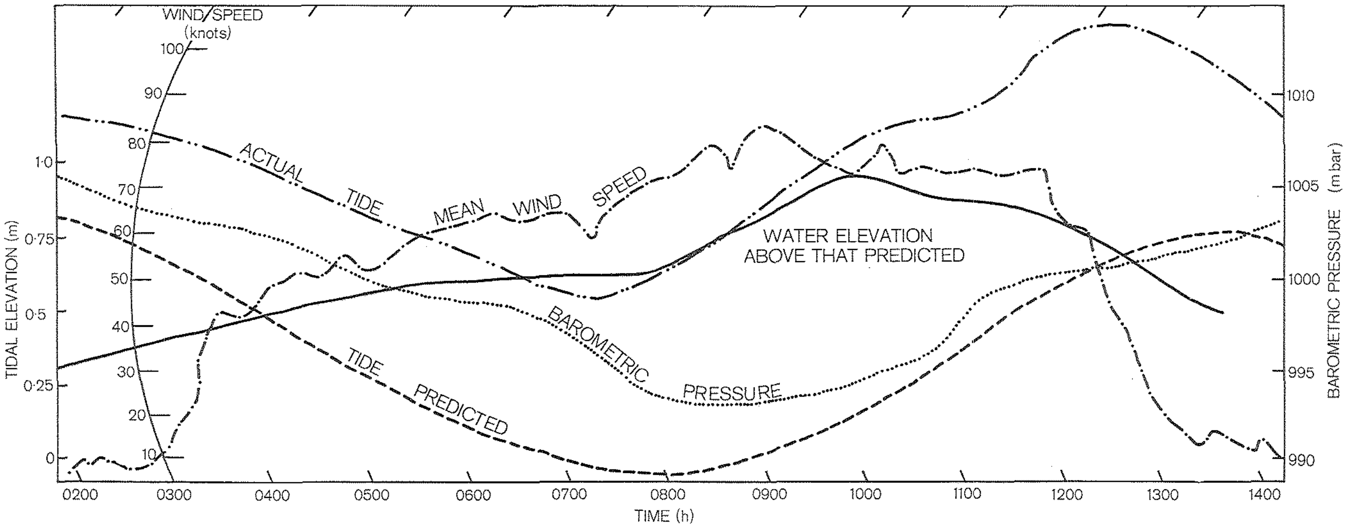

FIG. 3—Observed and predicted tide, barometric pressure, mean wind speed and difference between the observed and predicted tide in Wellington Harbour from 0200 h to 1400 h, 10 April 1968. The observations in this graphic form were kindly made available by the Wellington Harbour Board; tidal elevations and atmospheric pressures were recorded in Lambton Harbour by the Wellington Harbour Board; predicted tidal readings are from the New Zealand Nautical Almanac; wind speeds were compiled from an anometer recording at Wellington Airport.

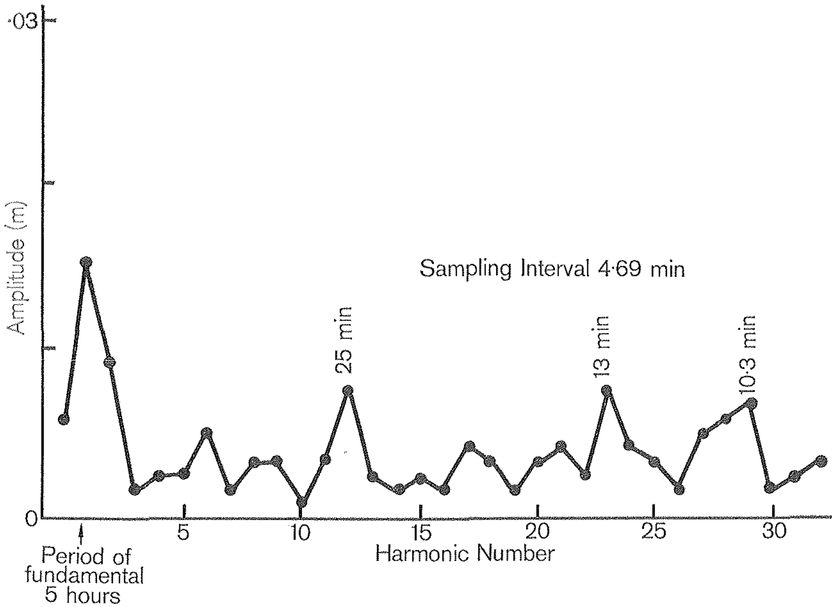

FIG. 4—Line spectrum of residual elevations in Lambton Harbour. The residuals were found by subtracting a smooth tidal curve from the observed curve. The first data point was 1300 h (NZST) on 10 April.

non-tidal flow through the entrance accompanying the 53-cm change in 6.75 h assuming the change took place throughout the harbour, would be 0.13 $m \cdot s^{-1}$. The reinforcement of the tidal flow even in this extreme case would not be substantial.

