# PROCESSES OF SEDIMENTATION ON THE SHOREFACE AND CONTINENTAL SHELF AND THE DEVELOPMENT OF FACIES PAKIRI, NEW ZEALAND

Thesis submitted by

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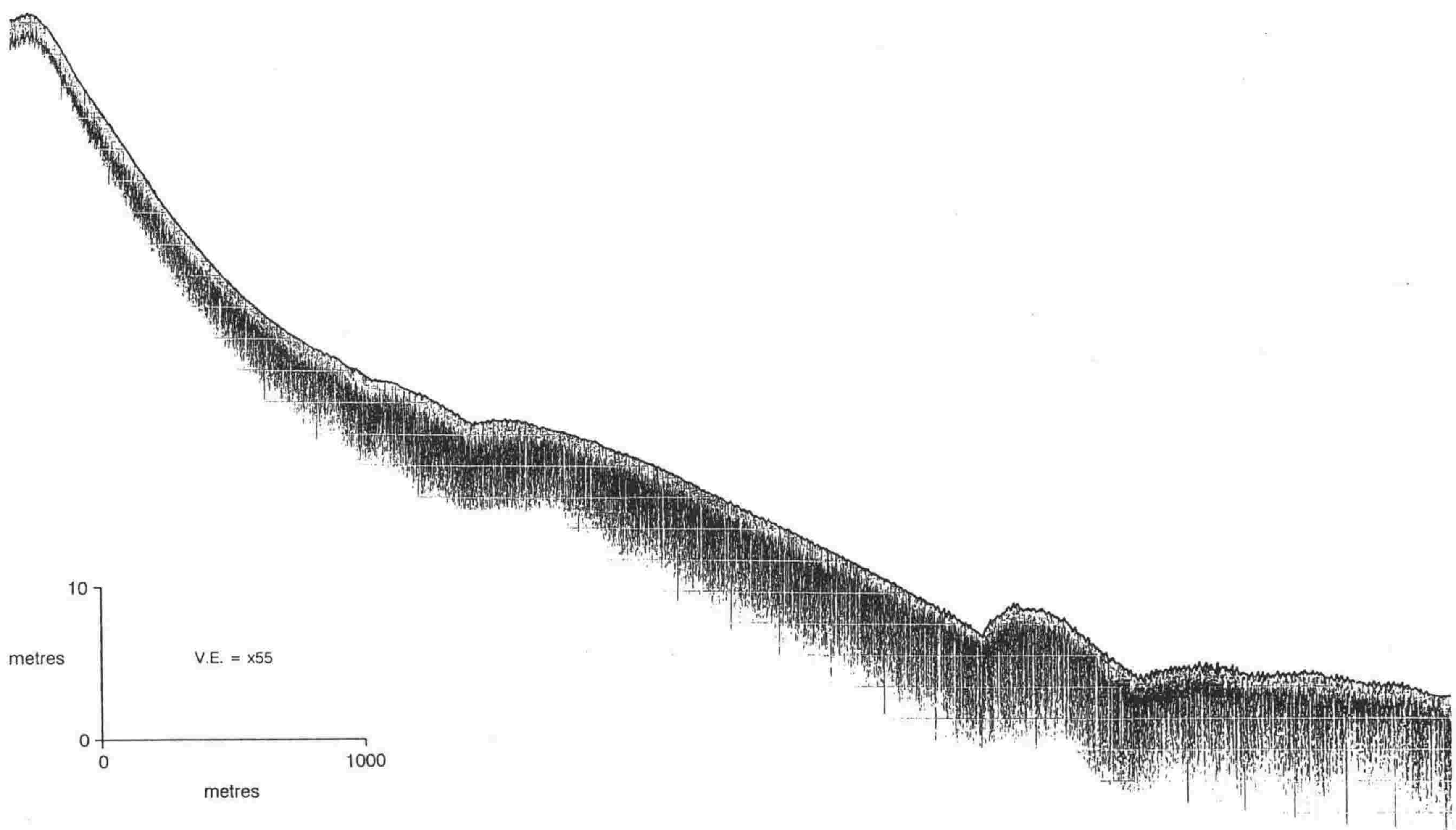
the Department of Geography at the
University of Auckland

**Frontispiece** A typical shore-normal echosound record across the shoreface and continental shelf, Walkway transect (08.05.89), Pakiri Bay, New Zealand.


10
metres
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metres
V.E. = x55

## ABSTRACT

This dissertation presents the results of research of physical and biological processes of sedimentation on the shoreface and continental shelf in Pakiri Bay, on the east coast of the Northland Peninsula, New Zealand. These environments comprise the subtidal portion of the Pakiri sand body.

Sand bodies that are contiguous with unconsolidated sediments of coastal barriers are characteristic of the embayed east coasts of the Auckland and Northland Regions, yet little is known of their geomorphology. Existing models of shoreface and shelf sedimentation afford limited assistance because they were developed in different environments. Factors that distinguish the study area from other coasts include tectonic stability, lack of modern (non-biogenic) sediment inputs, the predominance of currents related to shoaling surface waves, and a sea level stillstand for the last 6,500 years.

The model of sedimentation developed is derived from intensive field investigation of the morphology, sedimentology and ecology of the Pakiri Bay shoreface and continental shelf. Investigations of sediment transport entail interpretations of the sediments and sedimentary structures of the seabed, application of existing sediment transport models and the analysis of morphodynamic data.

The geomorphology of the Pakiri sediment body is characterized by a regular pattern of morphologic components and associated sediment types. Alongshore variation in these characteristics is generally minor compared with shore normal variation. The shoreface comprises a curvilinear concave surface, that extends offshore from the alongshore bar approximately 1500 m, to water depths of about 22 m. The inner continental shelf comprises an equally curvilinear, mostly convex, surface that slopes seaward to the relatively flat middle continental shelf. Secondary morphological variations result from the presence of large-scale bedforms on the middle continental shelf

and landward margin of the inner shelf.

The sediments of the shoreface are fine, very well sorted quartz-feldspathic sands of 2 $\phi$ mean grain size. The inner shelf sediments grade offshore from a medium sand to very coarse sands and fine gravels (mean grain size 0.0 to 0.5 $\phi$). In contrast the sediments of the mid shelf are very fine sands (mean grain size 2.0 to 2.5 $\phi$), with a mud content of 5 to 10 percent.

Carbonate skeletal debris, derived mostly from molluscs, comprises a significant proportion of inner and mid shelf sediments. The concentration of carbonates in the sediments increases offshore from 0 to 5 percent on the shoreface to 30 percent at the base of the inner shelf. The carbonate fraction of the sediments is size graded on the inner shelf and mid shelf in accordance with the grain size characteristics of the non-carbonate fraction.

A model of the distribution and abundance of living macrobenthos (mostly of the phyla mollusca) is derived from benthos surveys in Pakiri Bay. Species that are diagnostic of high and low energy environments are characteristic of the shoreface and middle continental shelf respectively. The pattern of carbonate concentration in the sediments of the subtidal sediment body does not correlate with the pattern of modern biogenic production. Highest levels of modern shell production occur across the shoreface, whereas carbonate concentrations are greatest at the base of the inner shelf. Hypotheses are advanced to explain this dichotomy.

The geomorphology of the shoreface and inner continental shelf is seen as a response to modern processes of sedimentation. Sediment transport occurs primarily in response to currents related to shoaling waves. Two process regimes are recognized. During typically calm (swell wave) conditions the fine sands of the shoreface may be transported landward as a result of an onshore mass transport current. During severe storm events this process may transport bed sediments landward across the inner shelf and middle

continental shelf, forming the characteristic sediment and morphologic patterns observed. However, during such events this onshore flow is probably counteracted by return flows that are able to transport eroded foreshore and inshore sediments seaward.

**Key words:** Sedimentation, shoreface, continental shelf, wave dominated, carbonate sedimentation, sediment body, facies.

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# Chapter 1

# SHALLOW MARINE SEDIMENTATION

## 1.0 Introduction and Rationale

The shoreface is a major feature of many wave dominated, sandy coasts (Niedoroda et al., 1984), recognized as a concave surface extending between the outer margin of the surf zone and the inner continental shelf. On unconsolidated coasts the inner shelf is usually a more gently sloping surface, extending seaward a variable distance depending upon the local process regime and geology. Collectively the shoreface and inner continental shelf comprise a transition zone between processes of sedimentation on the beaches and those on the middle continental shelf. As such they are subject to wave and current-driven processes acting in both environments (Field and Roy, 1984). Close to shore the energy budget of the sea floor is thought to be dominated by wave-driven flows, while sedimentation seaward of the inner shelf is thought to be largely due to tidal and other long period water flows (Swift, 1976 b).

Marine scientists have generally neglected the problem of modeling processes of clastic sedimentation in these shallow marine environments. The shoreface and inner continental shelf have been considered too close to shore for classic oceanographic investigations, whereas coastal workers have been preoccupied with processes of sedimentation in the surf zone, where proximity to land facilitates deployment of instruments (Swift, 1976 b). Investigations near exposed sandy coasts entail substantial logistical difficulties since it is difficult to secure platforms in these situations or navigate large vessels. In addition, waves, currents and sediment transport patterns across the shoreface, and the inner shelf, are characterized by strong temporal and spatial gradients (Niedoroda et al., 1984). Interpretations to date have been impeded by the scarcity of hydraulic observations during extreme (storm) events, which may be of primary importance along wave-dominated coasts. Investigations of modern shoreface and inner shelf sedimentation must also interpret the effects of the Holocene transgression and changes of sea level on shelf sediments. The cumulative effect of these factors has been to forestall research of shallow marine sediments and processes of sedimentation.

Beach and dune sediments commonly represent the landward margin of extensive subtidal sediment systems that may comprise the shoreface and inner shelf. Understanding long term as well as contemporary processes of coastal development may be contingent upon advancing our understanding of the nature of these systems, particularly their dimensions and dynamics. The extent to which the apparent global trend of coastal erosion is related to internal adjustments or is partly or entirely due to variations in external factors, such as sea level or storminess, is of immediate interest.

Existing process models of sedimentation in shallow marine environments are largely derived from investigations of the North American Atlantic coast (for example, Fischer, 1961; Howard and Reineck, 1972; Swift _et al_., 1971 b; Swift, 1976 b), and the tide-dominated shelves of the North Atlantic and the North Sea (Stride, 1963; Johnson _et al_., 1982). Their efficacy in the New Zealand coastal context, and along the east coast of Auckland and Northland in particular, has not been ascertained. This coast is deeply embayed and apparently little affected by alongshore long period shelf or coastal flows, that characterize the Atlantic barrier coast of North America for example. Further, the sea level history of the New Zealand coast in the Holocene contrasts with that experienced in either North Atlantic or North Sea situations. New Zealand shelf sedimentation models may be quite different to those of the United States east coast.

Along wave-dominated coasts there is general agreement as to the factors involved in shallow marine sedimentation. Regional slope, sediment character (type and availability), and nearshore energy (particularly wave power) are considered the most important (Wright and Coleman, 1972; Swift, 1976 b). Aside from these general observations our understanding of the response of shoreface and inner shelf sediments to contemporary processes of sedimentation is imperfect.

Geological models have been developed that document trends in coastal sedimentation along the North American Atlantic coast (for example, Kraft, 1971) and the east coast of Australia (for example, Thom, 1983; Roy et al., 1980). However, they suffer from the disadvantage that in areas of coastal recession information on the location of prior shorelines has been destroyed. It is therefore essential to complement existing geological models with investigations of processes of sedimentation that occur over medium and short-term time scales, of the order of days and years. Relatively few such studies have been attempted on the shoreface and inner shelf around the New Zealand coast or elsewhere.

The potential for onshore or offshore movement of sediment as a result of wave-induced currents under normal and storm conditions is not well understood. Furthering our understanding of such processes may also have implications for predicting the consequences for coastal, shoreface and inner shelf development of a possible 1 m rise in sea level by the year 2050. Field and Roy (1984) state that aside from some general relationships an understanding of the dynamics of sediment transport onto or away from the shoreface is largely incomplete. Some mechanisms, by which coastal sand is transported offshore to water depths beyond that from which it may return have been identified, but most are poorly understood (Chapman et al., 1982; Swift, 1982).

Determining the relationship between coastal, shoreface and shelf sediments has especial relevance for the management of some anthropogenic activities. For example, the seabed of the inshore and upper shoreface, as well as the beaches, have been mined for sand at many locations along the east coast of the Auckland Region, New Zealand. Yet consent-granting authorities have continued to license these activities in ignorance of the actual or potential environmental impacts. In particular at open coast mining sites, little, if anything, is known of the relationship between coastal and offshore sediments. Healy and Dell (1982) comment on the 'perplexing problem of the relationship of the sand on the beaches to that on the continental shelf', and note our ignorance of the potential for sediment interchange onshore-offshore or alongshore. They conclude that resolution of this problem is;-

> '...of fundamental importance in the resource management of the Coromandel Coast. It relates directly to the contentious issue of episodic beach erosion, continuous shoreline retreat, implementation of building setback in coastal subdivision and commercial extraction of sand from the coastal sediment systems.'

This study seeks to further understanding of processes of shallow marine sedimentation, and the dynamics and dimensions of coastal sediment systems in particular, by empirical field investigation of the geomorphology of the shoreface and continental shelf in Pakiri Bay, on the east coast of the Northland Peninsula, New Zealand.

## 1.1 Research Objectives and Thesis Organization

Specifically, the study aims to:-

(1) Describe the sedimentology of the surficial sediments of the Pakiri shoreface and inner continental shelf.

(2) Identify and define sediment facies in the study area.

(3) Investigate the extent to which the sediment facies result from modern processes of physical and/or biological sedimentation, are inherited from past environmental conditions (are relict), or are a product of both (palimpsest).

(4) Identify and describe the morphological components of the study area.

(5) Investigate the potential for processes related to shoaling waves, tidal and other currents, to disturb the sediments of the study area and initiate sediment transport. In particular, investigate the potential for onshore-offshore sediment movement related to wave motions and wave induced currents, and address the question of the relationship between the sediments of the continental shelf and coast.

(6) Assess the concept of the 'sediment system' with regard to the Pakiri study area, and identify, if applicable, the dimensions of the Pakiri Sediment System. In particular, identify offshore and alongshore limits to sediment transport.

(7) Derive a model of modern shallow marine sedimentation on the shoreface and continental shelf in Pakiri Bay.

The ensuing sections describe the characteristics of the study area and review the existing understanding of sedimentation in the study area and the adjacent Hauraki Gulf. The final section outlines the methodology employed in the present investigation.

Chapter Two reviews the literature pertaining to shoreface and inner shelf sedimentation generally, and processes of onshore-offshore sediment transport specifically.

Chapter Three presents the results of investigations of the surficial sediments of Pakiri Bay. This work is based on extensive and intensive sampling of the sediments of the coast, shoreface and continental shelf, and forms the basis of an initial classification of sediments in the study area.

Chapter Four researches the nature and origin of the carbonate fraction in the sediments of the shoreface and continental shelf. A model of contemporary benthos distribution and abundance is developed, based on sampling of the living macrobenthos. This model is used to interpret the pattern of carbonates in the surficial sediments of the study area.

Chapter Five investigates the morphology and morphodynamics of the Pakiri sediment body. Echosound, side-scan and sub-bottom sonar provide data on the alongshore and onshore-offshore variations in bathymetry within Pakiri Bay. The extent to which these results indicate sediment transport on the shoreface and continental shelf are considered. Existing bathymetric data, and data gathered during the present study, are analyzed and interpreted in terms of indirect evidence of sediment transport.

Chapter Six describes the bedforms and bed configurations of Pakiri Bay. The chapter reports the results of field surveys involving echosound and side-scan sonar, and the deployment of remote-controlled photographic instruments. The results are used to relate bedform geometry to flow conditions.

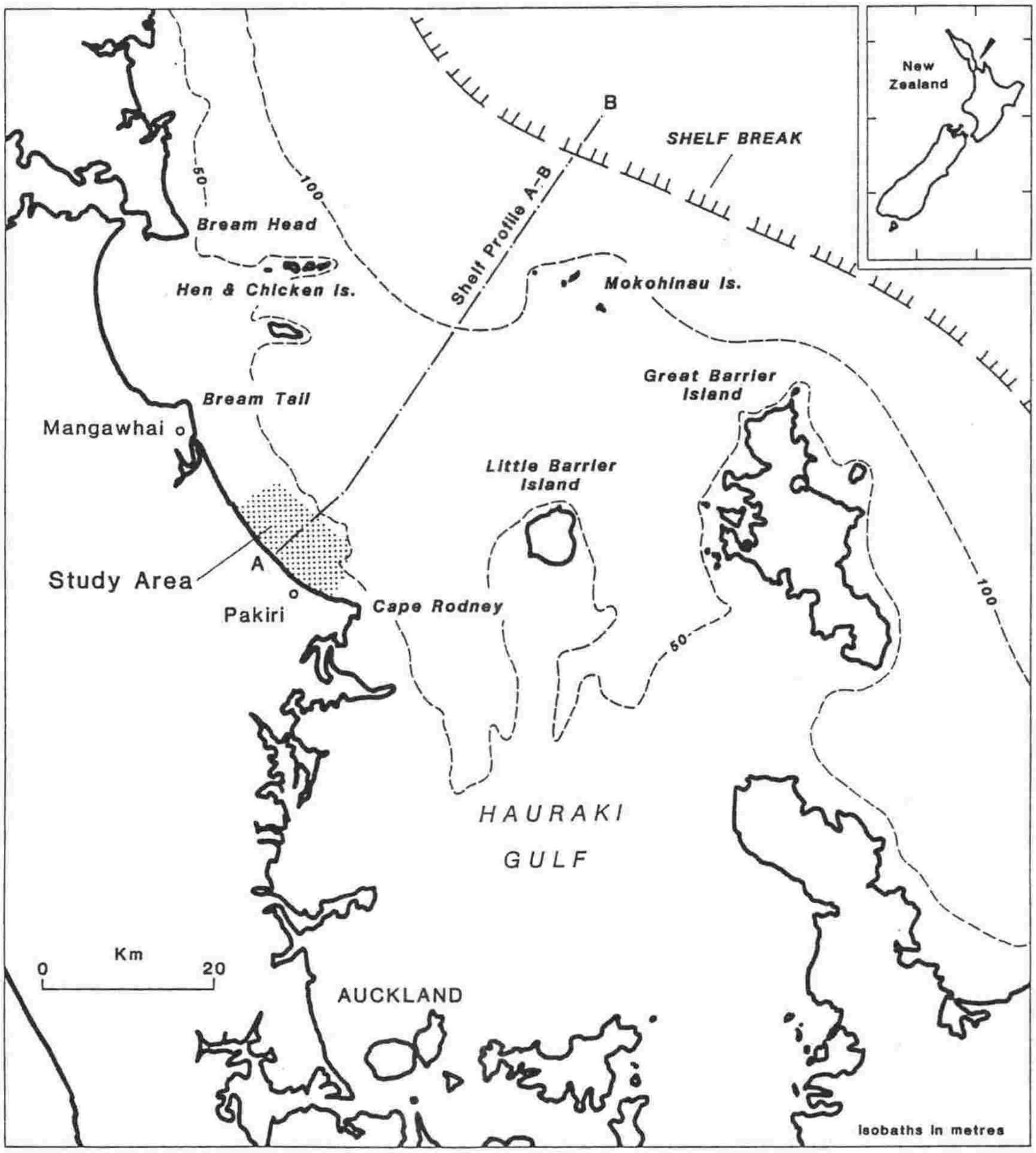
Chapter Seven investigates the potential for near-bed currents to transport sediments on the shoreface and continental shelf. A model of sedimentation in these environments is proposed. Chapter Eight concludes the thesis with a reiteration of the major conclusions and a discussion of the implications of the results for understanding coastal, shoreface and shelf development.

## 1.2 Characteristics of the Pakiri Coast

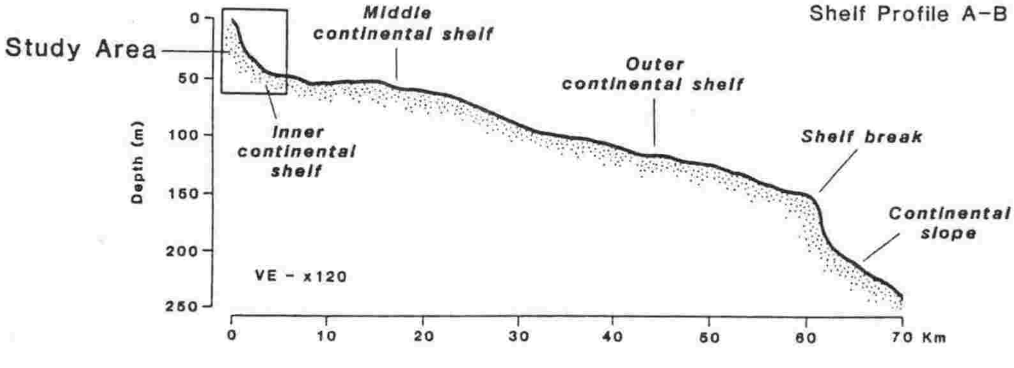
The study area is located in Pakiri Bay, the southern half of an embayment that extends between Bream Tail and Cape Rodney in the Outer Hauraki Gulf (Figure 1.1 a). The bed of the subtidal sediment body in Pakiri Bay constitutes a relatively steeply-sloping surface that extends between the coast and the middle continental shelf of the Outer Hauraki Gulf (Figure 1.1 b). The adjoining sandy coast extends 25 km from Mangawhai to 2 km south of the Pakiri River. Te Arai Point, a small rocky headland, subdivides the embayment into Mangawhai and Pakiri Beaches. Coastal dunes extend the length of both beaches, increasing in height and width towards the north. At either end of the broad Pakiri-Mangawhai embayment the headlands comprise cliffed, rocky coasts.

Figure 1.1 Location of the study area in (a) the Outer Hauraki Gulf and (b) relative to the major morphologic components of the continental shelf (from Thompson, 1975)

a.


New Zealand
SHELF BREAK
B
Shelf Profile A-B
Bream Head
Hen & Chicken Is.
Mokohinau Is.
Bream Tail
Great Barrier Island
Mangawhai
Little Barrier Island
Study Area
A
Pakiri
Cape Rodney
HAURAKI GULF
Km
0
20
AUCKLAND
Isobaths in metres
50
100

b.


Study Area
Middle continental shelf
Shelf Profile A-B
Outer continental shelf
Inner continental shelf
Shelf break
Continental slope
Depth (m)
VE - x120
0
50
100
150
200
250
0
10
20
30
40
50
60
70 Km

The morphological features of the Pakiri coast are characteristic of those commonly described from exposed sandy beaches (Komar, 1976, for example). These comprise the landforms of the backshore (dunes), the foreshore and inshore (Figure 1.2 a). The Pakiri sediment body extends from the landward limit of the coastal dunes to the base of the inner continental shelf, approximately 4500 m offshore, in 45 m water depth (Figure 1.2 b). The shoreface and inner shelf environments, which constitute most of the subtidal sediment body, are the focus of the present study.

### 1.2.1 Geology

The oldest rocks in the area are indurated Mesozoic greywackes (Figure 1.3). These rocks are relative resistance to erosion, and tend to form the headlands and peninsulas of the east coast of the Auckland Region. Greywacke outcrops at Cape Rodney, Te Arai Point and Bream Tail. These rocks are overlain by less resistant bedded sandstones and siltstones of Tertiary age. Except for occasional volcanic intrusions these latter rocks are the surface rocks over most of the hinterland bordering the Pakiri-Mangawhai Coast.

Holocene sediments comprise the unconsolidated sands of the coast and the alluvial and lacustrine sediments that separate the marine sediments from the rocks of the hinterland. A moderately to well-indurated, deeply weathered sandstone is seen to underlie the unweathered sands of the coastal dunes at several locations between the Poutawa Stream and Mangawhai (Figure 1.4). This material is similar to deposits interpreted as last interglacial at Bream Bay and Omaha to the north and south of the study area respectively.

The Mangawhai-Pakiri embayment in which the late-Quaternary marine sediments have been deposited is part of the aseismic Northland land mass, considered to have been tectonically stable since the upper Miocene (Lensen, 1977). Unlike broad areas of the east coast of the lower North Island the geomorphology of the coast should not have been much affected by movements of the land relative to the sea.

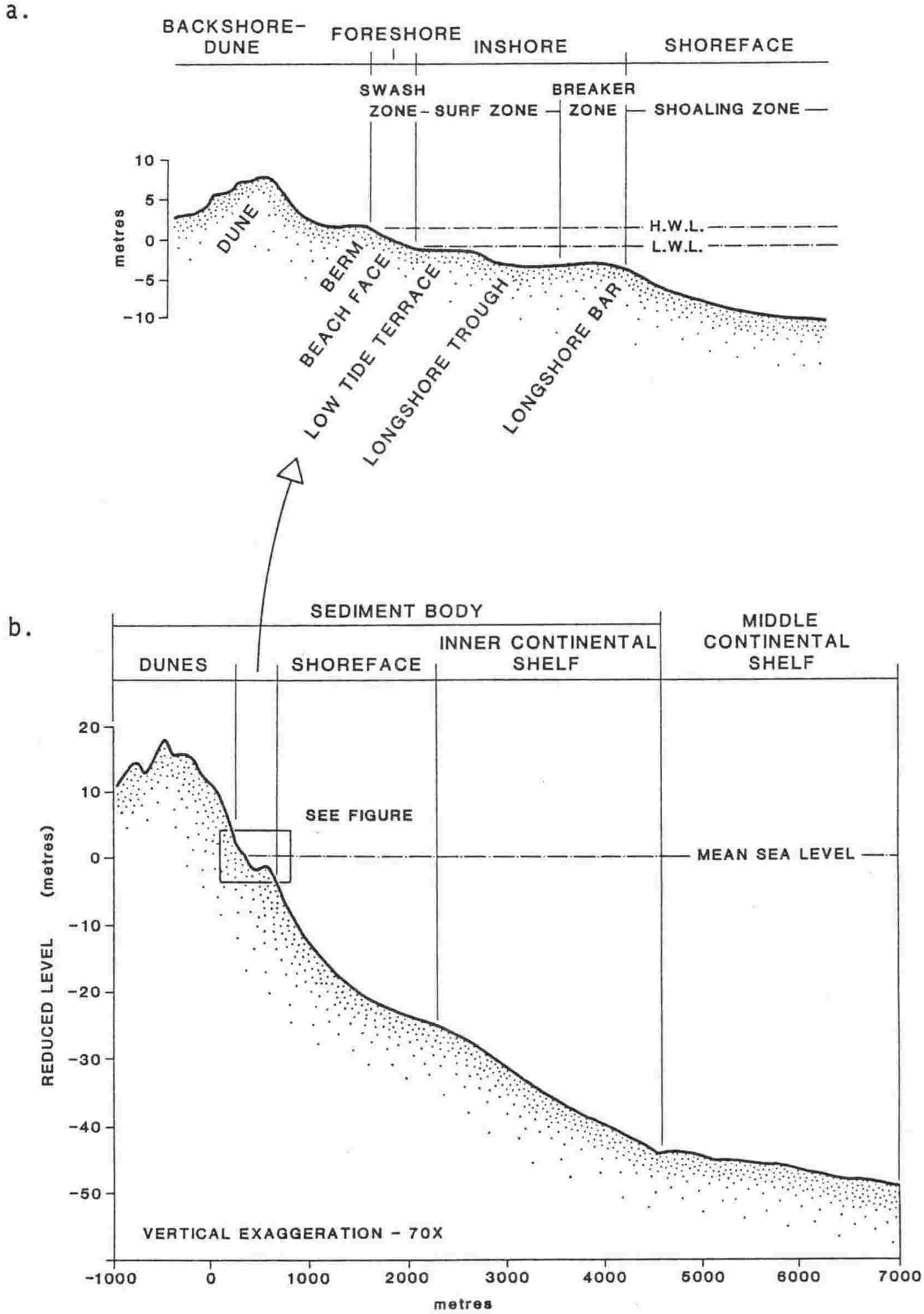



**Figure 1.2** Characteristic morphologic components of the (a) coast and (b) coast, shoreface and continental shelf, Pakiri Bay

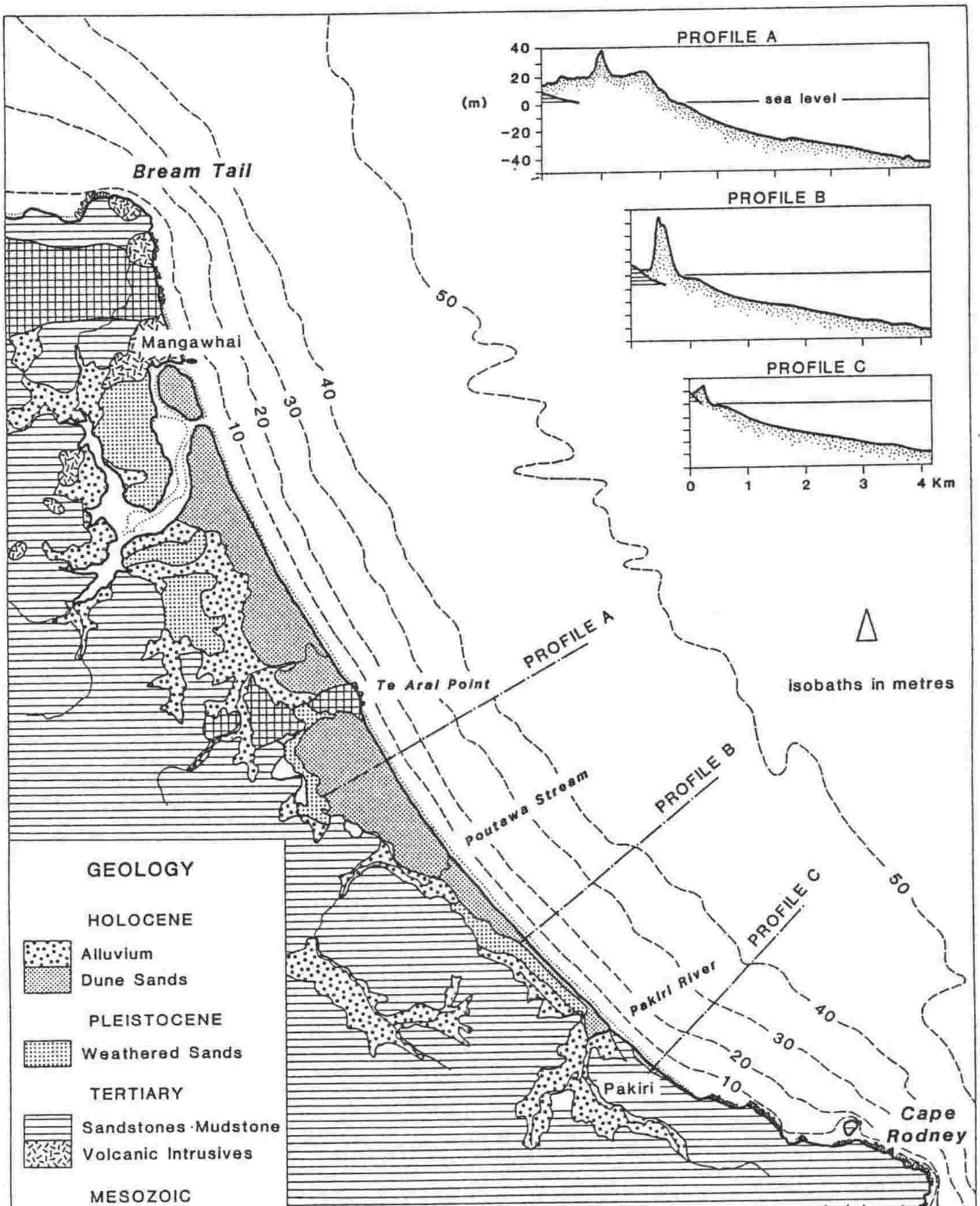



**Figure 1.3** Geology and bathymetry of the Pakiri-Mangawhai coast and shore-normal dune, shoreface and inner shelf sections (source: survey data, NZMS 290 R08/09, RNZN Hydrographic Chart, 1974)

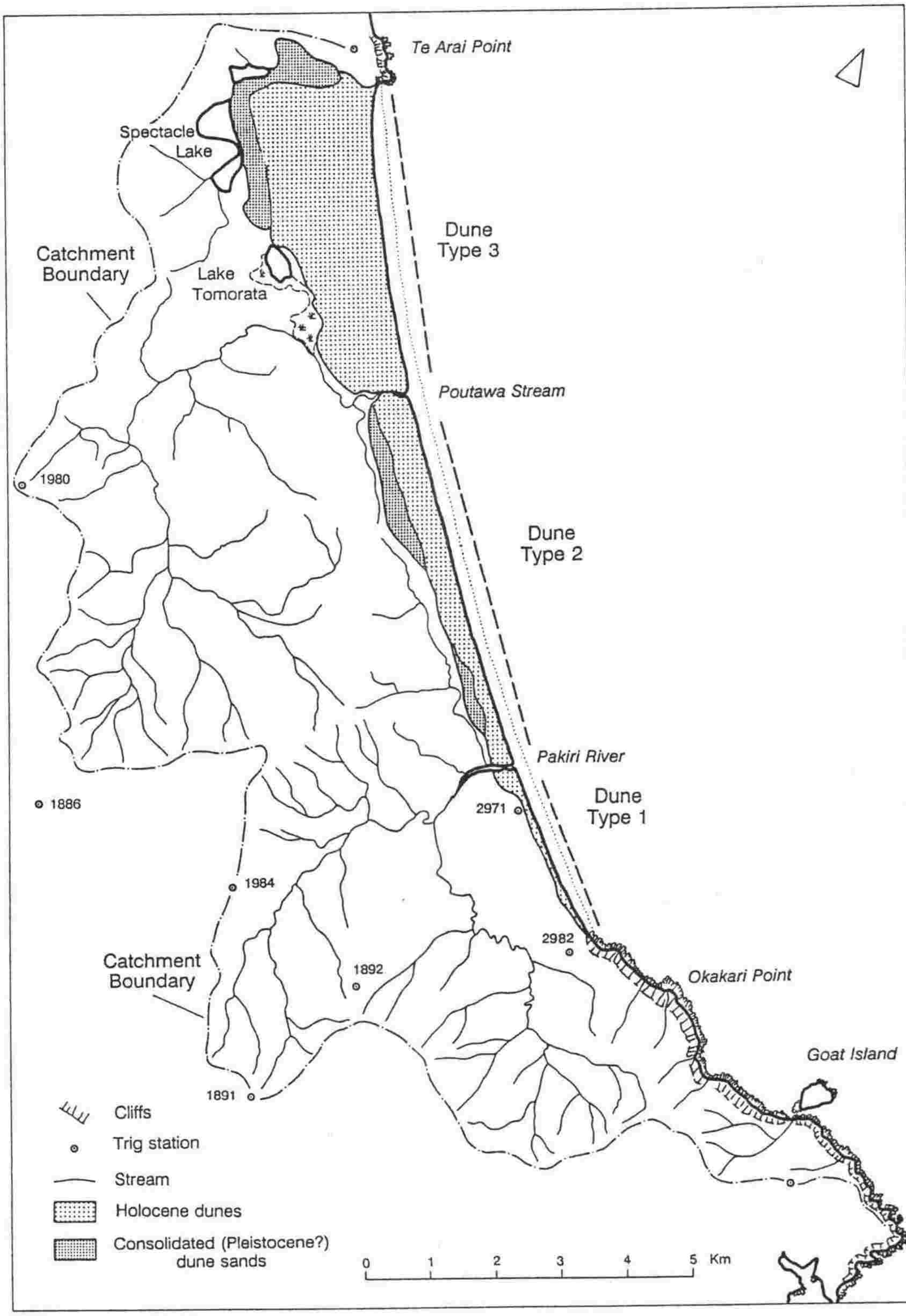



**Figure 1.4** Areal extent of the Pakiri dune field, and drainage pattern of the Poutawa and Pakiri Stream catchments (source: field survey and NZMS 290 R08/09)

### 1.2.2 Sedimentology

The dune and beach sands of the coast are mostly fine to medium (Wentworth size) grade, quartz-feldspathic sands. These sediments are contiguous with, and generically related to, the unconsolidated sediments of the shoreface and continental shelf (Thompson, 1975; Schofield, 1978).

The New Zealand Oceanographic Institute (Coastal Series) map of the sediments of the Hauraki Gulf (Carter and Eade, 1980) identifies the sediments of the continental shelf in the study area as predominantly sands, with a significant component of carbonate gravel (Wentworth, 1922, size grades). The sediments become muddy seaward of the 50 m isobath. Few samples have been previously described from the study area landward of the 25 m isobath.

Schofield (1970) ascribes the sediments of the Hauraki Gulf to one of two facies. The Hauraki A Facies, which mantles the floor of the Gulf, is thought to be derived from sediments emplaced by episodic discharge of the ancestral Waikato and other rivers during late-Quaternary times (Cuthbertson, 1981; Greig, 1982). The Hauraki B facies is considered a coastal derivative of Hauraki A, caused by prolonged coastal transport and sorting (Thompson, 1975). This facies characterizes the coast from Whangarei to Kawau Island, grading into the coastal Bay of Islands Facies to the north and the Orewa Facies of the Inner Hauraki Gulf beaches to the south.

Thompson (1975) found the majority of sediments in the Hauraki Gulf to be highly biogenic in nature, reflecting low levels of modern sediment input. The sediments of most of the Hauraki Gulf are assigned to one of two shelf facies. A 'Central Shelf, Biogenic, Carbonate-Gravelly Sand' facies in areas subject to intense current action, and an 'Offshore, Biogenic' facies comprised of muddy sands and sandy muds. These sediments are interpreted as essentially relict. In contrast the six samples analyzed by Thompson from Pakiri Bay are clean, compacted, medium to fine sands, with a carbonate content of approximately 20 percent. The carbonate fraction contains relict bryozoan and molluscan material, but is dominated by living and/or recently dead molluscan skeletal fragments.

Seaward of the inner shelf in Pakiri Bay the sediments are predominantly fine, increasingly muddy, sands. Compared with the sediments of the inner shelf they are relatively homogeneous, with mud and fine sands comprising 90 percent of the samples. Their terrigenous and carbonate contents are reported by Thompson (1975) to be the same as for those of the inner shelf sands. These muddy, fine sands extend to approximately the 75 m isobath, seaward of which the sediments are again more mixed, although still with a greater proportion of mud (70 percent).

The Pakiri-Mangawhai sediment body appears to be isolated from alongshore sediment movement from either the north or south. Studies of sediment movement in Omaha Bay (for example, Raudkivi, 1976) have concluded that drift around Cape Rodney, linking Omaha and Pakiri Bays, is most unlikely. At the northern end of the Pakiri-Mangawhai sediment body there is the possibility for limited movement of fine sand between Mangawhai Bay and Bream Bay (McCabe, 1985). However, the indications are that alongshore sediment movement is negligible.

### 1.2.3 Fluvial Sediment Inputs

Two catchments, with a combined area of 75 $km^2$, discharge into Pakiri Bay (Figure 1.4). Most of this area is vegetated with introduced grasses, and although hillslope instability has greatly increased since the original forest cover was cleared, areas of bare earth resulting from mass movements are rapidly revegetated. Annual mean rainfall at the adjacent Leigh Marine Laboratory is only about 1100 mm and apart from infrequent periods of very intense rainfall, runoff is low (Evans and Ballantine, 1985). The potential for fluvial input of sediments into Pakiri Bay, derived from erosion of the catchment rocks, is therefore considered very small, and insignificant compared with the area of the unconsolidated sediments of the study area. Nor is the mineralogy of the sediments of Pakiri Bay consistent with a local (hinterland) provenance (McCabe, 1985).

### 1.2.4 The Marine Environment

Measurements of the direction and speed of coastal currents have been made at Cape Rodney, near the southern margin of the study area (Barker, 1971; Rickard, 1976; Walls, 1982). The records are dominated by flows of less than 25 cm $s^{-1}$, with ebb tidal flow vectors alongshore to the northwest and flood alongshore to the southeast. Tides in the region are semi-diurnal and meso-tidal, with a maximum range of 3.0 m at springs and 1.5 m at neaps.

The East Auckland Current is known to result from the interposition of the north-east trending coastline of the Northland Peninsula across a generally westerly and locally southwesterly flow of sub-tropical water from the Trade Wind Drift (Brodie, 1960). This current flows south to the Bay of Plenty but is not thought to impinge into the Hauraki Gulf and have any significant effect on the coast (Ridgeway, 1979; Harris, 1985).

The coasts of the Outer Hauraki Gulf are exposed to high levels of wave energy. The results of waverider deployments between East Cape and North Cape (Figure 1.5 a) are reported by Peek (1979), Ewans and Kibblewhite (1981) and Harris et al. (1983). In addition, observations of shoaling and breaking waves have been made at several east coast locations, including the 20 year 'wave surge' data recorded at the Leigh Marine Laboratory, situated at Goat Island, near Cape Rodney. Wave energy is lower and more variable along the north-east coast than other exposed coasts around New Zealand, with local storm events the dominant influence. The dominant wave arrives from a northeast direction (Figure 1.5 b). The mean deep water wave height is 1.4 m and rarely exceeds 3.0 m (Figure 1.5 c). Periods are mainly in the range 6 to 9 s (Figure 1.5 d,e), with 6.55 s the average. Longer period swell waves, with

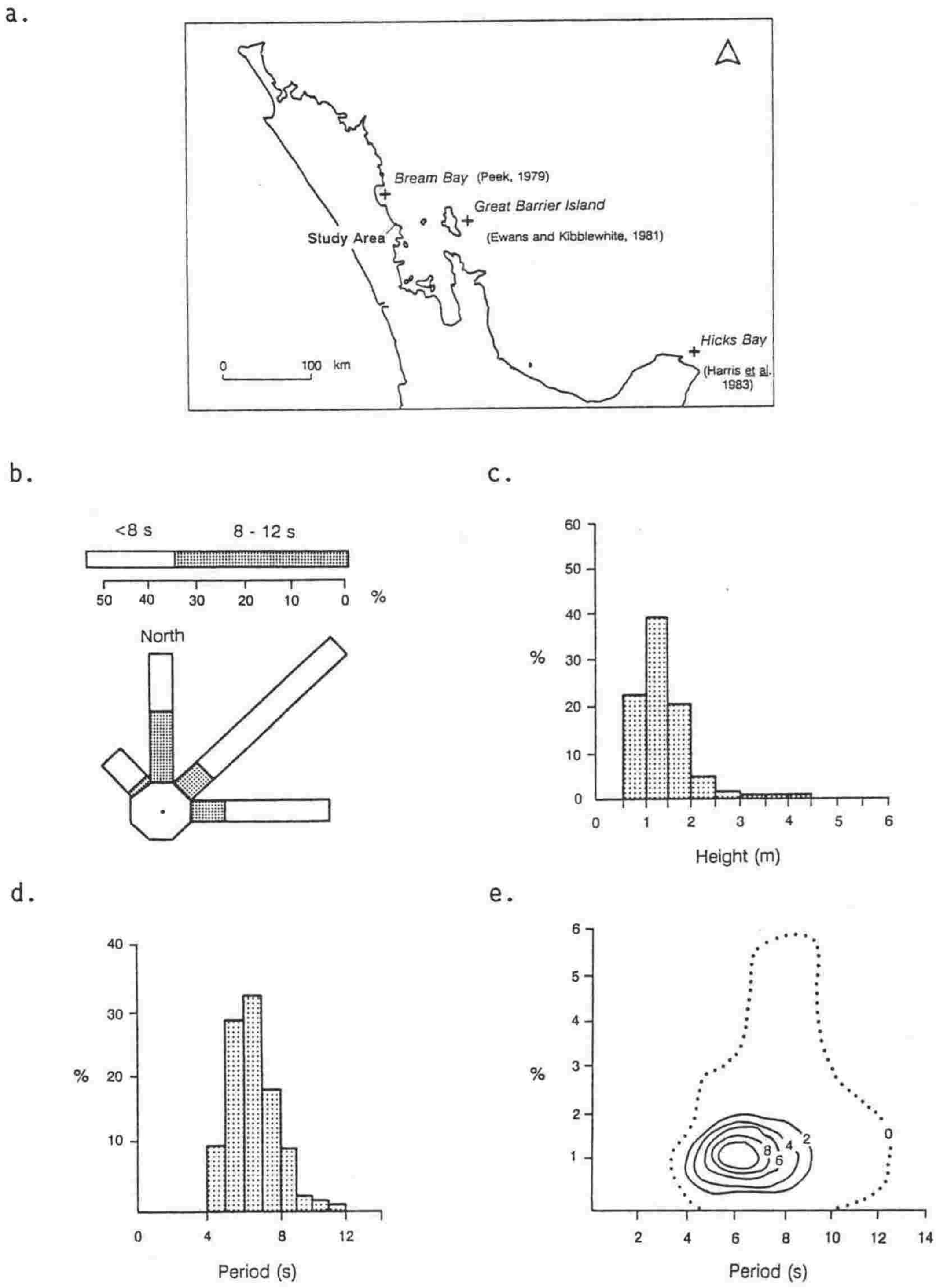



**Figure 1.5** (a) Location of wave-rider buoy measurements, frequency of (b) wave directions, (c) significant wave heights, (d) wave periods and (e) percentage occurrence of height-period combinations (from Pickrill and Mitchell, 1979)

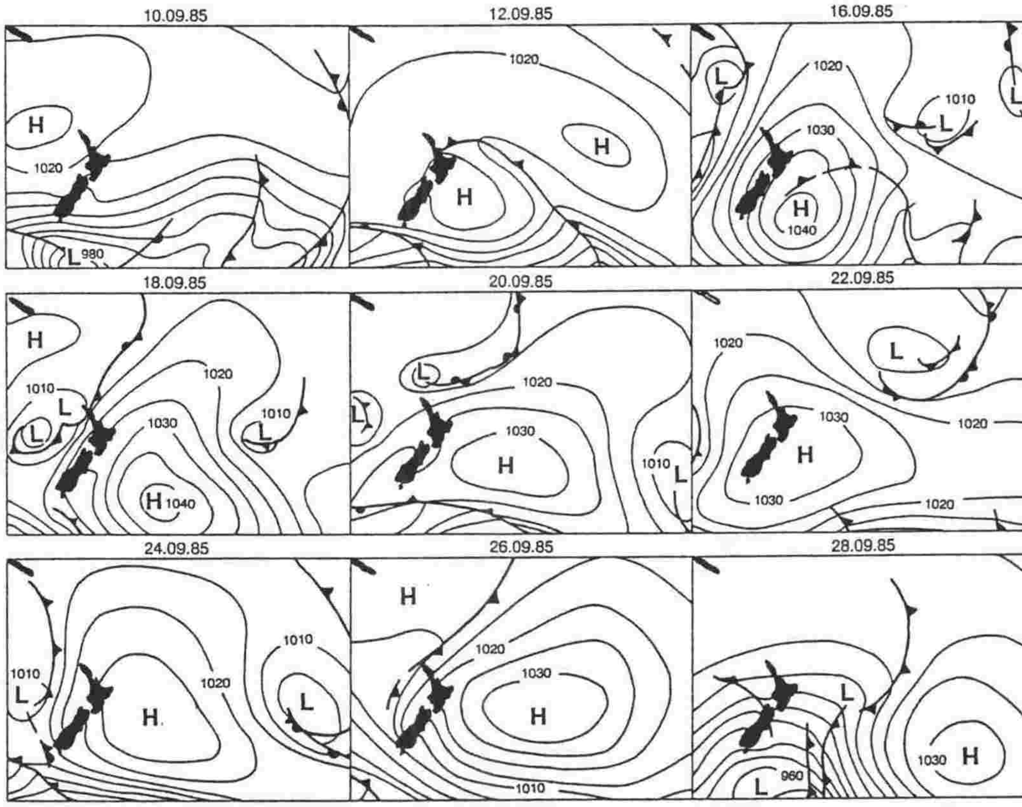
periods of 8 to 12 s, tend to arrive from the north, and probably reflect the influence of the southeasterly movement of tropical cyclones to the northeast of New Zealand.