The storm of 10 April induced significant seiching within Wellington Harbour. A line spectrum of the residual elevation (i.e., after subtracting the tide) computed using the "Extra Fast Fourier Transform" (Bice 1970) with 64 ($= M$) data points at a sampling interval of 4.69 min, reveals that most of the seiche energy was at 25.1 min and 10.3 min (Fig. 4). According to the study of oscillations in Wellington Harbour by Heath (1974), these oscillations would correspond to the first 2 modes of a seiche between Petone Foreshore and Lambton Harbour; the position of the tide gauge in Lambton Harbour favours response from this seiche. No appreciable seiche driven from the entrance was generated, and therefore the flow at the entrance associated with the seiching would have been small.

FLOW FROM TSUNAMIS

There was a substantial response in Wellington Harbour to the tsunami produced by the 1960 Chilean earthquake, with oscillations of amplitude about 0.8 m (Heath 1974, fig. 4), being developed within the harbour. Seiche periods around 160, 28, and 27 min were excited, these corresponding to a quarter-wavelength response driven from the entrance, and the first harmonics along and across the harbour respectively. The maximum speed of the water motion at the harbour entrance accompanying the quarter-wavelength response to the tsunami has been calculated as 2.3 $m.s^{-1}$ (Heath 1974), indicating how effective they are in producing large flows which presumably have a substantial scouring effect at the entrance. However, with the quarter-wavelength resonance, there is a substantial radiation loss out of the harbour and the response at this period decays quickly: the response was only felt for about 1.5 d. Also tsunamis are not frequently felt in New Zealand (e.g., Laing 1954) and therefore probably have little control on the size of the entrance to Wellington Harbour.

WIND WAVES, SWELL

The entrance to Wellington Harbour opens directly to the south and is exposed to an effectively unlimited fetch. Sea conditions in the entrance are seldom calm: swell, generated by storms south of the North Island, is present at most times. Although the harbour as a whole can have substantial wind waves generated locally, the swell impinging from the south is usually severely damped on the reduced depths at the entrance (Fig. 1). Maximum speeds at the surface and bottom in 12 m of water (a typical maximum depth in the entrance) versus period for swell are shown in Fig. 5. These were calculated from simple theory using an amplitude of 2 m: they vary linearly with amplitude. Speeds accompanying the swell are substantially larger than those in any of the other common motions considered, and presumably the frequent presence of this swell reinforced by the tidal flow keeps the harbour entrance at its present cross-sectional area.

LYTTELTON AND AKAROA HARBOURS

Both Lyttelton and Akaroa Harbours indent Banks Peninsula on the east coast of the South Island. They are similar to Wellington Harbour in that the tidal flow of their entrances is less than that associated with those entrances under tidal control. Although the largest recorded responses to tsunamis around New Zealand have been in Lyttelton Harbour (Heath 1976), their occurrence is infrequent and they probably have little control on the entrance cross-sectional areas. Refraction diagrams (Dingwall 1974) show that swell both from the south-east and north-east is directed into both Lyttelton and Akaroa Harbours. Large swell is frequently encountered (Hydrographic Dept 1971) and as with Wellington Harbour, it is presumably this swell that keeps the entrance larger than that associated with purely tidal control.

PATERSON INLET

The transport of sediment in Foveaux Strait is small (Cullen 1967, 1976), and the entrance to Paterson Inlet is protected from swell, and hence a substantial energy source for moving sediment, by many islands.

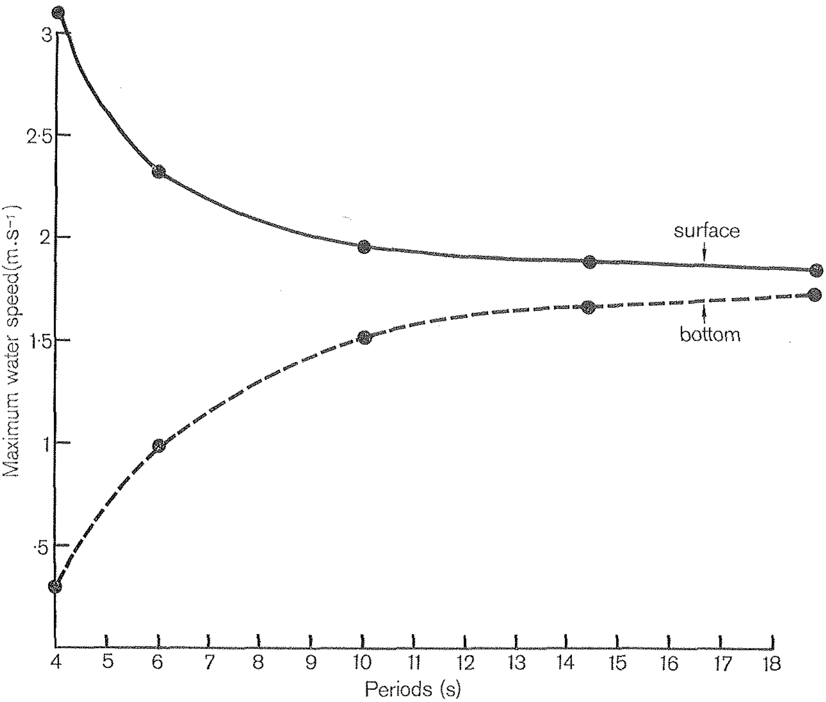

FIG. 5—Maximum speeds at the surface and bottom in water of 12 m depth for swell of amplitude 2 m and different periods.

In consequence, any sediment transport into the entrance of Paterson Inlet from outside will probably be small, and therefore there is little sediment supply for a tidally controlled entrance to develop.

DISCUSSION

The quickest water motions in the entrances to Wellington, Lyttelton, and Akaroa Harbours appear to be those accompanying swell. Under periods of heavy swell the accompanying water motion, in association with the tidal flow, will transport the sediment in the entrance either into or out of these harbours. We can ask then why does swell not have a substantial effect on the 16 inlets (Heath 1975) conforming to the tidally controlled entrance cross-sectional area? Studies of existing data on tidal inlets (e.g., Bruun & Geritsen 1960, table 7) indicate that the size of the shear stress on the bottom for these 16 inlets is consistent with inlets under heavier littoral drift and sediment load (Heath 1975).

Many of these 16 inlets have a bar or banks seaward of the entrance on which the swell is substantially dissipated, or lie in relatively sheltered locations. Their entrances are therefore protected from severe swell, allowing tidal control to develop. On coasts with a substantial sediment transport close inshore, sediment entering the entrance of an inlet in its formative years is either swept into or out of the entrance channel to form shoals. The shoal offshore subsequently forms a bar which acts as a bypass for the littoral drift of sediment, besides acting as dissipators of incident wave energy. In contrast, if the sediment transport along the coast close inshore is small, no bar appears to be formed.

The coastline of Banks Peninsula is very rugged, with beaches formed only at the heads of the inlets. The seafloor there deepens rapidly adjacent to the coast and is presumably maintained in this steep condition by the substantial swell (Hydrographic Department 1971) which reaches right to the coast without losing much of its energy; on a gradually sloping beach the erosive power of the swell is substantially diminished before it reaches the shore. Dingwall (1974) remarks that wave action even within the bays around Banks Peninsula is more like that on exposed beaches than on beaches at the head of most bays elsewhere. The northwards transport of sediment (Dingwall 1974) past Banks Peninsula takes place in the deep water of this exposed coast.

In fact, only fine mud is found in the entrance to Lyttelton Harbour (R. H. Herzer, NZOI, pers. comm.), which lies in the lee of the general northwards offshore transport of sediment and away from the southwards transport along the beaches north of Banks Peninsula (Dingwall 1974). The presence of mud on the seafloor is usually associated with a quiet hydraulic regime. The presence of mud offshore adjacent to the entrance to Lyttelton Harbour could therefore seem in conflict with the frequent occurrence of grounding waves. However, the mud here is an indication of a slow mean flow (possibly an anticlockwise eddy), with deposition presumably taking place under calm conditions. The mud then binds together so that it is not eroded under stormy conditions. Also, as mentioned above, the mud deposit lies between regions of sand transport both inshore and offshore, and presumably therefore there is little deposition of sand over the mud under stormy conditions.

Similarly, the entrance to Wellington Harbour lies amongst rugged rock outcrops (see e.g., Stevens 1974), which hinder the transport of sediment and force any substantial transport to take place in deep water.

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