The relationship between synoptic climatic conditions and local wave generation along the east coast has been described by Harris et al. (1983). The passage of mid-latitude depressions was the most frequent type of weather situation encountered. Over the period of the record the average wave height is 1.25 m, but heights rarely fall below 0.50 m. The highest significant wave was 5.2 m, the result of the action of a merged Tasman Sea cyclone and a weak ex-tropical cyclone. Significant waves also exceeded 5 m when a Tasman cyclone was 'blocked' from moving east by a slow-moving high pressure cell. A comparable situation produced 26 days of onshore (easterly) winds of up to Beaufort Force 8 in Pakiri Bay in September, 1985 (Figure 1.6).

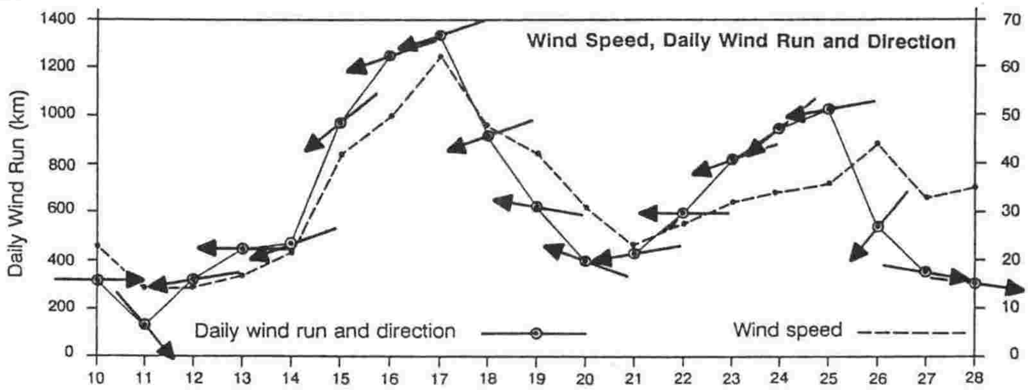
Most periods of high wave activity along the east coast of Northland result from intense depressions that form in the north Tasman Sea or subtropical or tropical cyclones that originate to the north of New Zealand. The storm of 18-21 July 1978 is an extreme example of the former. This depression originated as a low pressure system to the northwest of New Caledonia, and intensified as it moved to the southeast onto the north of New Zealand (Hume, 1979). The cyclone brought near hurricane force northeast to southeast winds, of between 80 and 100 knots, and very low atmospheric pressures to the east coast of the Auckland Region. Tide gauges recorded sea levels about 1 m above predicted levels. McCabe (1985) calculated a storm surge for the Mangawhai coast of 2.24 m above predicted sea level. Daily observations of sea state at Goat Island show that the largest seas occurred over the 18-21 July and that storm waves had periods of 10-15 seconds. At both Goat Island and Marsden Point breaking waves of up to 4 m were observed on the 19 July (Table 1.1). Following a review of ship and lighthouse reports off the Northland Coast Reid (1979) concludes that wave heights probably reached 15 m in the Outer Gulf. A waverider buoy recorded storm waves in Bream

**Figure 1.6** (a) Southwest Pacific synoptic meteorological situation, 10-28 September 1985, showing blocking pattern; (b) wind speed (maximum daily gust), daily wind run and (0900 hours) direction, and (c) wave surge observations (derived from data in Evans and Ballantine, 1985)

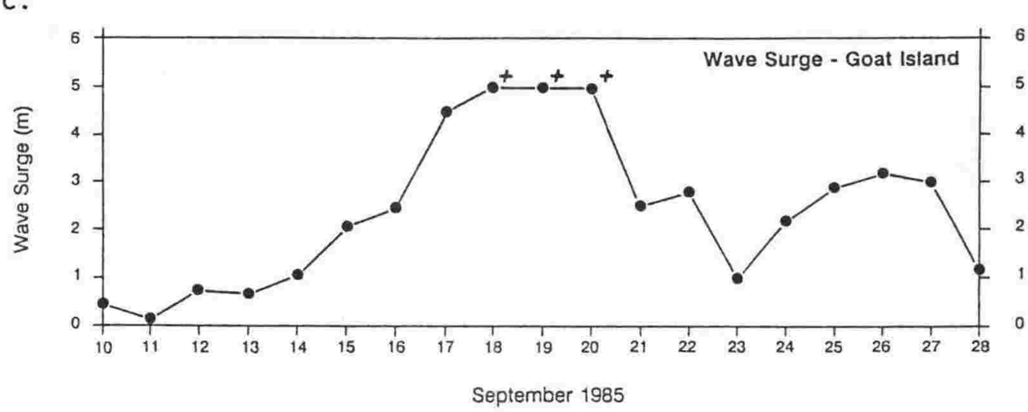
a.


10.09.85
12.09.85
16.09.85
18.09.85
20.09.85
22.09.85
24.09.85
26.09.85
28.09.85

b.


Wind Speed, Daily Wind Run and Direction
Daily Wind Run (km)
Wind Speed (knots)
Daily wind run and direction
Wind speed

c.


Wave Surge - Goat Island
Wave Surge (m)
September 1985

Bay of 9.0 m maximum height and 12 s period (Peek, 1979). These exceptional waves were probably the result of the combination of distant swell waves, locally generated sea and waves generated at intermediate distances.

**Table 1.1 Sea State Observations, Goat Island, 16-23 July 1978**

| Date July 1978 | Wave Surge (m) | Sea State Period (s) | Sea State Beaufort Scale |
|---|---|---|---|
| 16 | 0.2 | - | 1 |
| 17 | 0.1 | - | 1 |
| 18 | 4.5 | 12 | 8 |
| 19 | $5.0^{+}$ | 12 | 9 |
| 20 | 4.5 | 15 | 8 |
| 21 | 4.5 | 10 | 3 |
| 22 | 3.5 | 10 | 3 |
| 23 | 2.8 | 12 | 3 |

Source: After Hume (1979)

Periods of high wave energy do not, however, persist for long. The Hicks Bay records (Harris et al., 1983) show that waves greater than 3 m never persisted for longer than 36 hours. Above 4 m the persistence was no greater than 12 hours. In contrast low waves, less than 1.5 m, could persist for as long as 300 hours (Figure 1.7).

Harris et al. (1983) believe that (in general) exposed coasts between North Cape and East Cape experience the same deep water waves and receive the same total energy as Hicks Bay. The Bream Bay records show the same patterns of wave height, period, direction and persistence described from both Hicks Bay and the deep water record from the Outer Hauraki Gulf (Ewans and Kibblewhite, 1981). These results are of relevance to Pakiri Bay, given the proximity of Bream Bay (Figure 1.1), although the Hen and Chickens Islands probably affords the latter some shelter from waves arriving from the northeast. Pakiri Bay is exposed to a swath either side of the Mokohinau Islands of unlimited fetch, and wave heights are probably somewhat greater than experienced in Bream Bay.

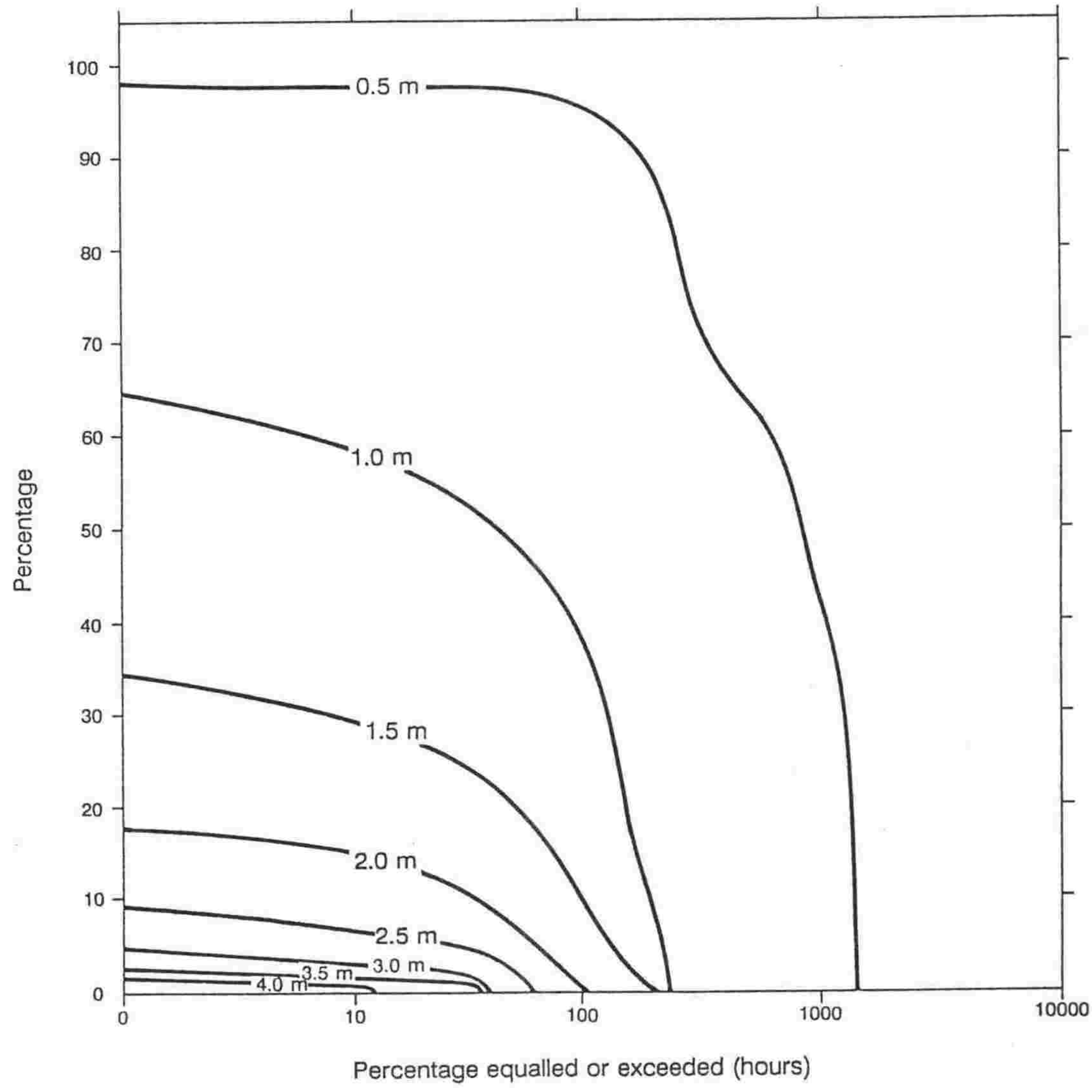



**Figure 1.7** Percentage of the total time that waves having significant heights greater than given values persisted for given times, or longer, Hicks Bay, East Cape (from Harris et al., 1983)

The wave climate in Pakiri Bay is characterized by variability at short and medium term time scales, of the order of hours and days respectively. Time series of coastal observations of breaking waves in the Outer Hauraki Gulf indicates incident wave energy in the study area also varies significantly from year to year. Daily observations of wave surge (an estimate of height of waves as they break over a sloping rock platform) have been made at the Leigh Marine Laboratory since 1967. A comparison of the sums of the monthly means of wave surge indicates considerable scatter about the mean (Figure 1.8). The data show that the period during which field investigations were conducted for the present study (1985-1987) experienced relatively low levels of incident wave energy. Although the wave surge data are a crude measure of incident wave energy, the trends may have implications for interpreting the geomorphology of the study area in what are postulated to be wave-dominated environments.

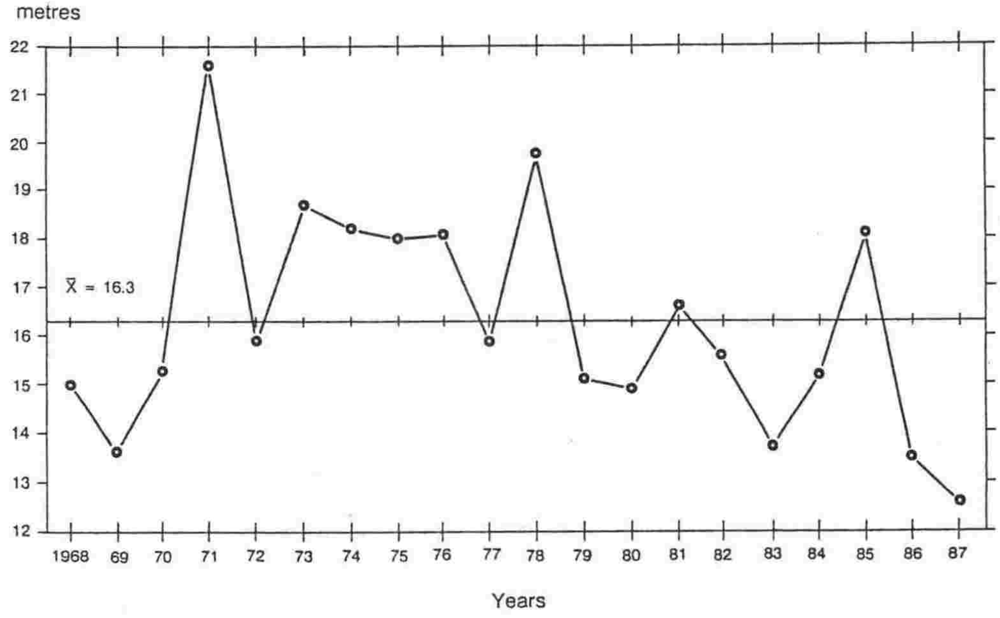



**Figure 1.8** Sums of the monthly means of wave surge, 1968-1987, Leigh Marine Laboratory (from Evans, 1988)

### 1.2.5 Summary

The aseismic Pakiri-Mangawhai embayment has experienced extensive deposition of sediments, mostly in late-Quaternary times. These deposits comprise the Mangawhai-Pakiri sediment body, a continuous accumulation of unconsolidated marine sediments incorporating dune, coastal, shoreface and continental shelf depositional environments. The sediments are thought to be mostly sands, and derived from the sediments of the Hauraki Gulf. Local sources of non-biogenic sediments, including erosion of the hinterland and coastal rocks, and alongshore exchange with neighbouring bays, are not considered significant. The only likely source of sediment therefore is offshore, or as a result of local biogenic production.

Virtually no investigations of the hydraulic regime of Pakiri Bay have been undertaken. However, it is probable that currents at the bed are predominantly wave-induced. Measurements of currents near the southern boundary of the study area suggest that tidal and other long period flows are relatively weak.

## 1.3 Variations in Shelf Sedimentation, New Zealand

The geomorphology of the Pakiri embayment differs from many other New Zealand coasts. The factors that seem of particular importance in explaining this variation include the local wave and current regime, the lack of fluvial supplies of sediment to the coast, the characteristics of the bedrock framework, the tectonic stability of the site, and fluctuations in late-Quaternary sea level over a shelf that generally terminates at the 130 m isobath.

The effect of localised supply of modern terrigenous sediment to the coast, following sea level stillstand, has been shown to be important to the development of inner shelf sediment bodies. Carter (1986) and Carter and Carter (1986) have shown sediment discharge from rivers bordering the South Otago Shelf has resulted in deposition of a 34 m thickness of modern sands and gravels on the shelf since stillstand (c.6,500 years BP). Griffiths and Glasby (1985) calculate the Clutha River annually supplies 3.14 million tonnes of sediment to this coast to be subsequently deposited across the inner shelf. In contrast the little sand and gravel sized sediment that reaches the Northland east coast via rivers is mostly trapped within the barrier-estuary complexes. In the absence of modern fluvial input to the coast biogenic production of sediments is relatively important. On the east coast of Northland such sediments are derived mostly from mollusca, foraminifera and bryozoa (Carter, 1975).

Tectonic processes have been an important control on sedimentation in the Hawkes Bay-Wairarapa (Lewis 1973 a,b) and Westland (Norris 1972, 1978) regions. In these areas tectonic uplift of the landmass has precluded development of deeply embayed, submerged coastlines, allowing rivers to continually discharge sediment directly onto the shelf. The relative narrowness of the shelves in these areas and high sediment discharge rates from local rivers has further encouraged deposition of modern terrigenous sediments. This also contrasts with the situation along the east coast of the Northland Peninsula where the coastal facies are considered to be reworked derivatives of palimpsest shelf sediments (Schofield, 1970).

The morphology of the inner shelf, and the sedimentary characteristics of that surface, show considerable variation from region to region, and particularly between the relatively exposed west and sheltered east coasts of the North and South Islands. However, two patterns are described from most locations (for example, Norris, 1978; McLean, 1979; Carter et al., 1985; McCabe, 1985):- (1) A fine sand facies associated with the concave-upward shoreface, extending seaward to the 25 m isobath, and (2) a coarse sand and/or shell gravel facies further offshore on the inner continental shelf.

The extent to which the coarse offshore deposits are relict, palimpsest or are a response to contemporary process regimes is generally problematic. Schofield (1975, 1978) interprets the coarse offshore deposits in Omaha Bay, Northland, as lag deposits resulting from episodes of shoreface erosion related to minor fluctuations in sea level during the last 5000 years. Along the east coast of the Coromandel Peninsula Dell et al. (1985, p.493) conclude "an outstanding feature common to the entire inner shelf region ... is the occurrence of a distinctive textural boundary at about the 20 m isobath, separating fine inshore sediments from offshore coarser sediments".

Sediments of the West Coast consist mainly of sand and mud (Carter, 1980) exhibiting a pattern of inshore sand fining to mid-shelf sandy mud and mud, coarsening again on the outer shelf to sandy mud or muddy sand. Probert and Swanson (1985) report that clean fine sand covers most of the shoreface and inner shelf to 30 m. This is deeper than at east coast locations but probably reflects the high energy coastal process regime, the relatively narrow shelf and the voluminous discharge of river sediments on to the inner shelf. No precise mechanism has been proposed to account for the existence of this fine sand facies, although Norris (1978) suggests sorting by waves is a contributing factor.

Fluctuations of sea level in late Quaternary times is thought by most workers (for example, Schofield, 1978; Herzer, 1981; Carter, 1986) to have exerted an important control on shelf sedimentation and morphology. Herzer (1981) provides an interpretation of the evolution of shelf lithology based on a derived sea level history for the Canterbury Bight and Pegasus Bay. On the Otago shelf, Carter (1986) associates the formation of the Holocene sediment wedge with two shorelines. At Omaha, in the Hauraki Gulf, Schofield (1978) argues that net sedimentation results from an interplay of first order and second order sea level fluctuations, and that an apparent contemporary episode of erosion is the result of a minor, second order, rise in sea level.

Carter and Heath (1975) conclude that the mean circulation over the New Zealand shelf is insufficient to induce transport of sediments. Meso-tidal flows attain sufficient velocities only where the tidal wave is constricted through Cook and Fouveaux Straits or perhaps in major channels near islands. However, storm waves are thought to have the potential to disturb sands to depths of at least 50 m across the inner and mid continental shelves. Harris et al. (1983, p.80) describing the wave climate of the east coast of the North Island, conclude '... that at 40 m the stirring of a 0.22 mm sediment should seldom occur, but at 20 m it should be significantly common'. Other studies, on the South Otago inner shelf (Carter and Carter, 1986), the Canterbury shelf (Carter and Herzer, 1979), the Coromandel inner shelf (Dell et al., 1985) and the Northland inner shelf (Gillie, 1981) conclude shoaling waves affect sediment transport on the inner shelf. In general the sediments of the inner shelf are considered to be palimpsest at most locations where there is a dearth of modern fluvial sediment supply to the coast.

## 1.4 Research Methodology

Investigations reported in this study are primarily based on field observations of the Pakiri sediment body. Intensive and extensive sampling of the surface of the Pakiri Bay seabed was conducted over a 3 year period (1985-87). Flow conditions at the bed are inferred from the physical nature of the bed, including bedform patterns, benthos and sediment patterns and the morphology of the sediment body.

This is different from other approaches to problems of coastal sedimentation, including the construction of physical scale models, application of existing empirically-derived sediment transport models, derivation of geological models and direct and indirect observation of sediment movement.

The present study reports investigations of the sedimentology, bedforms and bed configurations, morphology and morphodynamics, hydraulic conditions and modern patterns of biological production of sediments. This multifarious approach has facilitated the recognition of interrelationships that are fundamental to the understanding of sedimentation in Pakiri Bay. For example, the morphology and sedimentology of the inner continental shelf are interrelated and interpreted to result from the same processes of sedimentation.

The methodology employed is an effective approach in marine environments in which hydraulic processes are characterized by strong temporal gradients. Observations of near bed currents, or sediment movement over finite periods, is problematic where sedimentation occurs infrequently, perhaps over time scales of months. In addition, these environments are extremely hostile to attempts to establish permanent bed stations or deploy instruments for any length of time.

Most previous investigations of sedimentation in shoreface and inner shelf environments have involved relatively few, highly specific, observations over a short time period. The present investigation has endeavoured to develop a time series of observations, by making use of existing data, as well as repeating particular observations over the three year time frame of the study. This affords some confidence that the results obtained are representative of conditions over time scales of years.

Sampling is based on a system of shore-normal transects. This approach allowed extensive coverage of the Pakiri Bay seabed, while also facilitating more intensive station or continuous sampling. It is based on initial and pilot surveys of the morphology and sedimentology of the Pakiri Bay seabed that showed that alongshore variations in the sedimentology and morphology of the Pakiri Bay seabed are relatively minor compared with shore-normal variations. The use of transects also facilitated the comparison of data from different surveys obtained at different times, and navigation and station location in the field.

The boundaries of the coastal sediment system are not presupposed, but derived as a result of field investigation. Existing interpretations of sedimentation along the east coast of the North

Island envisage reasonably frequent disturbance by waves to about the 25 m isobath. The study area of the present investigation extends well beyond the shoreface in Pakiri Bay, incorporating the inner shelf and part of the adjacent middle continental shelf.

# Chapter 2

# INTERPRETATIONS OF SHALLOW MARINE SEDIMENTATION

## 2.0 Concepts of Shoreface and Shelf Sedimentation

Early interpretations of clastic shelf sedimentation were much influenced by the concept of the 'graded shelf' (Johnson, 1919) in which the slope and grain size of the sediment substrate is envisaged as a system in dynamic equilibrium with the flux of wave energy at the seabed. The resulting surface was visualized as an exponential curve in profile, concave up, with the steeper segment being the shoreface. Grain size was predicted to decrease as a function of increasing depth with distance from shore, as a consequence of the diminishing input of wave energy onto the sea floor.

The concept of the graded shelf was widely accepted until field investigations revealed the surficial sediments to be more complex. Shepard (1932) noted the prevalence of a mosaic of sediment types on the continental shelves of the world. He proposed that these mosaics were deposited during Pleistocene low sea levels, and were not formed in Holocene times. Emery (1952, 1968) classified shelf sediments on a genetic basis, as authigenic (glauconite or phosphorite), organic (foraminifera, shells), residual (weathered from underlying rock), relict (remnant from a different earlier environment such as a now submerged beach or dune), and detrital, which includes material now being supplied by rivers, coastal erosion, and eolian or glacial activity. On most shelves a thin nearshore band of modern detrital sediment is supposed to give way seaward to a relict sand sheet veneering the shelf surface. Within this classification a general distinction is made between relict sediments and all other types of modern sediments (Curray, 1965; Emery, 1968). Relict sediments were considered coarser, lying seaward of the modern material, and showing weathering features characteristic of Pleistocene subaerial weathering (Emery, 1965).

Investigation of processes of shallow marine sedimentation was initiated by van Veen (1935) in the southern North Sea, and developed in the seas around the British Isles (for example, Stride, 1963). In these areas development of sedimentation models was facilitated by the conspicuous evidence of the role of tidal currents in shelf sedimentation, the abundance of hydrographic data and the development of acoustic methods such as side-scan sonar. Research during the 1960s and 1970s quantified the role of tidal currents in sediment transport and development of bedforms (for example, Belderson and Stride, 1966; Kenyon, 1970; McCave, 1971), as well as demonstrating that wave agitation affected most shelf bottoms during storms (see, for example, Johnson and Stride, 1969).

The initial preoccupation with relict sediments delayed the derivation of process-response models to other types of shelves, particularly wind and/or wave-dominated types (Johnson and Baldwin, 1986). However, since the 1960s studies on North American shelves have shown that present day processes of sedimentation can re-work pre-Holocene deposits (Swift, 1969; Swift et al., 1971 a). Most North American shelves have been found to be wind/wave dominated, experiencing seasonally-controlled shelf hydraulic regimes, with a pattern of alternating storm and fair weather periods (Lavelle et al., 1978; Swift et al., 1983; Cacchione et al., 1984). An awareness of the importance of modern processes in shallow marine environments has led to a distinction between true relict sediments, comprising unworked sediments, palimpsest sediment, which is a reworked sediment possessing aspects of both its present and former environments, and modern sediment supplied from outside the shelf area (Swift et al., 1971 a).

## 2.1 The Origin of Facies in Marine Environments

The meaning and concept of 'facies' has been long debated (see Middleton, 1973, for discussion). The term 'sediment facies' is used by Moore (1949) to describe an areally restricted, lithologically or paleontologically distinctive component of any body of genetically related sedimentary deposits. Two spatial scales and levels of complexity may be identified. Facies elements are the smallest facies units that may be identified. Facies systems comprise a group of contiguous, related sediment facies elements. This association of elements may be considered to comprise a veneer of sediment the character of which is controlled largely by processes operative in the immediate vicinity, except where the deposit is relict. In the context of the present study the Pakiri sediment body is investigated as a facies system.

Each facies element represents a response to a particular coastal setting, and a potentially complex web of interrelating factors (Figure 2.1). Of these, however, two factors, the nature of the sediments and processes, exert a profound influence. Processes near to and at the depositional site act as a final control on the nature of the material and as the main control on the structure of the sediment (Clifton and Hunter, 1982). The processes themselves are classed as physical, biological and chemical. Physical processes of sedimentation involve the movement of sediment by fluids, especially water currents. Biological processes may involve the physical movement of sediment (by bioturbation for example), or affect the dynamic properties of the sediment by, for example, armouring or cementing the bed. Biogenic production of sediments is a chemical process, by which carbonates are precipitated as the tests of organisms.

Apart from the textural characteristics of the sediments and the nature of the processes the oceanic climate, meteorologic climate, biota and modern sediment input are important factors. These interact with each other and may be influenced by external controls such as the geologic setting. Of these the configuration of the shoreline and embayment is particularly important. The configuration does not directly determine the characteristics of the sediments, but may fundamentally affect the processes that do.

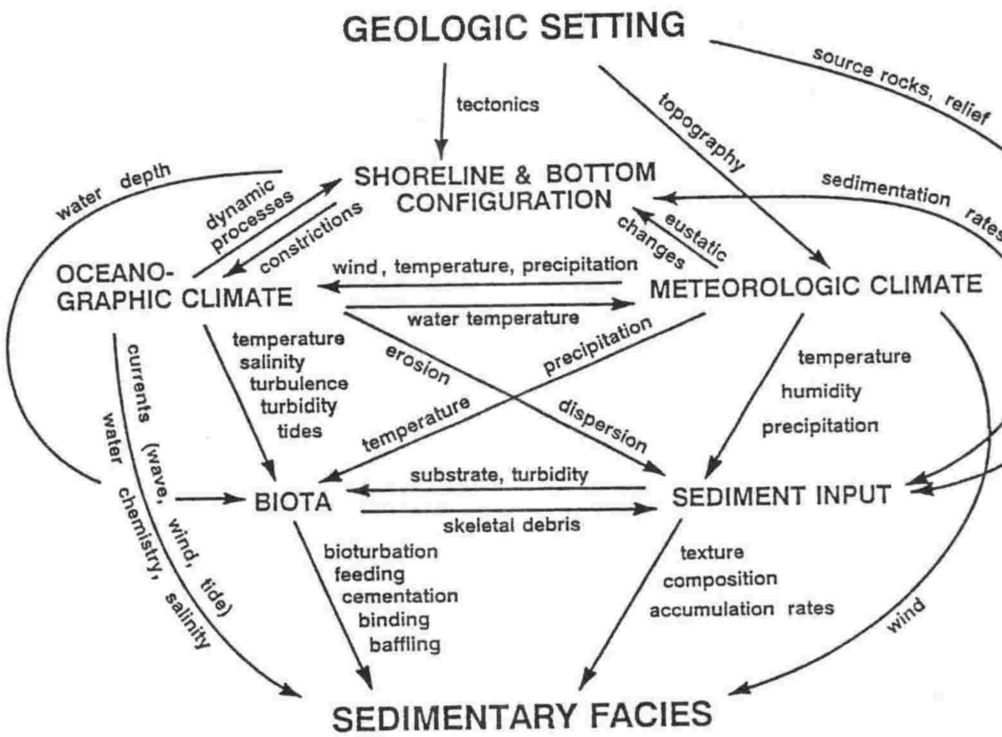



**Figure 2.1** Interrelationship of environmental factors and their control of coastal sedimentary facies (from Clifton and Hunter, 1982)

The rate at which modern sediment is supplied to a particular coastal environment, relative to the intensity and magnitude of processes of sedimentation, may determine the extent of development of facies elements. At a global scale input of modern river sediments to the continental shelf is thought to be negligible (Milliman and Meade, 1983). However, in some locations, including the Oregon inner shelf (Kulm et al., 1975) and South Otago inner shelf (Carter, 1986) sedimentation is significantly affected by fluvial inputs of modern sediment. At Pakiri, fluvial inputs at the coast are probably insignificant compared with the dimensions of the sediment body. Nor is there considered to be any significant alongshore transport of sediment, leaving onshore-offshore sediment transport as the most probable source of (non-biogenic) sediments. Under these circumstances facies elements of the Pakiri sediment body might be expected to more closely reflect contemporary processes of sedimentation. These may have persisted relatively unchanged since local sea level stillstand, ca. 6,500 years B.P. The situation is complicated however, because the nature of the surface sediments of the Pakiri Bay seabed prior to or immediately following sea level stillstand is not known.

## 2.2 Classification of Shoreface and Shelf Profiles and Sediments

Present-day shelf profiles and associated sediments are classified into six basic types (Figure 2.2). According to the dynamic transgressive-regressive model of shelf sedimentation proposed by Curray (1964, 1965) and Swift (1969, 1970) three main shelf facies are recognized. A shelf relict sand blanket comprising pre-Holocene deposits in disequilibrium with present day processes (Figure 2.2 A,B); a nearshore modern sand prism, comprising shoreline beaches, barriers and the shoreface (Figure 2.2 C); and the modern shelf mud blanket consisting of fine grained sediment which has by-passed the nearshore zone and been deposited on various parts of the shelf (Figure 2.2 D,E,F). Modern continental shelves may be further classified on the basis of shelf hydraulic regime, and the extent to which sediments are relict, palimpsest or modern (Swift, 1974). Three types of shelf are identified:- (1) Storm-dominated, palimpsest/relict sediment shelf (for example, Figure 2.2 B, Middle Atlantic Bight of North America); (2) tide-dominated, palimpsest sediment shelf (for example, Figure 2.2 D, NW European Shelf); and (3) storm-dominated, modern sediment shelf (for example, Figure 2.2 F, Niger Shelf).

Three further shelf types are widely identified (Johnson and Baldwin, 1986):- (4) Storm-dominated, palimpsest/modern sediment shelf (for example, Oregon-Washington Shelf); (5) storm-dominated, modern sediment, textually graded shelf (for example, southern Bering Sea, Figure 2.2 E); and (6) oceanic and current-dominated

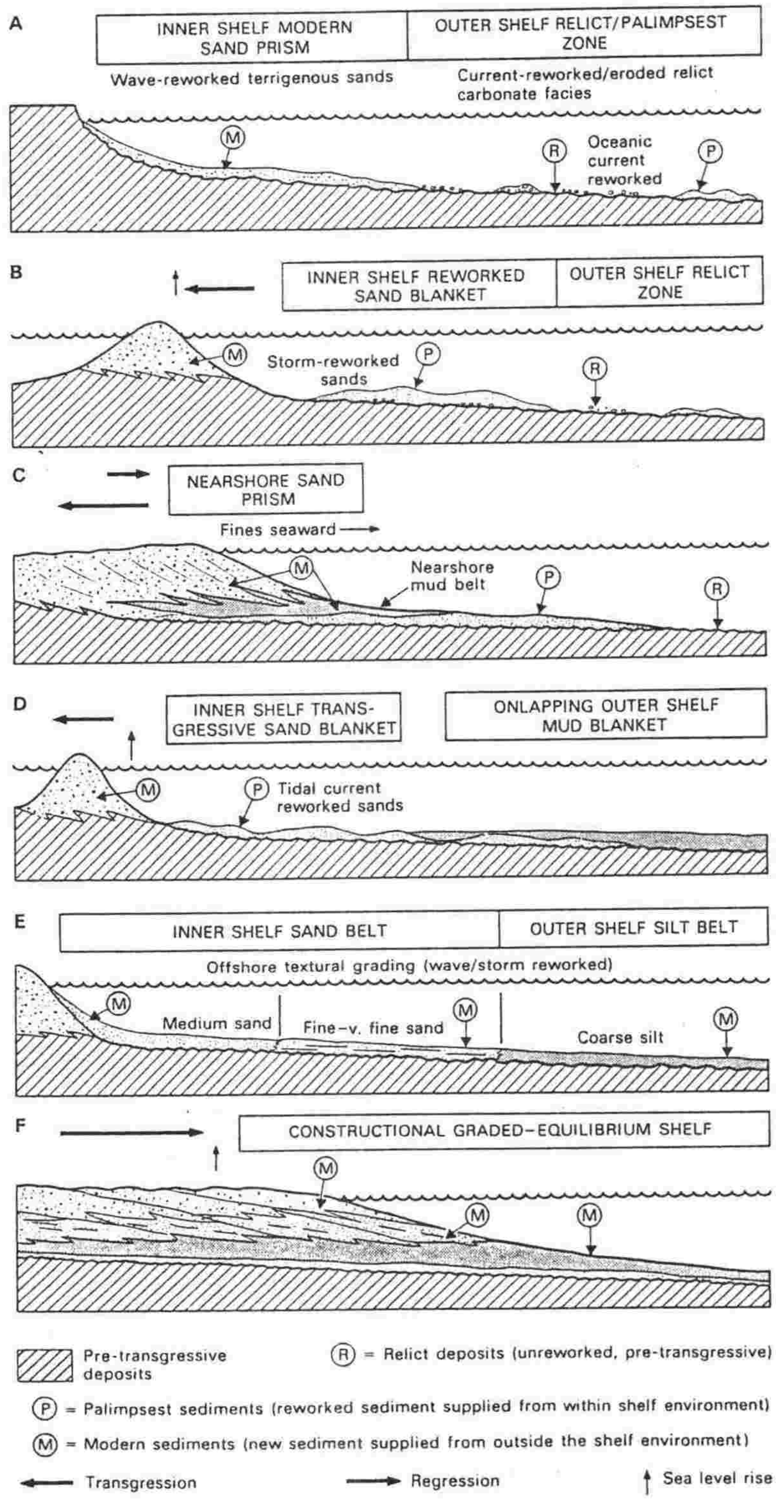



Figure 2.2 Interpretations of present-day shelf profiles and sediment covers (from Johnson and Baldwin, 1986)

palimpsest/modern sediment shelf (for example, SE African Shelf, Figure 2.2 A). Overall tide-dominated hydraulic regimes are thought to account for 17 percent of the worlds shelves, storm dominated for 80 percent and shelves dominated by intruding currents, 3 percent (Swift and Niedoroda, 1985).

Of these interpretations four are probably not applicable to the east coast of the Northland Peninsula, and the study area in particular. Interpretations B and D are representative of the depositional history on the relatively gently-sloping barrier coast and shelf of the Atlantic (U.S.) coast. Interpretation F is not consistent with the observation that most sandy coasts in New Zealand are either eroding or stable, and that instances of progradation in the remainder are mostly associated with harbour mouths (Gibb, 1979). The gently sloping bedrock configuration and the absence of inner barrier deposits renders interpretation C of unlikely relevance also. Interpretations A and E contain elements that are most consistent with the existing understanding, albeit incomplete, of sedimentation on the Hauraki Gulf shelf.

## 2.3 Concepts of Onshore-Offshore Sediment Transport

Few models of shoreface and continental shelf sediment transport have so far been proposed, and these are mostly empirical, derived from observations of particular coastal and shelf environments. Along exposed sandy coastlines most models predict a zone of wave-induced flows, resulting from the mass transport of water under shoaling waves near the coast. Further seaward the influence of oscillatory, gravity wave-induced flows diminishes with increasing water depth, and long period unidirectional flows become more important.

Swift (1976 b) recognizes three hydraulic zones. The zone of wave dominated flow extends from the water line to a depth, depending upon the wave climate, of about 10 m. The dominant fluid motion is oscillatory wave surge, and most other important water flows, such as rip and longshore currents, are driven partially or wholely by currents associated with shoaling and breaking waves (Bowen, 1969; Bowen and Inman, 1969). Water motions resulting in bottom shear stress sufficient to transport sediment are essentially continuous (Swift, 1982). Seaward of the outer margin of the wave-dominated zone extends a zone of low-frequency fluid motions. Currents are induced by the passage of the semi-diurnal tidal wave or by periods of prolonged wind stress and are more significant than high-frequency wave motions. Flow in this zone is thought to be primarily coast parallel, but onshore-offshore flows may result as a consequence of wind induced set-up or set-down of water against the coast. Further seaward is a zone of geostrophic flow. Flows in this zone are complex, but primarily the result of regional-scale oceanic water circulations.

The exponentially curved concave-upward form of the shoreface is interpreted by Swift (1982) to be an equilibrium response to the coastal hydraulic regime. The sandy sea floor erodes (or aggrades) to an ideal surface, whose depth at every point is that at which average wave orbital velocity is just sufficient to stir the available grade of sand. The ability of the shoreface surface to respond to the hydraulic regime demands that one portion of the profile be able to erode while another portion of the profile be able to aggrade. Swift (1982) states that if a given portion of the coast is a closed system, there must be a mechanism for shifting sediment onshore or offshore. If it is an open system then a change in the surface can be accomplished by means of a longshore gradient in sand discharge, such that more sand can be introduced into the coastal system than removed (or vice versa) by the steady stream of littoral drift and by the more intermittent tide or storm-driven sand transport (Figure 2.3).

## 2.4 Onshore-Offshore Sediment Transport by Storm Waves

Since Hayes (1967) study of the effect of Hurricanes Carla and Cindy on the Texas coast and shelf there has been interest in processes of

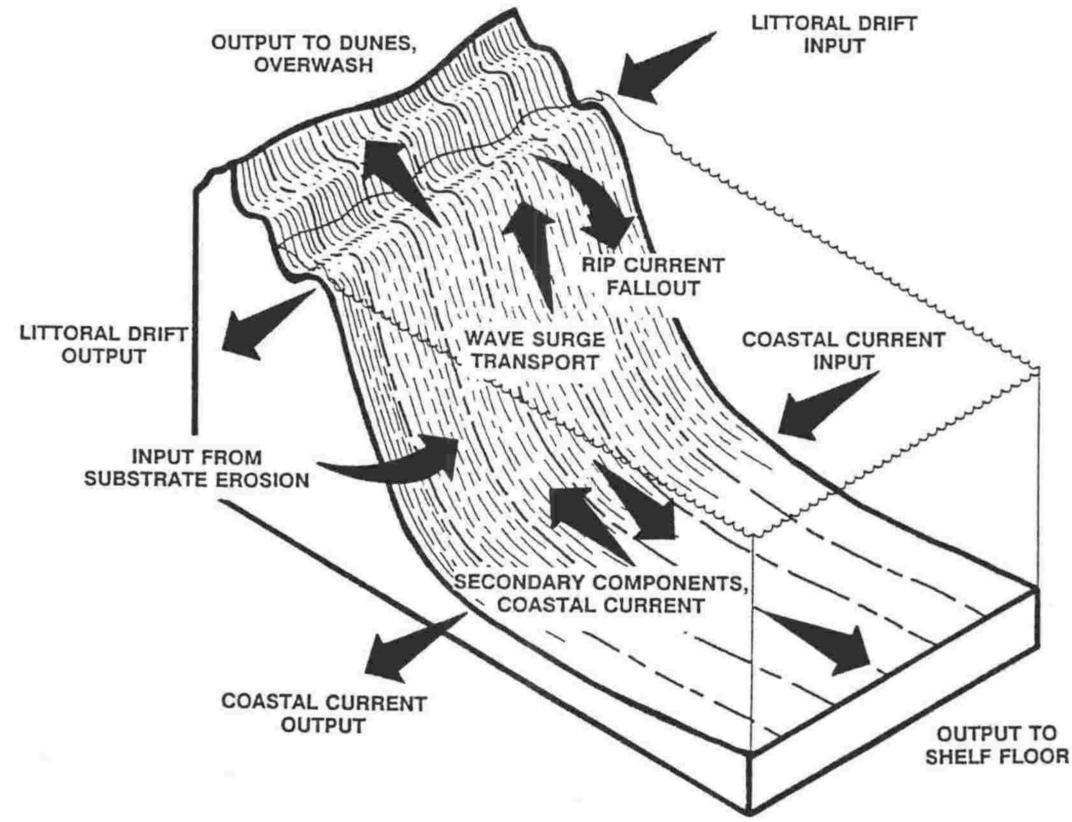



**Figure 2.3** Potential directions of sediment transport in response to onshore, offshore and alongshore coastal and shelf currents (from Swift, 1975)

marine sedimentation related to storm events, and in particular the potential for onshore-offshore sediment transport. Hayes suggested that during Hurricane Carla a density current had been generated which spread eroded sand from the barrier island across the shelf as a graded modern bed. Interpretations of modern shallow marine sedimentation have postulated the importance of storm related flows (Kumar and Sanders, 1976; Lavelle et al., 1978; Nelson, 1982; Swift et al., 1983; Cacchione et al., 1984; Swift, 1984).

Walker (1984) identifies wind-forced currents, relaxation (storm ebb surge) currents and turbidity currents as important storm processes. Measurements by Swift et al. (1979) and Swift and Field (1981) have shown near-bottom flow velocities, related to wind-forced currents, of up to about 60 cm $s^{-1}$ on the Atlantic Shelf in water depths of 10 to 20 m. Velocities of several tens of cm $s^{-1}$ occur several times per year as a result of northeasterly storms. These flows generate current ripples and megaripples, and also deposit abundant graded beds. During more catastrophic events, such as during Tropical Storm Delila (Forristall et al., 1977) and Hurricane Camille (Murray, 1970) flows exceeded 1 $ms^{-1}$.

Relaxation (storm surge ebb) currents are emphasized by Hayes (1967) and have been subsequently invoked in many geological interpretations (Walker, 1984) (for example, Kumar and Sanders, 1976; Brenchley et al., 1979). Nelson (1982) interprets recent marine sediments on the Bering Shelf as storm surge ebb deposits, and proposes a model of shallow marine sedimentation to explain graded sand layers in the Bering Sea. Turbidity currents have been proposed as a third mechanism by which sediment might be transported seaward across the shoreface and inner shelf. Walker (1984) states that they are simply a special case of density current, where the excess density of the flow is due to suspended sediment (rather than elevated salinities or reduced temperatures). However, although the phenomena is interpreted from the rock record (Walker and Hunter, 1982; Walker, 1985), it has not been reported from modern shelf environments (Walker, 1984), and the model remains speculative.

Gordon and Hoffman (1985) argue the importance of processes of sedimentation related to extreme storm events along the New South Wales Coast of Australia. Down-welling during storms is thought to result in offshore sediment movement. A similar mechanism is proposed by Field and Roy (1984) to explain the formation of sand bodies on the New South Wales Shelf. The surficial sand of the sediment bodies is commonly well-sorted and generally coarser than sand mantling the concave, active shoreface zone elsewhere along the eastern Australian Coast. The sand shows no seaward-fining trend across the surface of the sediment bodies except where it grades into the relatively finer sands of the upper inner shelf. These features are thought to result from an inner shelf depositional system dominated by offshore sand transport by currents generated during winter storms. Strong southeasterly winds would cause onshore transport of surface water, a temporary rise in sea level, and an offshore subsurface flow to maintain continuity. The sediment bodies may subsequently be modified by alongshore currents, but these are of secondary significance in the sediment body formation.

Niedoroda et al. (1984) have investigated bedload sediment transport across the shoreface along a wave-dominated sandy coast. During a typical north-east storm coastal down welling tends to result in net offshore bedload sediment transport. Offshore transport may extend over the entire shoreface and onto the inner shelf, in water depths greater than 25 m, 6000 m offshore. Deposition however, is concentrated on the upper shoreface, and only a small percentage of transport occurs over the lower shoreface and onto the inner shelf. During post-storm conditions some or all of the sediment may be transported back onshore, although this is not thought to occur seaward of the 15 m isobath under the influence of waves alone.

## 2.5 Onshore-Offshore Sediment Transport by Shoaling Waves

Onshore-offshore sand transport has been widely observed as a response to variations in wave energy. At short term time scales it is well documented that high, steep waves associated with storms tend to erode the beach and transport sediment offshore to form a longshore bar, which may in turn move onshore during the ensuing period of fair-weather swells (King, 1972). This cycle of onshore-offshore beach transport may be superimposed on a longer term cycle involving the entire shoreface. Moody (1964) has described the process whereby sand is carried beyond the bar by rip currents and deposited over the shoreface, with the result that over time the shoreface tends to aggrade toward the ideal wave-graded profile.

The steepening process is terminated by a major storm, during which time the gradient is reduced and a significant landward translation of the shoreline occurs.

Aside from these general relationships the response of a sandy bed to shoaling waves has remained problematic since Cornish (1898) proposed an hypothesis of asymmetric sediment thresholds under waves. The hypothesis states that the higher onshore velocities and shorter durations will move both large and small particles in the onshore direction, and that the lower offshore velocities will return only the finer material seaward. Because offshore velocities are of larger duration however, the process results in a net offshore movement of this fine material.

Subsequent work has involved the null-point hypothesis, which combines the forces due to current asymmetry with the downslope component of the gravitational force. Theoretical studies of the null-line hypothesis (see, Ippen and Eagleson, 1955; Eagleson and Dean, 1961) support Cornaglia's interpretation. However, field studies have yielded ambiguous or negative results (Zenkovich, 1967; Miller and Zeigler, 1958, 1964; Jago and Barusseau, 1981). Komar (1976) provides a detailed criticism of the hypothesis. He concludes that because it does not consider unidirectional currents, even those induced by waves, and because it probably over-rates the importance of the offshore gravity component acting on the grains, the null-point hypothesis is not a valid model for sediment transport under waves. For instance, no account is taken of the process of ripple sorting, or that a significant portion of shoreface sand travels not as bed load, but in suspension (Swift, 1976 a).

Shoreward movement of sand as bedload is predicted by existing wave theory. In deep water, where the wave motion is sinusoidal and there is no mass transport of water, the Airy linear wave theory yields near-bed velocities which are in reasonable agreement with observations. But as waves enter shallow water and approach their break point, they become asymmetrical with strong onshore velocities under the crests and weaker offshore velocities under the troughs. At this stage the Stokes second order wave theory predicts a mass transport of water in the direction of wave motion. The paths of water particles over one cycle are no longer closed loops. Near the sea floor, at a water depth of about one-half to one-quarter the deep water wavelength, the time-velocity asymmetry gives rise to a residual wave drift current toward the shore.

Other hypotheses have been proposed to account for sand movement under shoaling waves. Grant (1943) assumed that because of the theoretical inequality of onshore and offshore surge velocities all bottom sand should be transported toward the beach. A balance is maintained by seaward flowing rip currents laden with sediment. King (1972) argues that the asymmetry of shore normal currents would cause onshore transport if the grain transport threshold were only exceeded by the higher onshore velocities. However, if the magnitude of both onshore and offshore velocities were ever to exceed this threshold, then the longer duration of the offshore flows would result in a net offshore sediment movement. This latter condition should only occur under higher, steeper waves.

Field studies by Cook and Gorsline (1972) indicate that the seaward-fining grain-size gradients of the shoreface, predicted by the null-line hypothesis, are more likely to be caused by rip current fallout, rather than by the null-line mechanism. They considered that existing hypotheses of shore-normal sand transport resulting from oscillatory currents, of Grant (1943), the null-point hypothesis, and the diffusion model of Murray (1967), were based on dubious assumptions. Observations of sand transport on the California inner shelf indicated the conventional concept of wave drift is inadequate since a net transport of water frequently takes place towards the offshore. Seaward bottom drift was found to be associated with onshore winds and short period waves, while long period swells cause shoreward pulses to predominate. Further, they concluded that wave-generated currents do not sort fine sand but cause the entire grain population to migrate as a unit.

In conclusion, there is no readily applicable model with which to predict the response of the unconsolidated sediments on the shoreface and continental shelf to shoaling waves. Most discussion has been concerned with sediment transport on the beach, and hypotheses of sediment transport and textural differentiation are of undetermined relevance on the shoreface and continental shelf. However, these hypotheses reflect a general belief in the potential for orbital velocity asymmetries to initiate sediment entrainment and transport. There seems little subsequent agreement on the nature of the ensuing directions of sediment transport and sorting. The transport of large volumes of sediment on the continental shelf need not be explained solely in terms of short period (1-15 s) gravity waves where tidal, oceanic or other currents are weak. Boczar-Karakiewicz and Bona (1986) propose that long period (0.5-5.0 minutes) infragravity waves may contribute to the formation and mechanism of sand ridges on the North-American Atlantic shelf.

## 2.6 Investigations and Interpretations of Sediment Texture on the Shoreface and Continental Shelf

Investigations and interpretations of sediments in wave dominated marine environments have been reported from relatively few locations. Most notably the Pacific and Atlantic Coasts of North America, the Bering Sea and the east coast of Australia. Significant studies of shoreface and shelf sedimentology are also reported from Argentina (Parker _et_ _al_., 1982), South Africa (Flemming, 1980) and New Zealand (see Carter, 1975; Carter _et_ _al_., 1985).

Much early work involved investigations on the seabed off the Atlantic Coast of the North American continent. Stetson (1938), Gorsline (1963) and Pilkey and Frankenberg (1964) established the presence of a nearshore band of fine sediment flanked to seaward by coarser sediment. Sediments become gradually coarser over the shoreface and shelf offshore from the Georgia and South Carolina coasts. The boundary between the fine to medium sands of the nearshore and the medium to coarse sands of the shelf is considered by Bigham (1973) to represent the seaward boundary of the extent of modern sedimentation. This pattern differs somewhat from the sediment size distribution profile across the New Jersey shelf by Donahue et al. (1966). Except for a seaward fining to water depths of 25 m, 40 km offshore, no strong textural trend is reported. However, the median grain size of all the samples is in the range of fine sand (0.2 to 0.5 mm). Cook (1970) accounts for the fine, upper shoreface sand province as a mantle of rip current fallout, whose slope is adjusted by the regime of shoaling waves. However, the lower shoreface and shelf province of coarse variable sand does not fit the model of wave maintenance of the shoreface (Swift, 1976 a). The hypothesis is advanced that (instead) it is a response to the deeper, intermittent high-intensity flows of the zone of friction-dominated flow.

Three facies have been found to characterize the sedimentology of the Pacific Oregon shoreface and shelf of North America (Kulm et al., 1975). The inner shelf is mostly comprised of well-sorted, fine to very fine sand, extending to water depths between 50 and 90 m. Seaward of this facies the mid and outer continental shelf is mantled by a mud, and mixed sand and mud, facies respectively. The interpretation of this pattern entails marked seasonality in the delivery of voluminous quantities of fine sand to the coast. The sands of the inner shelf are thus considered modern, and responsive to the present shelf hydraulic regime, although the exact nature of sedimentation processes, and sediment dispersal within the inner shelf sand system, is not known.

Cacchione et al. (1984) describe a steep inner shelf zone off the California Coast, mantled by well-sorted sand which generally decreases in size in a seaward direction. The inner shelf comprises a wedge of fine sand that extends to the contact with the silty-sands of the central shelf, in water depths of 30 to 40 m. Rippled scour depressions on the inner shelf are thought to be induced by large waves and down-welling induced bottom currents. These offshore bottom currents are thought to erode the fine sands of the inner shelf along shore-normal depressions and transport them seaward. The spacing of the depressions may be influenced by bedrock outcrops on the inner shelf. The coarse sand of the depressions is then remolded into ripples by shoaling waves.

Work by Hunter et al. (1988) in Monterey Bay document a further example of the juxtaposition of coarse beach sands, a fine nearshore sand facies and a coarse lower shoreface or inner shelf sand facies. Bands of coarse sand that trend parallel to shore are described from water depths of 10 to 20 m, less than 1 km offshore. The coarse sands occur as rippled depressions and are of uncertain origin. Such occurrences of offshore coarse sediment are relatively common along the Oregon and California Coasts (Hunter et al., 1984).

Roy and Stephens (1980) and Roy and Crawford (1980) recognize four sediment facies offshore from the New South Wales coast to the middle continental shelf (Figure 2.4), a nearshore sand facies, comprising inner and outer types, inner shelf sand and mid shelf muddy-sand facies. The inner nearshore sand facies includes the beach and extends seaward of the beach to water depths of 4 to 12 m, and comprises medium to coarse-grained, moderately to well sorted, quartzose sands. The outer nearshore type consists of quartzose, fine grained, well sorted (unimodal) sands, extending to depths of 15 to 30 m. Both inner and outer nearshore sand facies occupy a zone of active reworking that corresponds to the seaward face of the coastal barriers. The inner shelf sand occupies the gently sloping inner shelf surface and extends seaward to depths of 50 to 60 m. The facies is characterized by iron stained, quartzose, medium to coarse grained, poorly sorted (polymodal) sands with some gravels. They therefore do not conform to the classical 'equilibrium' model of shelf sedimentation that predicts seaward-fining of sediments. Roy and Stephens (1980) interpret this facies as the result of modern reworking of relict deposits. Further seaward the middle continental shelf is mantled by dark grey, fine to very fine muddy sands. The relationship between sediments and morphology seaward of the surf zone is for nearshore sands to form a moderately steep, concave-up slope, across which grain sizes generally decrease seaward with increasing depth. This component corresponds to an active zone in dynamic semi-equilibrium with the local wave climate. Further seaward the inner shelf sands are considered palimpsest, forming a more gently-sloping planar surface. The relatively abrupt change in grain size between the fine outer nearshore sand and coarser inner shelf sand is interpreted as evidence that the latter are not a component of the modern coastal sediment budget.

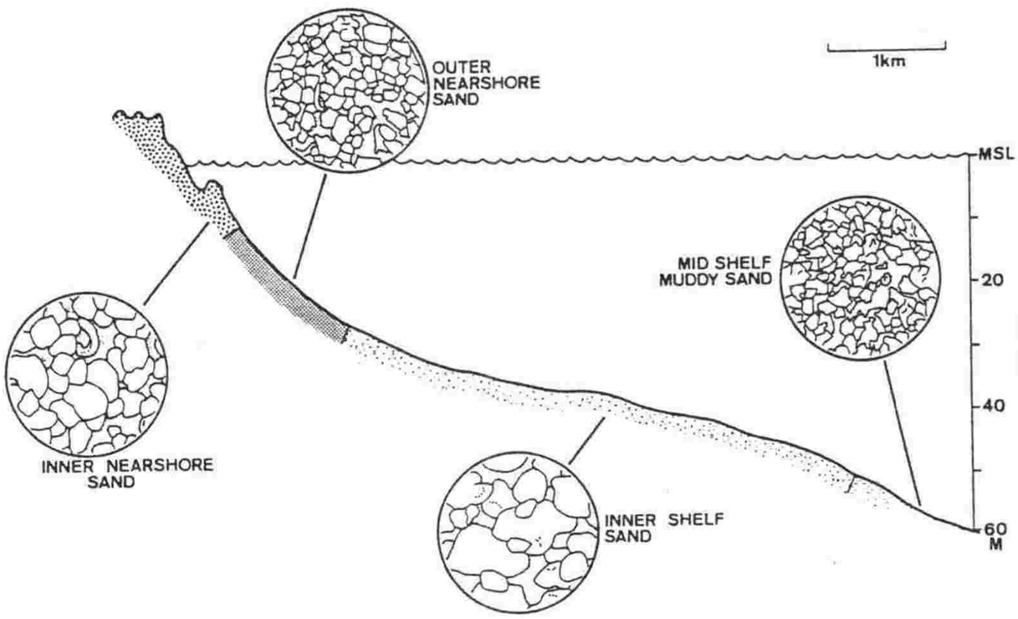



**Figure 2.4** Representative shoreface and continental shelf profile showing normal arrangement of inner nearshore, outer nearshore, inner shelf and mid shelf sediment types, New South Wales shelf (from Roy and Stephens, 1980).

The New South Wales model in particular may have implications for the interpretation of the facies elements of the Pakiri sediment body. The embayed east coasts of New South Wales and the Northland Peninsula share some characteristics, of which sediment supply, geology and (most probably) a similar Holocene sea level history are the most important. The following chapter presents the results of investigations of the sedimentology of the Pakiri sediment body. Textural criteria are employed to differentiate sediment types as an initial step towards the identification of facies elements. These allow comparisons to be made with the New South Wales and shoreface and continental shelf sediments described from elsewhere.

# Chapter 3

# SEDIMENT PATTERNS OF THE PAKIRI SHOREFACE AND CONTINENTAL SHELF

## 3.0 Introduction

This chapter reports an investigation of the textural characteristics of the surface sediments of the Pakiri Bay sediment body and adjoining middle continental shelf. The sampling strategy described below is based on an initial survey in 1984 (Hilton and McLean, 1984), in which a total of 90 samples were collected along 12 shore-normal transect lines, up to 8000 m offshore, between the Mangawhai Harbour entrance and Cape Rodney (Figure 3.1). Almost all the samples were well sorted sands, although mean grain sizes showed considerable variation within the sand class.

## 3.1 Sampling Strategy

The results of the preliminary survey pointed to an onshore-offshore pattern of variation in the grain size characteristics, and carbonate and mud content of the sediments. However, too few samples were obtained, over too large an area, to clarify the suggested patterns. A more sophisticated strategy was devised, based on seven equally spaced transects between Okakari Point, at the southern end of Pakiri Bay, and Te Arai Point at the northern margin. These transects are spaced about 2000 m apart, and were established in 1978 by the (then) Auckland Regional Authority.

The sampling strategy comprised two elements. The first entailed a one-off survey of textural variation between the coast and the middle continental shelf, the objective being to provide an instantaneous representation of the sediments of the study area. Sampling commenced as close to the beach as possible, usually

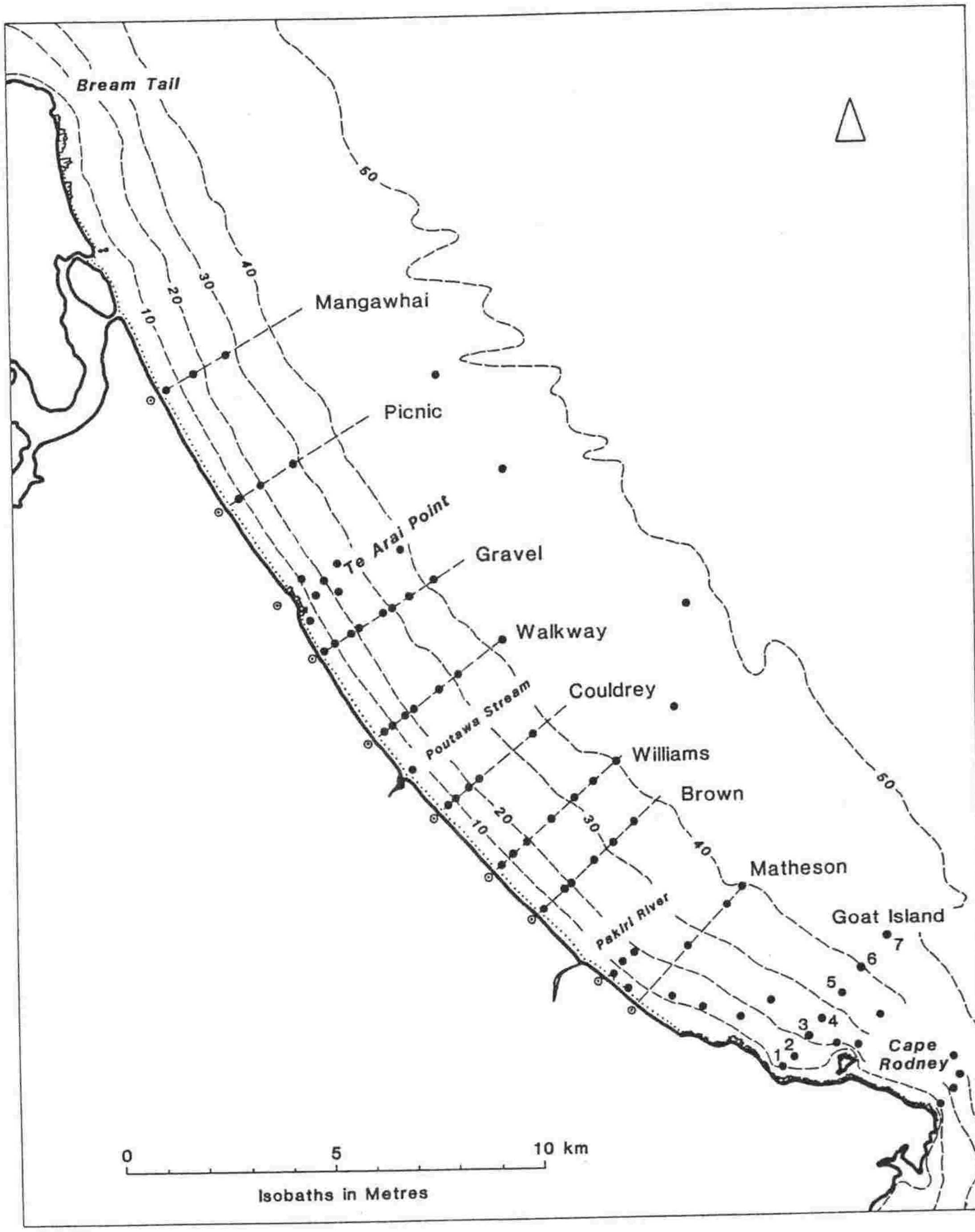



Figure 3.1 Location of samples obtained during initial survey of Pakiri Bay sediments (from Hilton and McLean, 1985)

landward of the crest of the alongshore bar, between 150 and 200 m from datum. Moving offshore samples were dredged at 90 m intervals for the first 800 m, then every 260 m thereafter. The closer initial spacing of sample stations reflects the relatively rapid change in bathymetry over the upper shoreface, and the desire to obtain samples from regular depth increments. Samples were located and extracted according to the methods and system of navigation described in Appendices A and B respectively. The total number of samples that could be extracted across each transect was constrained by the maximum able to be dredged in a single day by a crew of three using this method. In addition, beach samples were obtained every 600 m at high and low water levels. In total, 250 samples were collected and analyzed (Figure 3.2).

The second component of the sampling strategy involved the extraction and analysis of multiple samples from a selection of sample stations across a single transect. A total of 59 samples were obtained from 10 preselected stations across Williams transect over a 3 day period (Figure 3.2, Z-series samples). Stations were selected so as to represent the range of sediment types present in the study area. Each station was marked by a dan buoy and a maximum of eight samples were obtained from within an area of approximately 50 $m^2$ surrounding the buoy. This aim of this investigation was to determine whether the results of the one-off sampling programme, in which a single sample was obtained from each station at one time, accurately represents the range of sediments present, and to assess the natural variability in the sedimentology of the bed.

### 3.1.1 Sample Analysis and Interpretation

Sample analysis involves determination of grain size distributions (including and excluding carbonates), proportion of mud, proportion of carbonate material and composition of the samples, according to the standard procedures outlined in Appendix C.

An extensive literature discusses the environmental significance of grain size characteristics, and the various methodologies available to interpret and compare grain size distributions (see, for example, Folk and Ward, 1957; Friedman, 1961; Shepard and Young, 1961; Hand,

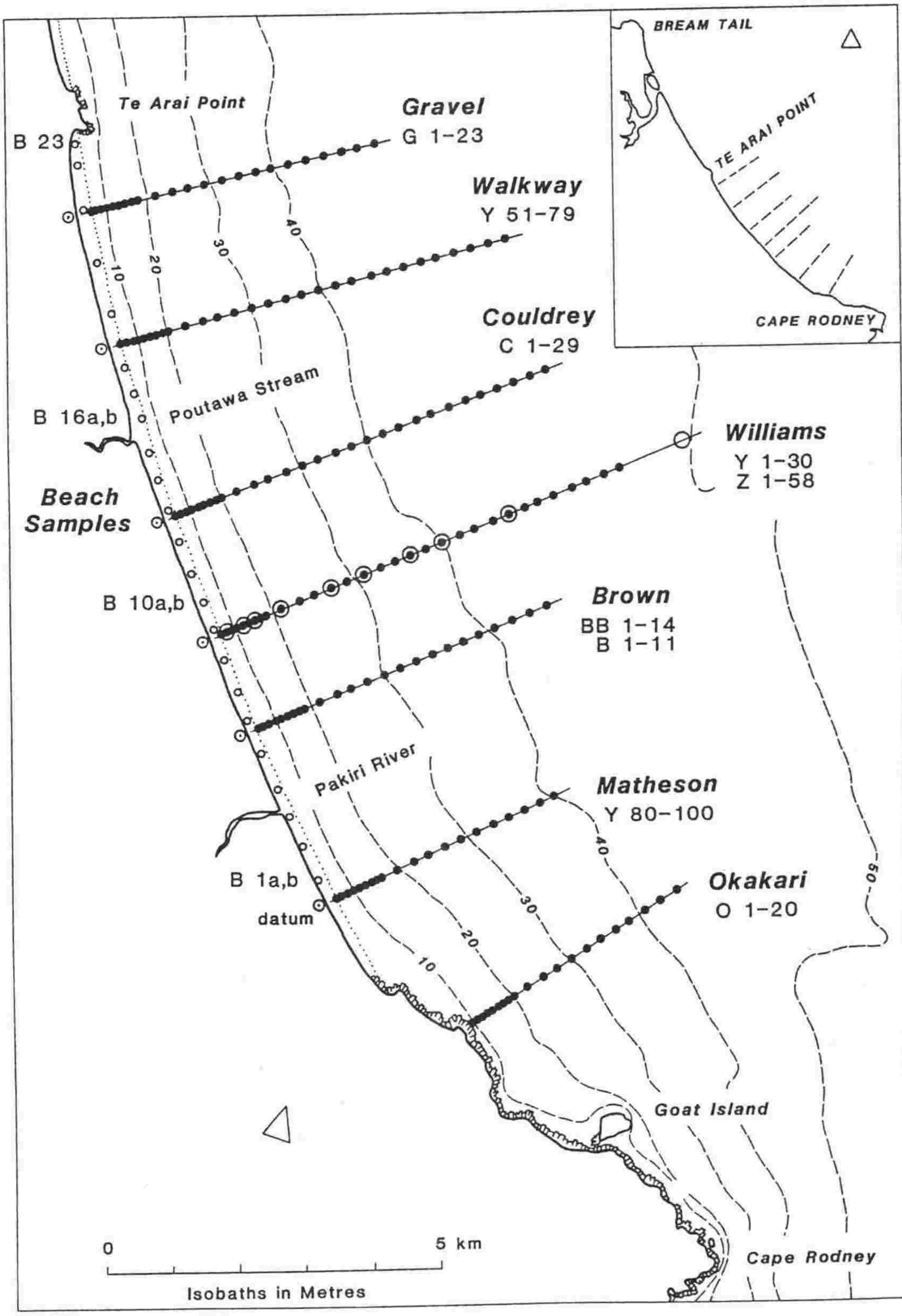



Figure 3.2 Location of Pakiri Bay beach and transect samples

1967; Visher, 1969 and El-Ella and Coleman, 1985). Statistical techniques involving factor analysis (for example, Klovan, 1966) and stepwise discriminant analysis (for example, El-Ella and Coleman, 1985) have been applied to sedimentological problems.

The techniques employed in the present study involve the visual interpretation of isoplots and scatterplots of summary statistics, and the visual analysis of graphic plots of raw grain size data. This approach is appropriate and effective because of the intensity of sampling and the nature of the variation in the sediments encountered. Mean grain size, sorting, percent fines and carbonate material results for all samples are tabulated in Appendix E.

## 3.2 Grain Size Characteristics of Beach, Shoreface and Continental Shelf Sediments

The results reported in the following sections are for the sand and coarser size grades, following removal of silt and clay finer than 4.0 $\phi$ (63 microns) and digestion of carbonate material. Grain size distributions of combined carbonate and non-carbonate materials are also described. Where results from the analysis of fines and carbonates are reported as percentages they refer to the proportion of the dry weight of the original untreated sample. Grain size determinations were derived using an automated rapid sediment analyzer (settling tube type device) as described in Appendix C, although some splits of samples from Gravel transect were sieved to allow a comparison of the two techniques (see Appendix C).

### 3.2.1 Variation in Mean Grain Size, Sorting and Fines

All samples obtained from the beach and seabed of Pakiri Bay are moderately to very well sorted sands, according to the Wentworth (1922) grain size scales. The mean grain size of these sediments varies between 0.0 $\phi$, very coarse sand, and 3.0 $\phi$, very fine sand. The mud content of the samples varies between 0 and 15 percent of the total weight.

These grain size variations are not haphazard within Pakiri Bay, but vary uniformly across the transects. This variation is exemplified by the results across Walkway transect (Figure 3.3). The sands of the inshore are slightly but consistently coarser ($M_Z$=1.7 $\phi$) than the medium to fine sands of the mid shoreface ($M_Z$=2.0 $\phi$), so there is a trend of initial fining offshore. The finer sands occur 800 to 1000 m offshore in water depths of about 15 m. Thereafter the sediments become progressively and uniformly coarser with increasing distance offshore. This trend culminates in deposits comprised mostly of very coarse sand, with some granules and pebbles, ($M_Z$=0.0 to 0.8 $\phi$) 3500 to 4000 m offshore, in water depths of 40 to 45 m. Immediately seaward of these very coarse sands the sedimentology of the bed is markedly different. In contrast to the sediments of the adjacent inner shelf, samples from the middle continental shelf are very fine sands. These sands are the finest in the study area, with mean grain sizes of about 2.5 $\phi$.

As the sediments coarsen offshore they become progressively less well sorted. The best sorted sediments (SD=0.35 $\phi$) are the fine sands ($M_Z$=2.0 $\phi$) of the upper shoreface, 200 to 1000 m offshore (Figure 3.3 a). The degree of sorting decreases offshore, with the least well-sorted sediments (SD=0.50 $\phi$), the very coarse sands and fine gravels at the base of the inner shelf. Seaward of this coarse material sorting improves, although the very fine sands of the mid shelf are still not as well sorted as the sands of the shoreface.

The textural transition from the very coarse sands of the lower inner shelf to the very fine sands of the middle continental shelf coincides with a relatively abrupt increase in the proportion of mud in the samples (Figure 3.3c). The proportion of mud (sediment less than 4 $\phi$) is essentially nil over the shoreface, and low (0 to 5 percent) over the inner continental shelf between water depths of 25 and 40 m. At the juncture between the inner shelf and the middle continental shelf however, the proportion of mud increases to between 10 and 15 percent.

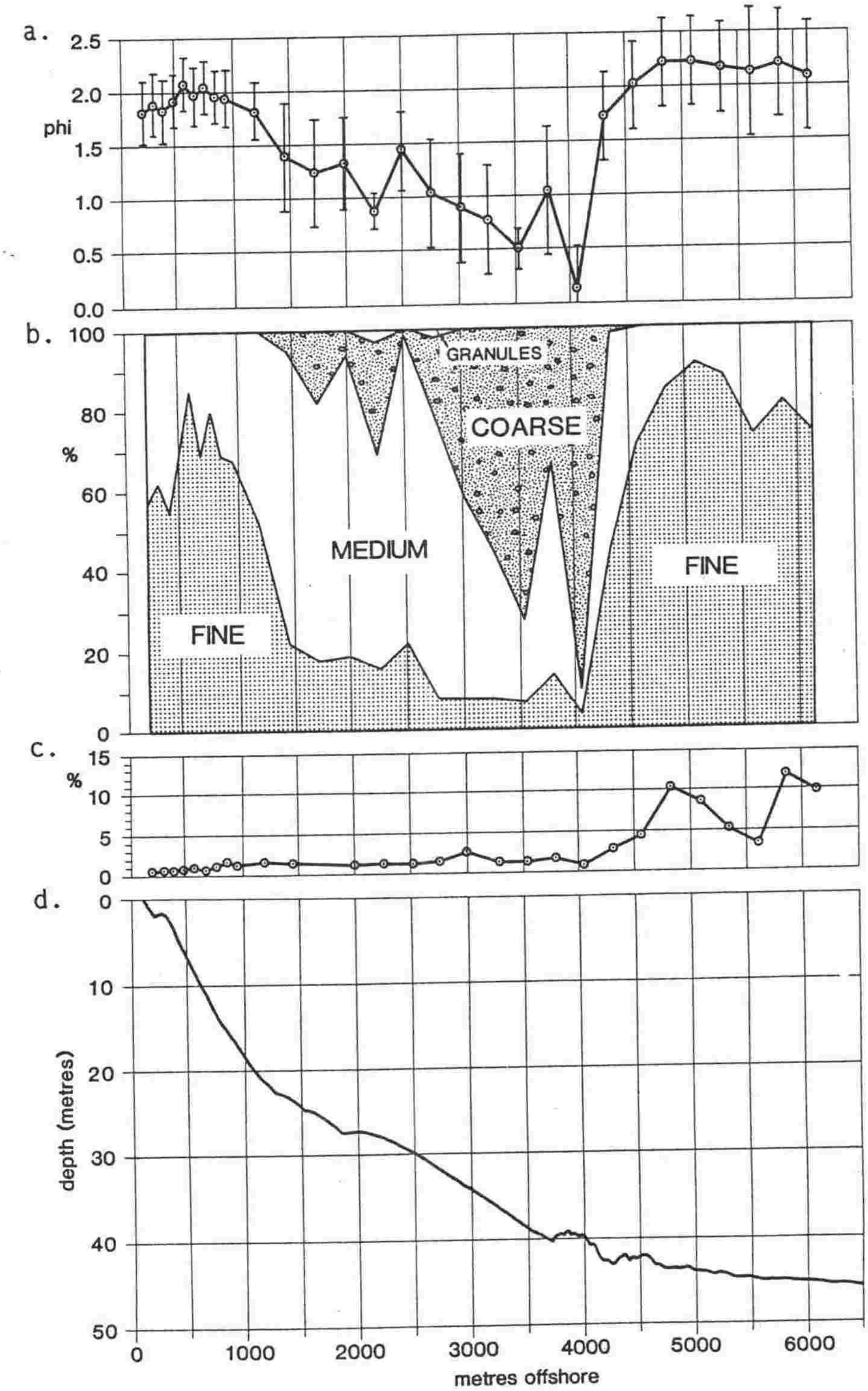



**Figure 3.3** Variation in (a) mean grain size and sorting (bars indicate standard deviations), (b) size grades and (c) percent mud across (d) Walkway profile.

The foreshore sands are coarser ($M_Z$=1.2 to 1.9 $\phi$) and less well sorted (SD=0.36 to 0.61 $\phi$) than the medium to fine, well sorted sands of either the upper shoreface or the coastal dunes. Schofield (1970) describes dune samples from along the Pakiri Coast as having median diameters around 0.25 mm, equating to about 2.0 $\phi$. Dune samples obtained during the present study (Appendix E) have mean grain sizes ranging between 1.1 and 2.1 $\phi$, with the average being 1.7 $\phi$. The standard deviation of these samples ranges from 0.22 to 0.47, with an average standard deviation of 0.34 $\phi$. The dune sands are therefore well to very well sorted, medium to fine sands.

With one exception the frequency distributions of all the 250 samples analyzed are unimodal. The nature and variation of the grain-size distributions across Williams Transect (Figure 3.4), is typical of the variation in Pakiri Bay. The distributions portrayed are representative of four, five, six or eight samples obtained at each of 10 stations across Williams Transect. The distributions tend to be near-symmetrical (Sk= -0.10 to +0.10) or fine skewed (Sk= 0.10 to 0.30), and mesokurtic (K= 0.90 to 1.11). The samples from towards the base of the inner shelf (sample Z49, for example) tend to be negatively skewed, indicating a dearth of fine sand. Samples from the mid shelf are weakly negatively skewed (Z53) and near symmetrical (Z56). In general the distributions tend to become more symmetrical across the inner shelf and shoreface, the most landward sample (Z5) being essentially symmetrical.

These data have implications for the interpretation of summary statistics, such as mean grain size ($M_Z$), and sorting (SD). For such statistics to have meaning the distributions from which they are derived must be normally distributed and not polymodal. Such is the case with the Pakiri sediments.

The pattern of grain size and sorting described is, more or less, characteristic of the variation across all seven Pakiri Bay transects (Figures 3.5 and 3.6). The range of values obtained varies somewhat from transect to transect, as does the location of the transition from the very coarse sands of the inner shelf and the

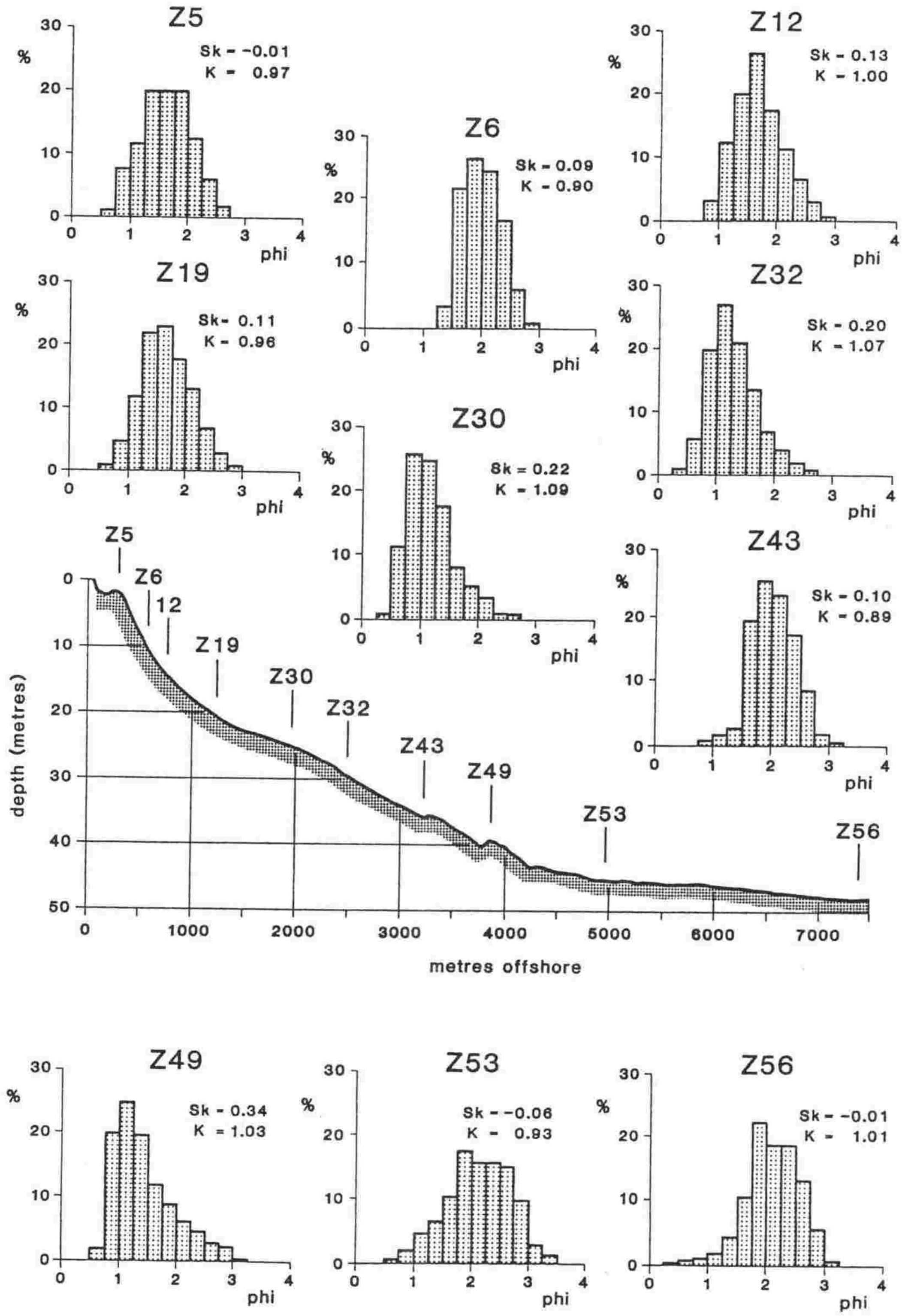
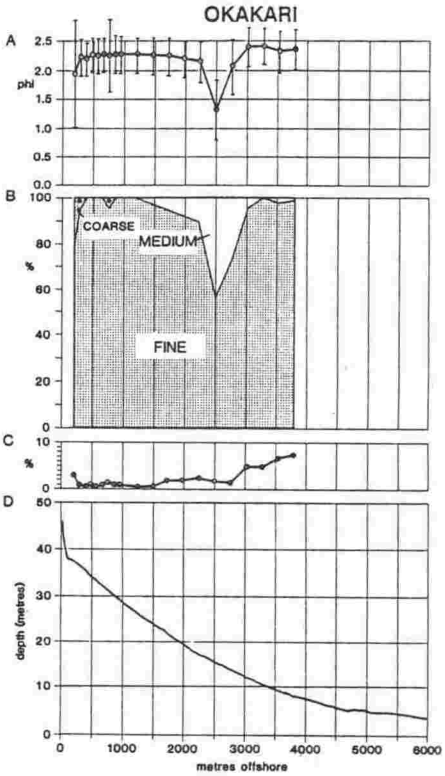
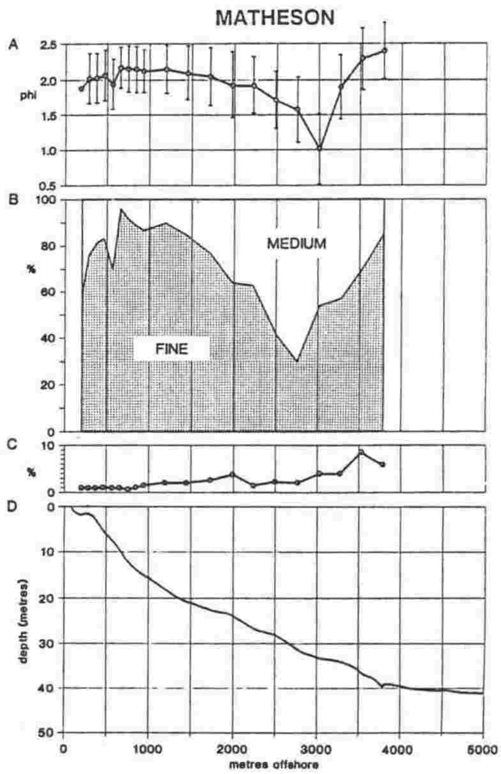
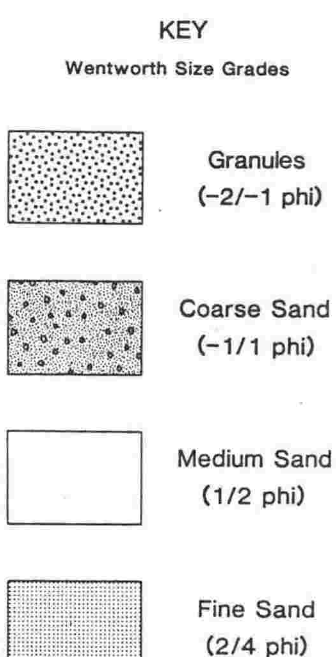



Figure 3.4 Representative grain size frequency distributions, Williams transect (samples Z 1-59)

Figure 3.5 Variation in (A) mean grain size, (B) sediment grades and (C) percent mud across (D) Okakari, Matheson and Brown transects


OKAKARI
A
phi
B
%
COARSE
MEDIUM
FINE
C
%
D
depth (metres)
metres offshore


MATHESON
A
phi
B
%
MEDIUM
FINE
C
%
D
depth (metres)
metres offshore


KEY
Wentworth Size Grades
Granules
(-2/-1 phi)
Coarse Sand
(-1/1 phi)
Medium Sand
(1/2 phi)
Fine Sand
(2/4 phi)

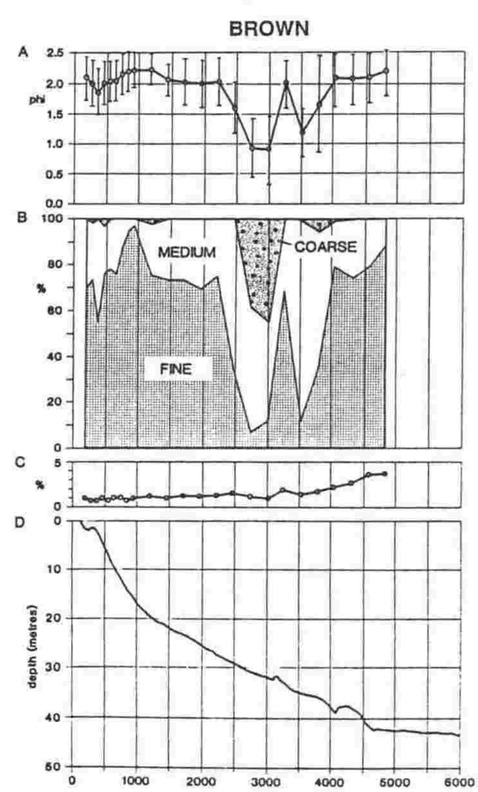
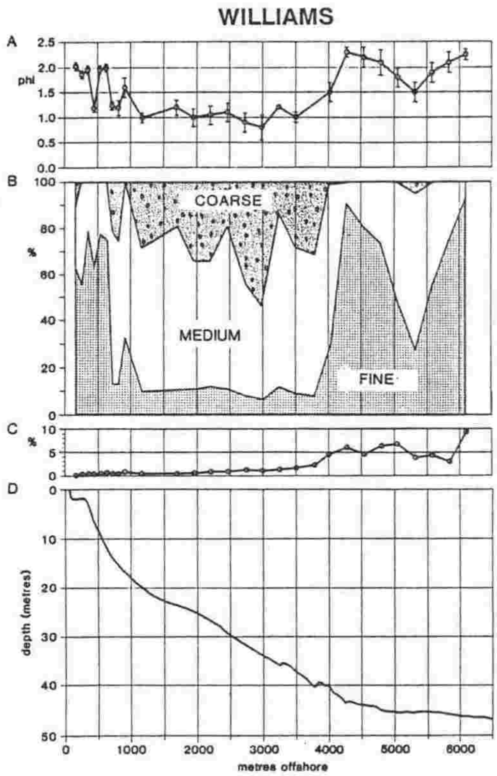
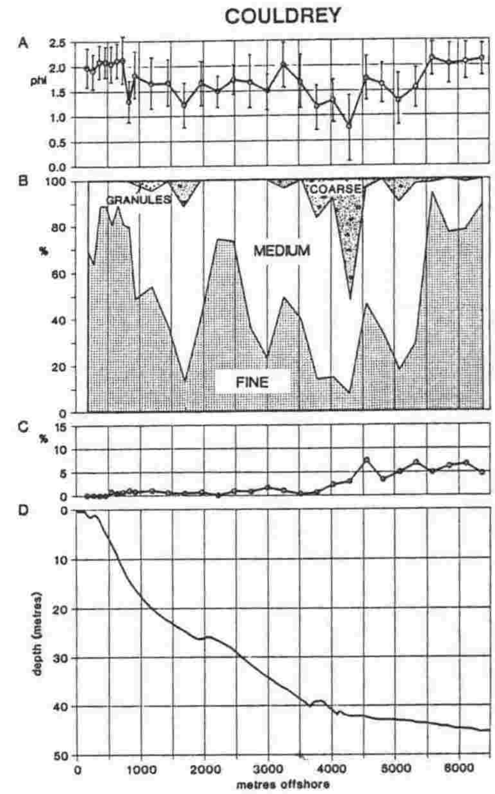
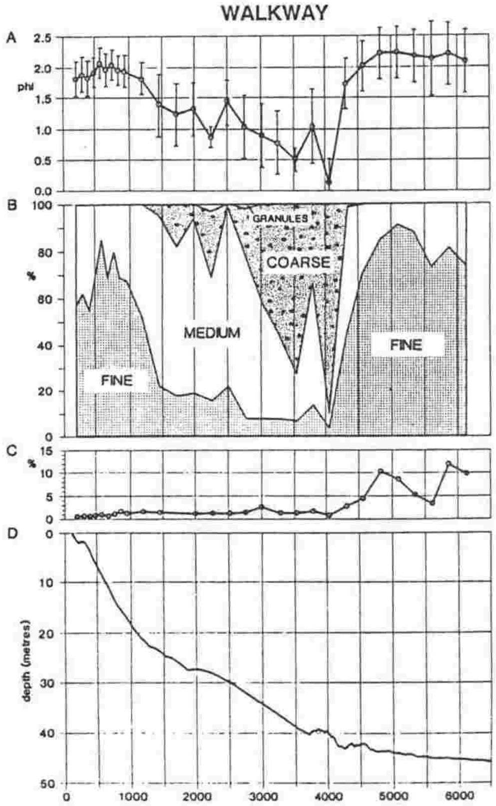
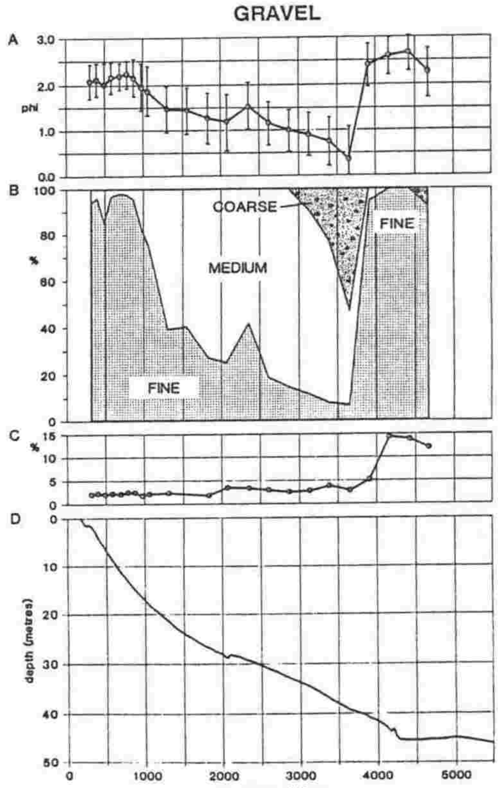

BROWN
A
phi
B
%
MEDIUM
COARSE
FINE
C
%
D
depth (metres)
metres offshore

Figure 3.6 Variation in (A) mean grain size, (B) size grades, (C) percent mud across (D) Williams, Couldrey, Walkway, Gravel transects.


WILLIAMS
A
B
C
D
phi
%
COARSE
MEDIUM
FINE
depth (metres)
metres offshore


COULDREY
A
B
C
D
phi
%
GRANULES
COARSE
MEDIUM
FINE
depth (metres)
metres offshore


WALKWAY
A
B
C
D
phi
%
GRANULES
COARSE
MEDIUM
FINE
depth (metres)
metres offshore


GRAVEL
A
B
C
D
phi
%
COARSE
MEDIUM
FINE
depth (metres)
metres offshore

very fine sands of the mid shelf. However, the major trends are evident across all transects. Minor variations are thought to be a function of the sampling strategy, as well as small scale, local variations in the sedimentology of the seabed. Such variations are investigated in the following section.

### 3.2.2 Intrastation Variations - Williams Transect

The transect results reported are based on a single sample obtained from each station on one occasion. This section describes the results of an analysis of multiple samples from fewer stations across a single transect. These data provide a means of determining whether the secondary variations about the onshore-offshore trends in grain size can be explained in terms of small scale, localized variations in bed sedimentology. Secondly, it provides a means of assessing the extent to which a single sample, single station approach, can provide an adequate assessment of grain size variations across the transects. The investigation also provides a means of supporting, or otherwise, the interpretation of the one-off transect data, since the samples were obtained 4 months prior to this survey. Results are presented as means of means, and the variance about the mean indicated by standard error bars.

Williams transect was chosen because of its medial position in Pakiri Bay, and because in terms of the strength of the morphological and sedimentological trends it is transitional between the three transects to the north (Couldrey, Gravel and Walkway) and the three to the south (Brown, Matheson and Okakari). In several respects then it represents the mean condition. The results (Figure 3.7) confirm the grain size trends outlined in the previous section (Figures 3.5 and 3.6). The intra-station variation in results is low relative to the inter-station variations, with a clear trend of offshore coarsening of sediment seaward of the lower shoreface and across the inner shelf. The magnitude of the standard error bars is, with the exception of samples Z44 to 49, insignificant. These results increase the level of confidence in the sampling design,

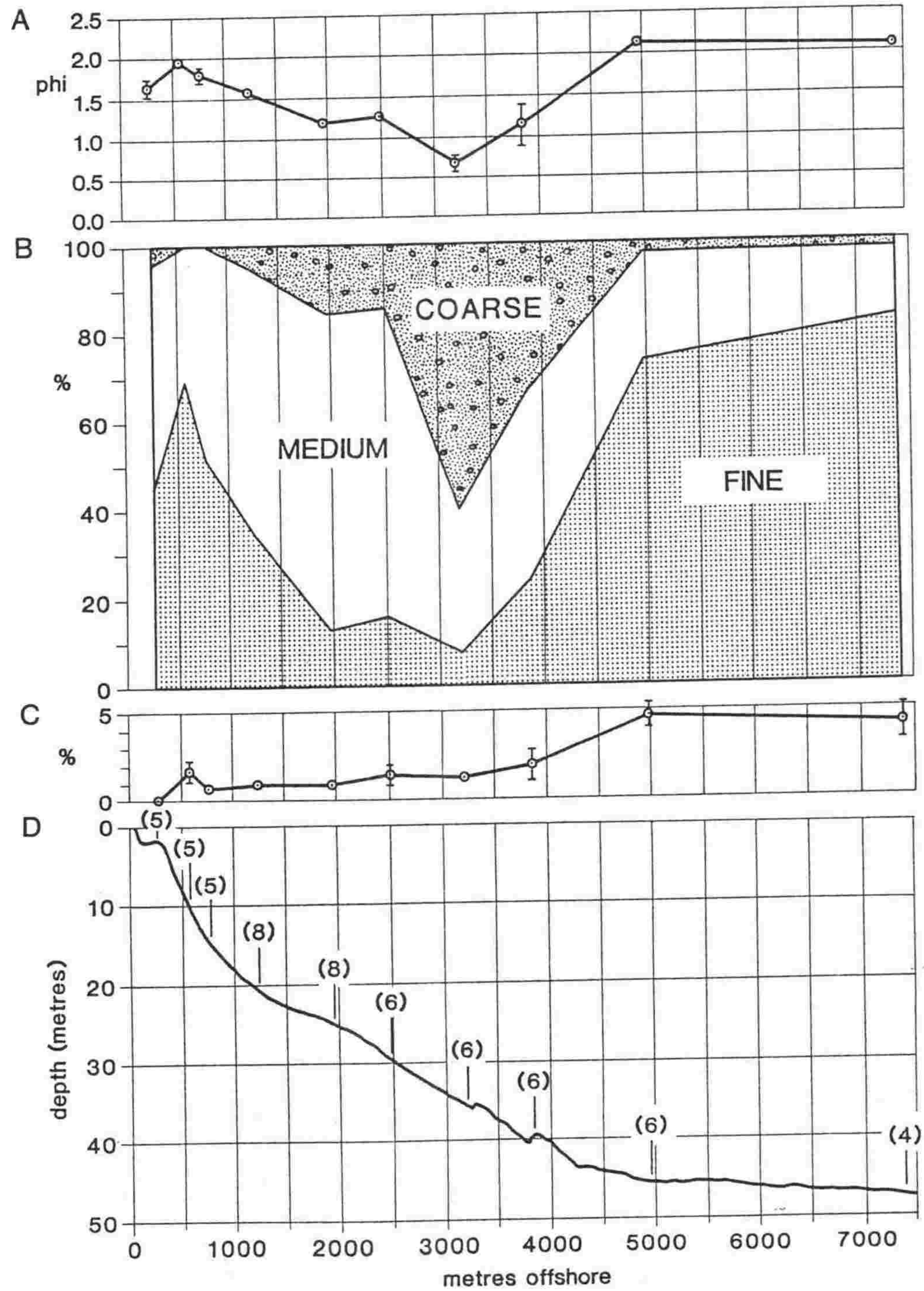



**Figure 3.7** Variation in (A) mean grain size, (B) sediment grades, (C) percent mud across (D) Williams transect. Variance about mean indicated by standard error bars.

based on single sample stations across shore-normal transects, as an appropriate strategy for the study.

Equally uniform trends in grain size variation across the transects would be attained if multiple samples were extracted from each sample station and the results averaged. That minor variations from the trend should occur, where only a single sample from each station is analyzed, is not overly surprizing. Small scale variations in sediment texture are associated with certain bedform configurations. For example, the crests of megaripples present on the inner shelf tend to be comprised of fine sands and the troughs coarse sands (Chapter Six). Variations in bed texture are also observed to result from the development of large scale bedforms on the mid shelf and at the juncture between the shoreface and the inner shelf.

### 3.2.3 Sediment Types and Morphological Associations

Scatterplots of the transect samples show that the shoreface, inner continental shelf and middle continental shelf sediments exhibit similar textural characteristics (Figure 3.8). Each sample is represented by its reference number, and plotted according to its mean grain size and standard deviation (as a measure of the degree of sorting). Lines enclose samples from the same environment. Samples from the shoreface, inner shelf and middle continental shelf are closely associated on the plots. Invariably the sediments from the shoreface and mid shelf are more closely grouped than those from the inner shelf, which display a wider range of mean grain sizes and standard deviations.

The scatter of points within each plot is greatest for the northern transects and least for the southern transects. In the case of the latter the groups overlap, and it becomes increasingly difficult to differentiate a particular sediment type. This is especially true of Okakari Transect (Figure 3.9) in which only samples from the middle continental shelf can be tentatively grouped. The one sample from adjacent to a subtidal rock platform contains gravel, and is

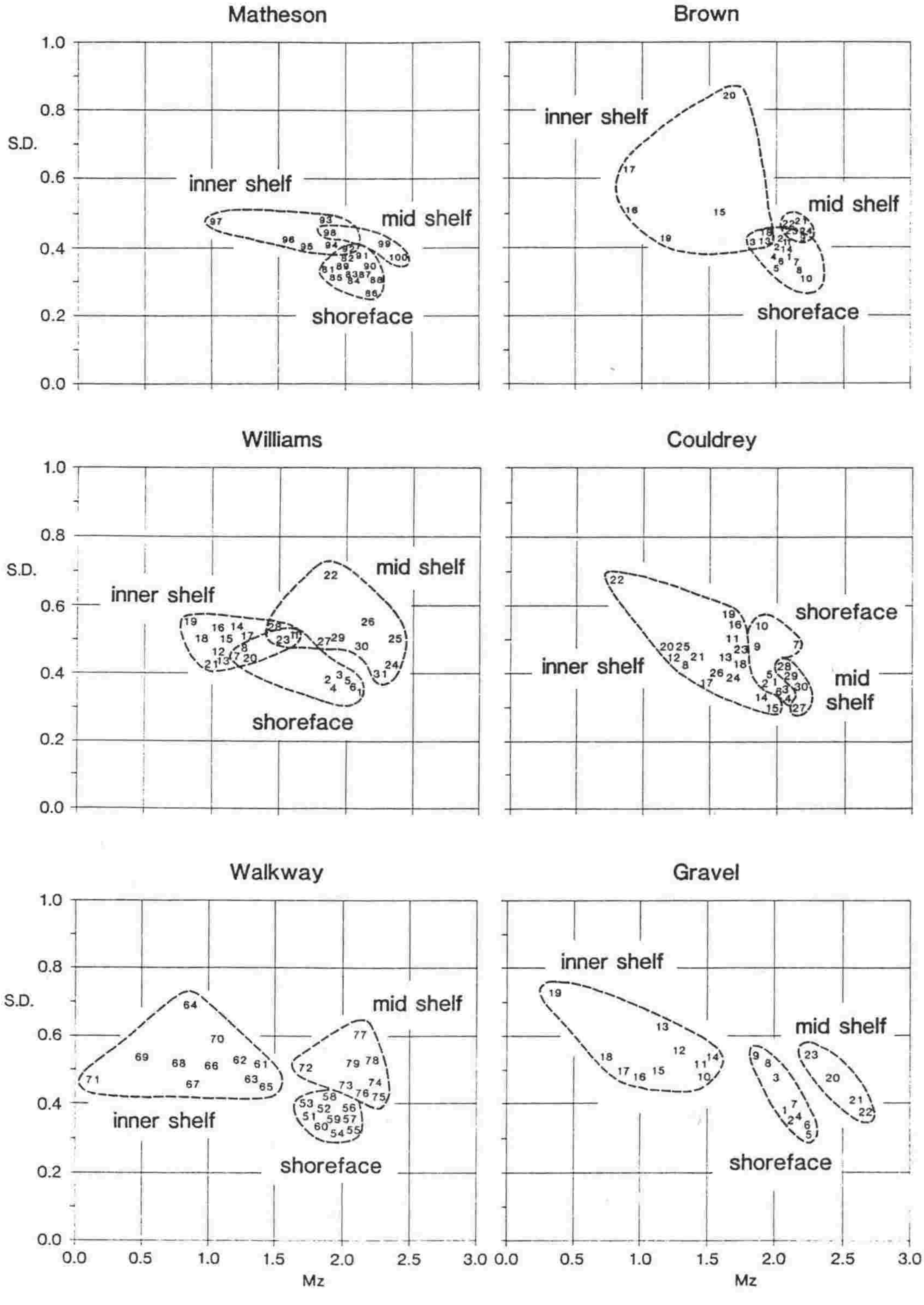



**Figure 3.8** Scatterplots of mean grain size against standard deviation (phi units), for shoreface, inner shelf and middle continental shelf sediments

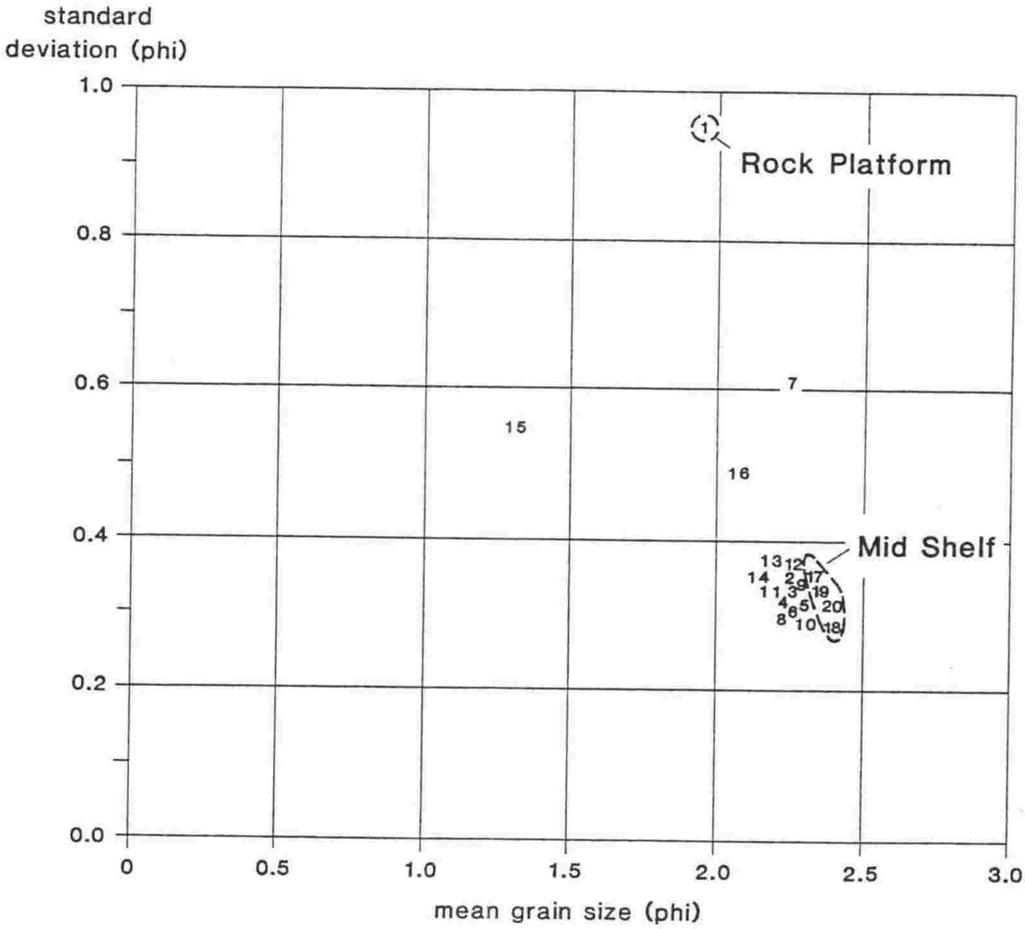


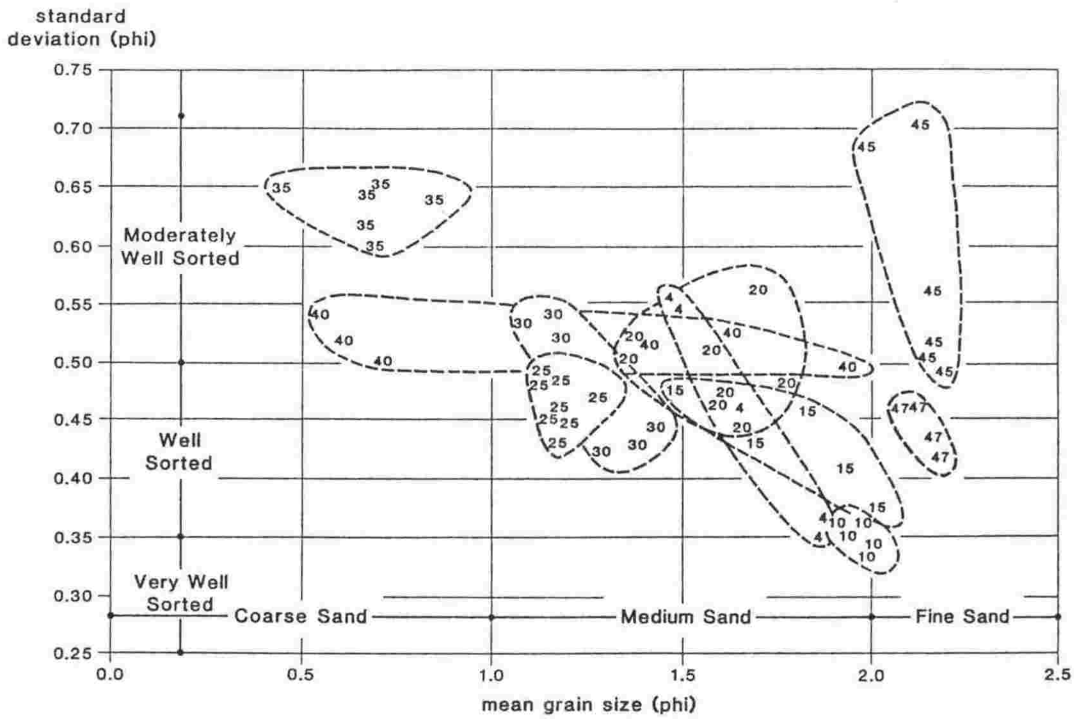

**Figure 3.9** Scatterplot of mean grain size against standard deviation (phi units), Okakari transect.

clearly anomalous. Comparable results are attained when multiple samples from individual stations are analyzed and the results plotted for depth stations across Williams transect (Figure 3.10 a,b).

There is a gradual transition between the sediments of the beach/inshore sediment type and the fine, very well sorted sands of the mid shoreface. A similar transition occurs between the shoreface sediment type and the medium to very coarse sands of the inner shelf type (Figure 3.11, samples 53, 57, 61). In contrast, the transition from the inner shelf sediments to the middle continental shelf sediments is abrupt. Adjacent samples on the

Figure 3.10 Scatterplots of mean grain size versus standard deviation, Williams transect, for (a) multiple samples (water depth increments) and (b) means of station means and standard deviations.

a.


standard
deviation (phi)
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
Moderately
Well Sorted
Well
Sorted
Very Well
Sorted
Coarse Sand
Medium Sand
Fine Sand
0.0
0.5
1.0
1.5
2.0
2.5
mean grain size (phi)

b.

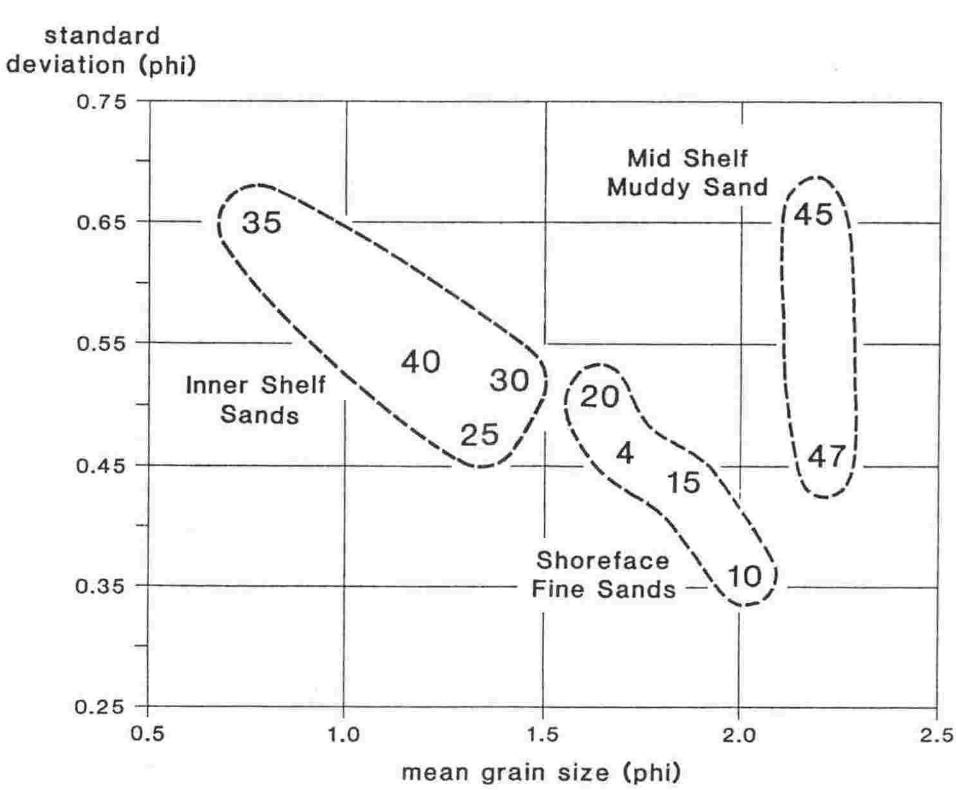
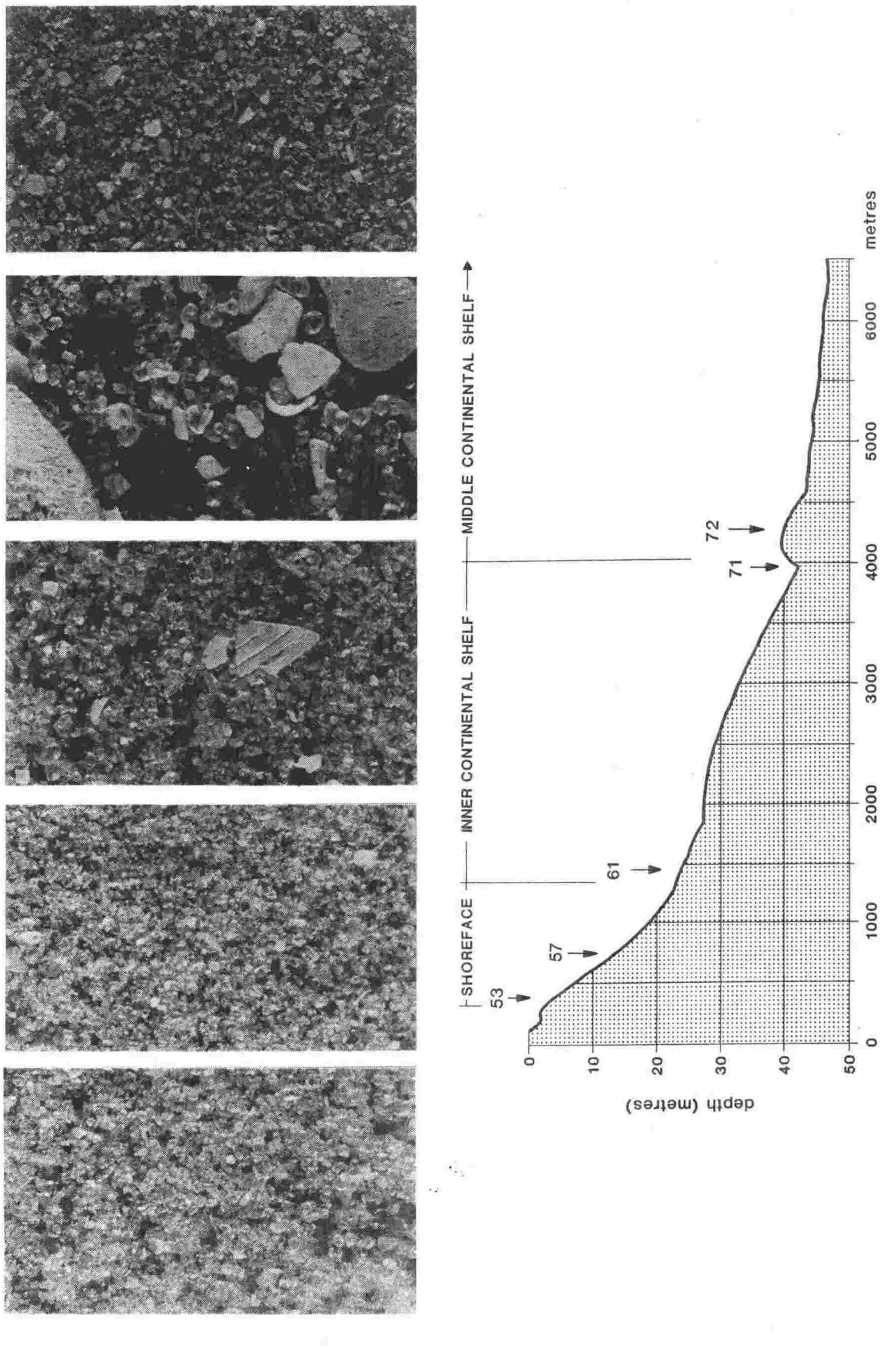

standard
deviation (phi)
0.75
0.65
0.55
0.45
0.35
0.25
Mid Shelf
Muddy Sand
45
47
35
40
30
25
Inner Shelf
Sands
20
4
15
10
Shoreface
Fine Sands
0.5
1.0
1.5
2.0
2.5
mean grain size (phi)

Figure 3.11 Photographs of sediment samples obtained from Walkway transect, illustrating the nature of the transition across the textural boundaries that delineate the shoreface, inner shelf and middle continental shelf sediment types (photoscale x3.5).


53
57
61
72
74
SHOREFACE
INNER CONTINENTAL SHELF
MIDDLE CONTINENTAL SHELF
depth (metres)
0
10
20
30
40
50
0
1000
2000
3000
4000
5000
6000
metres
53
57
61
71
72

profiles are very coarse sands/fine gravels and very fine, muddy sands, respectively (Figure 3.11, samples 71 and 72).

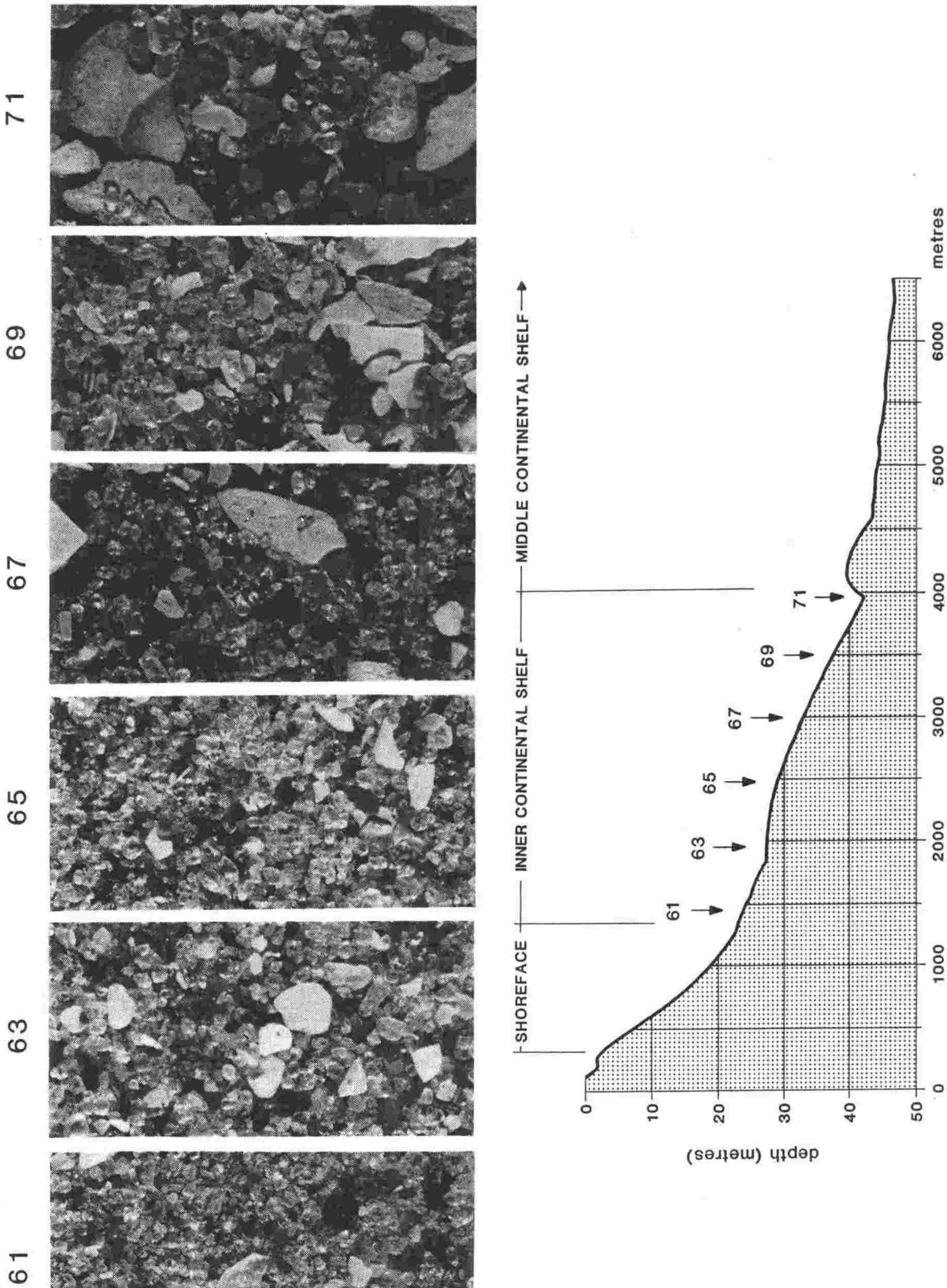
The degree of homogeneity within each sediment class also shows some variation. Although generally very fine sands the mean grain size of samples from the mid shelf may vary more than 0.5 phi. Such variations are usually accompanied by a decrease in mud content. The most striking variations however, are associated with the graded bed of the inner shelf. A typical shore-normal sequence of samples shows a regular offshore increase in the mean grain size of particles, between the fine sands of the shoreface to the very coarse sands and fine gravels of the (lower) inner shelf (Figure 3.12, samples 61 to 71).

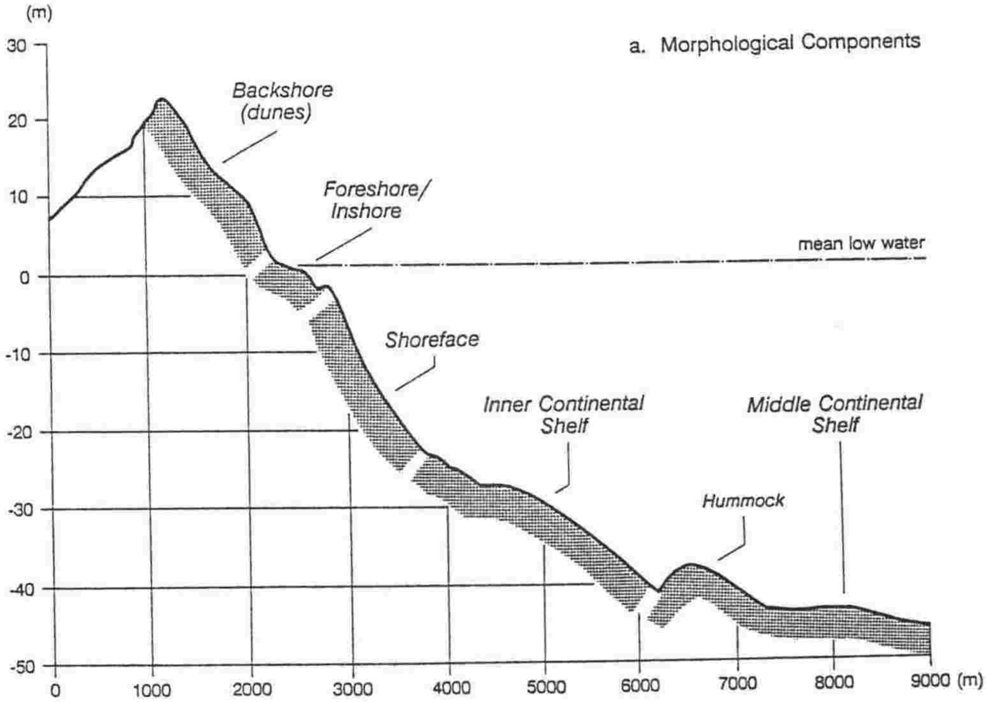
In summary, the sediments of the study area are interpreted as belonging to one of five sediment types. The two coastal types comprise the sediments of the coastal dunes and foreshore-inshore environments. The textural distinction between these and the sediments of the shoreface is subtle, although the latter are always better sorted and finer. The boundaries of the sediment types of Pakiri Bay correspond to changes in slope across the shore-normal profiles that delineate the boundaries between the major morphologic components of Pakiri Bay - the shoreface, inner continental shelf and the middle continental shelf. These sedimentological and morphological associations are summarized in Table 3.1, and portrayed diagrammatically for all sediment types identified in the study area in Figure 3.13. Okakari transect, the major exception to this pattern, is discussed in section 3.2.5.

### 3.2.4 Interpretation of Raw Grain Size Data

Summary statistics of the grain size frequency distributions are used above to distinguish three sediment types in Pakiri Bay. The variations in raw grain size data provide added justification for the divisions. The data presented in the present section is based on the analysis of multiple samples from Williams transect, and is

**Figure 3.12** Photographs of sediment samples obtained from across the inner continental shelf component of the subtidal sediment body, Walkway transect, showing pattern of increasing grain size with increasing distance from shore - Walkway transect (photoscale x3.5)


61
63
65
67
69
71
SHOREFACE
INNER CONTINENTAL SHELF
MIDDLE CONTINENTAL SHELF
depth (metres)
metres
0
10
20
30
40
50
1000
2000
3000
4000
5000
6000



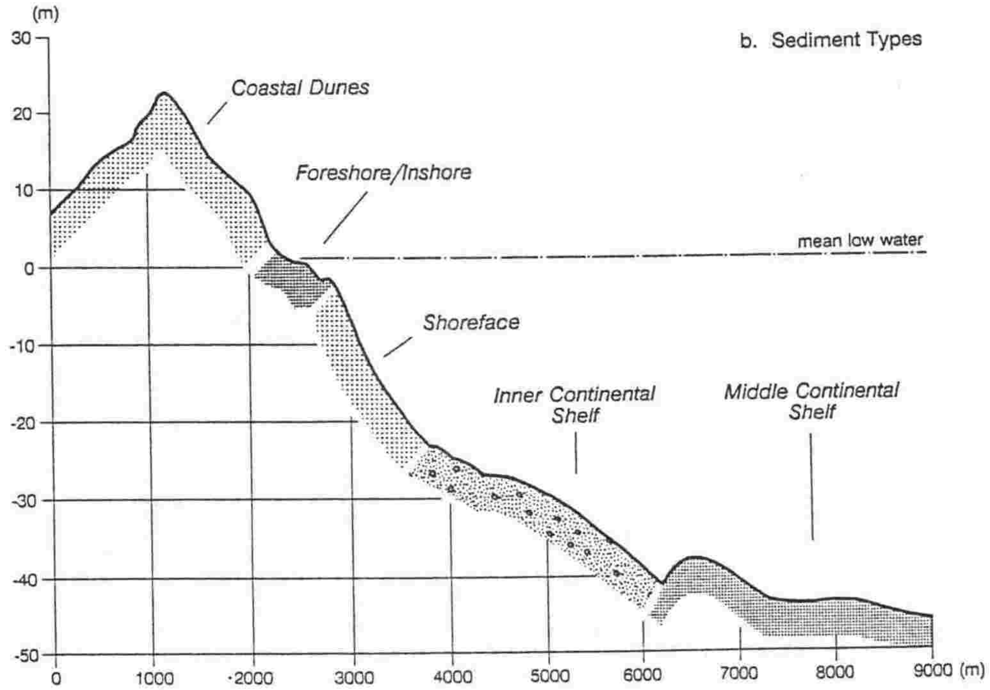




**Figure 3.13** Interpretation of (a) morphological components and (b) sediment types across a representative coastal and offshore transect, Pakiri Bay.

Table 3.1 Association Between Morphologic Components and Sediment Types

| Morphological Component | Geometry | Distance Offshore (m) | Water Depth (m) | Dominant Size Grade | Percent Fines |
|---|---|---|---|---|---|
| Shoreface | Concave | 250-1250 | 3-25 | Fine Sand | 0-1 |
| Inner Shelf | Convex | 1250-4000 | 25-40 | Medium to Very Coarse Sand | 1-5 |
| Middle Continental Shelf | Planar | 4000- | 40- | Very Fine Sand | 5-15 |

considered representative of the transect results generally (Figure 3.14). The differences between the sediment types interpreted are not just a result of differences in the relative proportion of sediment present in each phi size fraction. Rather the differences are due to the complete absence or presence of phi fractions at the extremes of the sand size grades. For example, 0.0 and 0.5 $\phi$ fractions are present only on the inner shelf, and 3.0 $\phi$ sand only on the mid shelf. The graded bed of the inner shelf results from the decrease onshore of the proportion of coarser sediment in the samples and commensurate increase in the proportion of fine sediment. As a result concentrations of 0.0 $\phi$ sand, for example, are greatest 3250 m offshore, whereas 1.0 $\phi$ sand peaks 2000 m offshore.

### 3.2.5 Alongshore Variation in Grain Size Characteristics

Figure 3.13 summarizes shore-normal variations in the morphology and sedimentology of the Pakiri sediment body. Relatively minor departures from this pattern occur as differences in the range of grain sizes present across each transect, and in the degree of concordance between the boundaries of the morphological units and

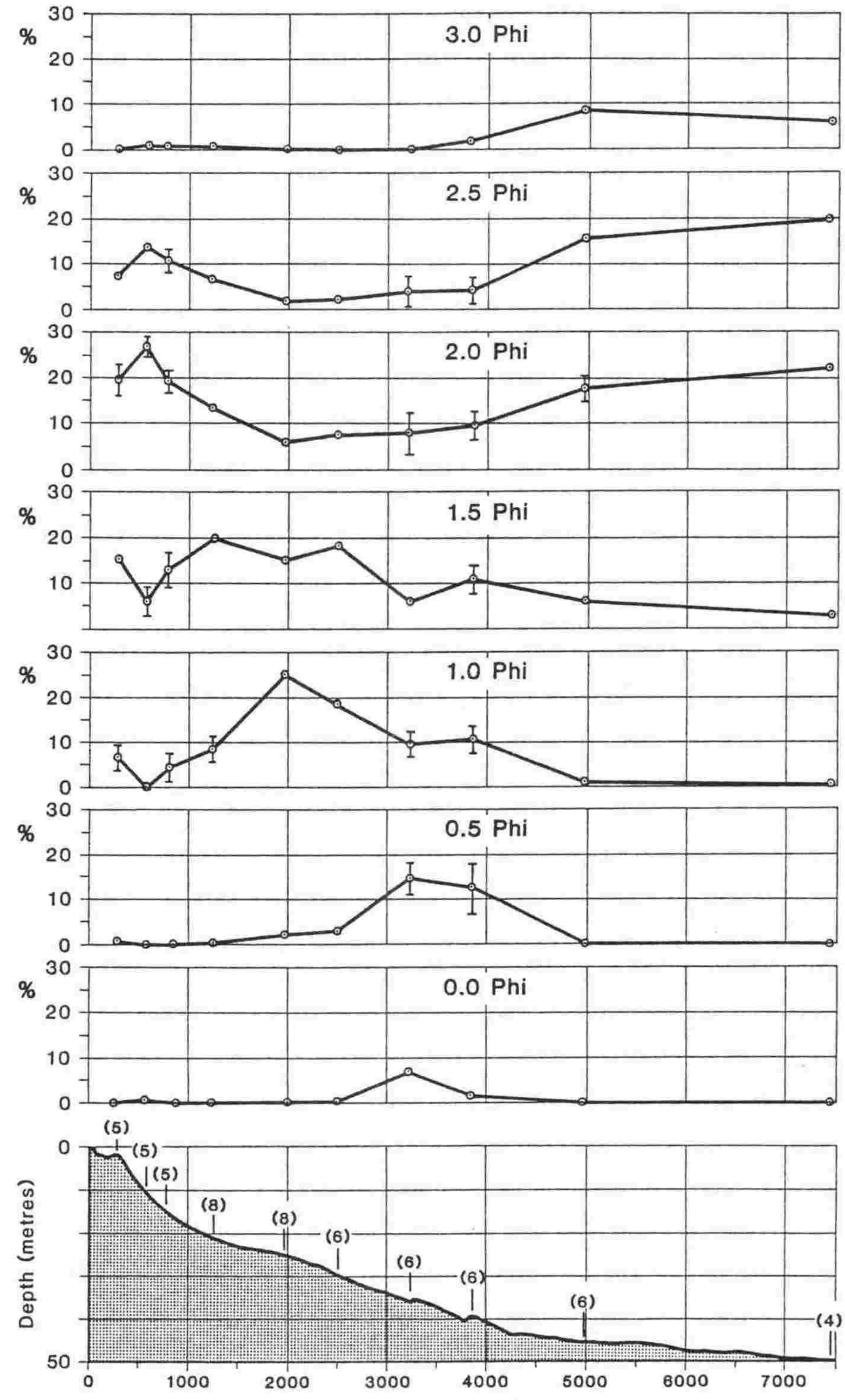



**Figure 3.14** Variation in the percent weight of sediment present in 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 phi fractions, Williams transect (variance about means indicated by standard error bars)

the sediment classes. In general these patterns are best developed across the northern transects and least well developed along the southern transects, though generally still evident. Possible causes of these differences are discussed in Chapter Seven.

The range of grain sizes present in the transect samples decreases from north (Gravel transect) to south (Okakari transect), although there is no comparable trend in sorting. Gravel, Walkway, Couldrey, Williams, Brown, Matheson and Okakari transects have ranges of 2.50, 2.30, 1.80, 1.65, 1.55, 1.50 and 1.10 $\phi$ respectively.

Isoplots of mean grain size (Figure 3.15), standard deviation (Figure 3.16) and mud concentration (Figure 3.17) exhibit some alongshore variability. In general however, the variation is predominantly onshore-offshore. It is suggested, given the results of the multiple sampling exercise, that most of the alongshore variation evident in these diagrams is an artifact of the one-off sampling technique, and that repeated and/or multiple sampling across each transect would yield uniform alongshore results.

Variations from the typical transect results are too pronounced across the three southern transects to be due solely to sampling error however. In the case of Brown transect (Figure 3.5) the transition from the very coarse sands of the (lower) inner shelf to the very fine, muddy sands of the mid shelf does not occur at the morphological break between the inner shelf and the mid shelf. However, the situation is complicated by the presence of large-scale bedforms, comprised of mid shelf sands, located on the lower slopes of the inner shelf. These features are discussed in Chapter Five.

In the case of Okakari Point the general pattern of onshore-offshore grain size variation is the same, with a pattern of fine sands close to shore grading into a coarser sediment, and then an abrupt change to a much finer, muddy sand (Figure 3.18). However, there are also significant differences. The range in grain sizes present is much less than observed over transects to the north, with sediment in the coarse sand grades almost completely absent. The morphologic

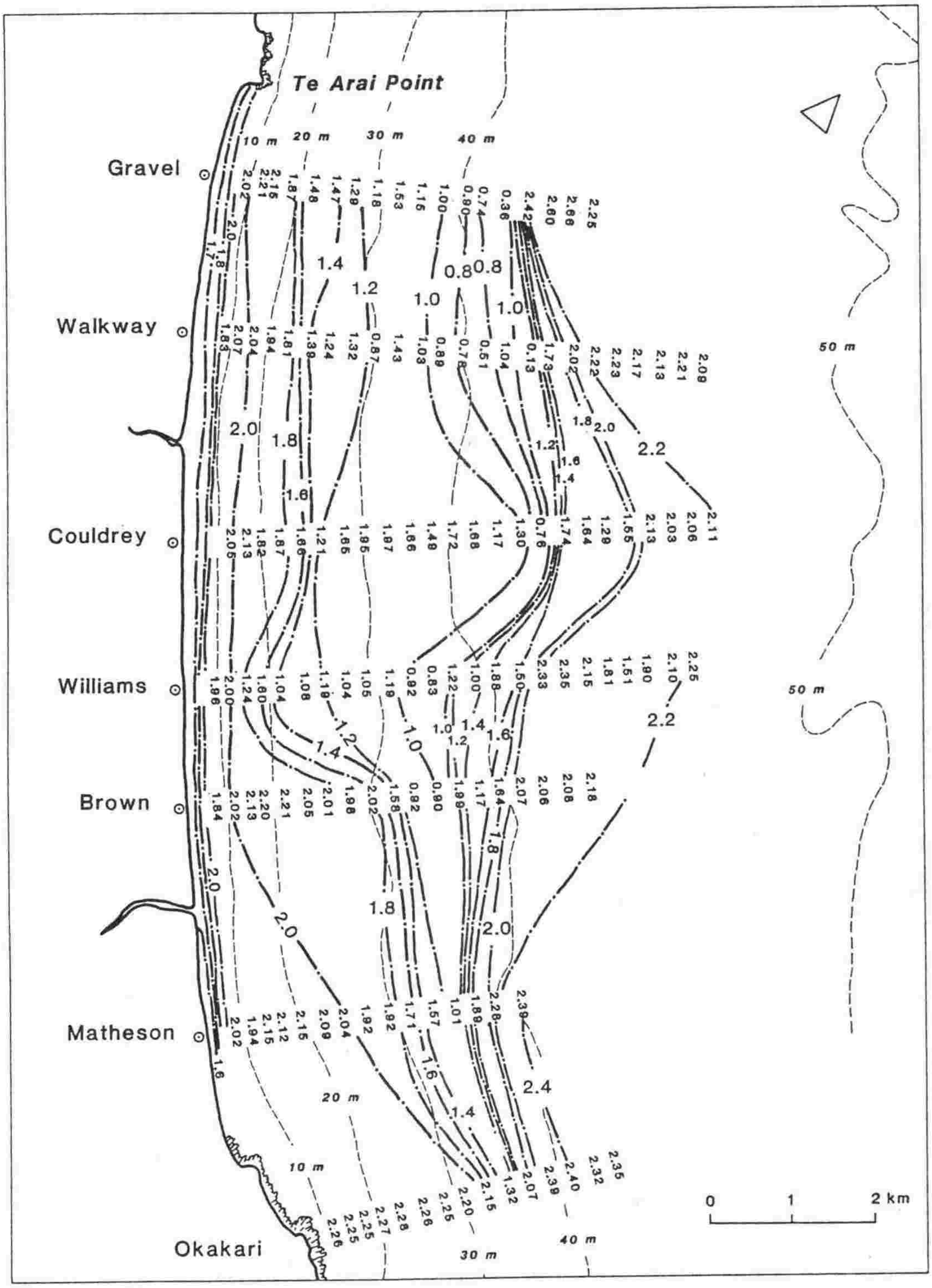



Figure 3.15 Isolines of mean grain size (phi units), Pakiri Bay

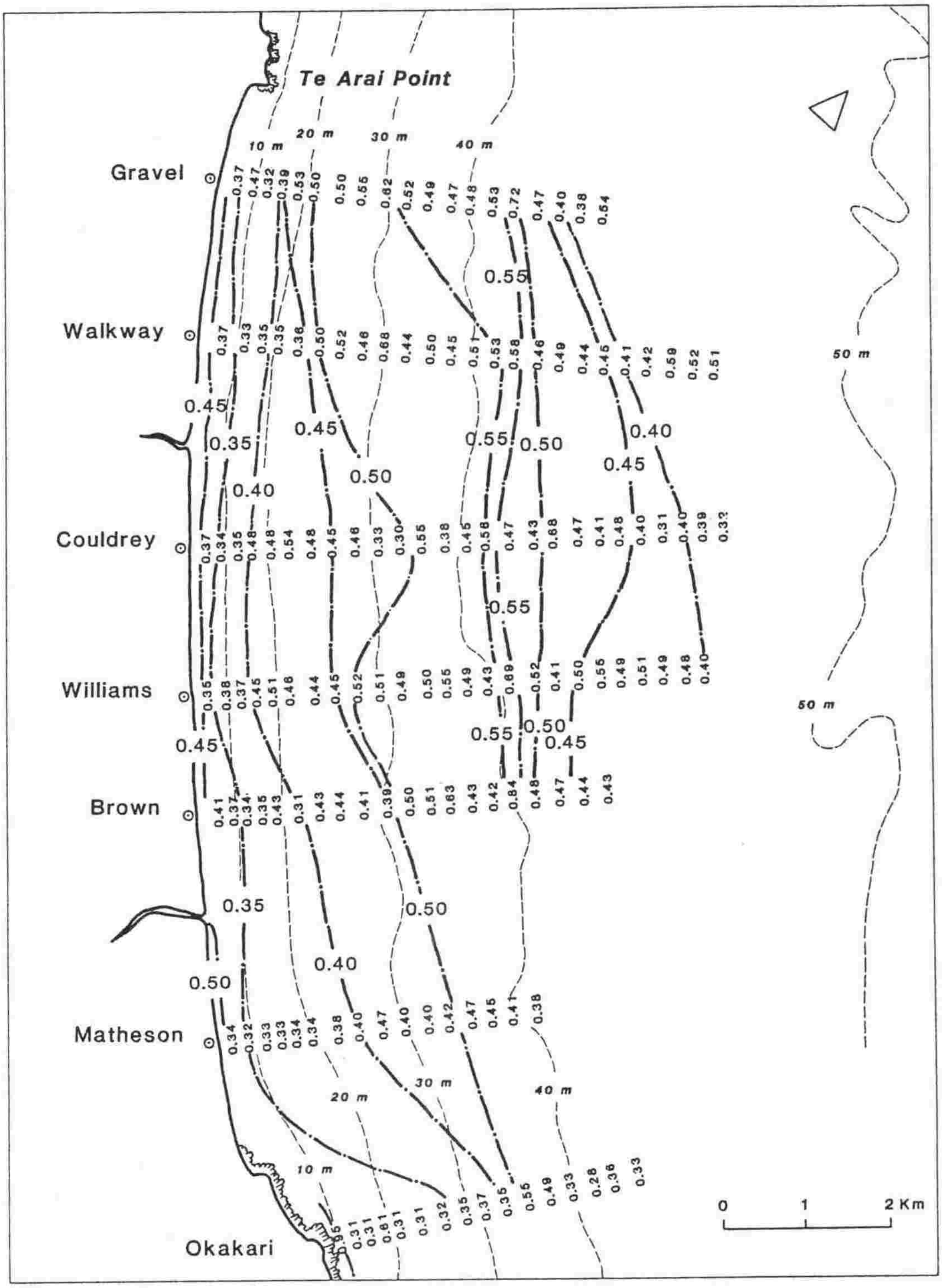



Figure 3.16 Isolines of standard deviation (phi units), Pakiri Bay

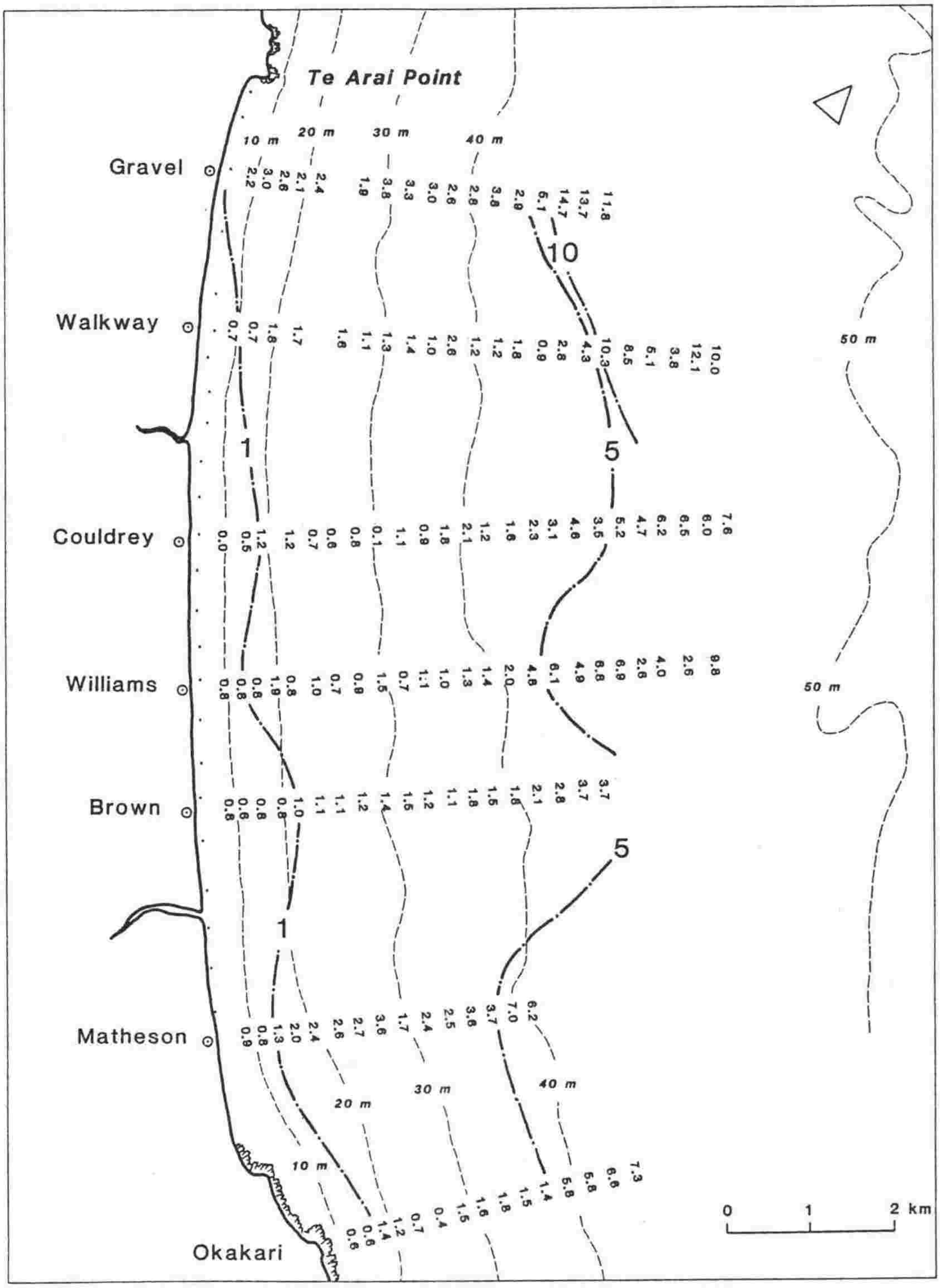



Figure 3.17 Isolines of fines concentration (percent), Pakiri Bay

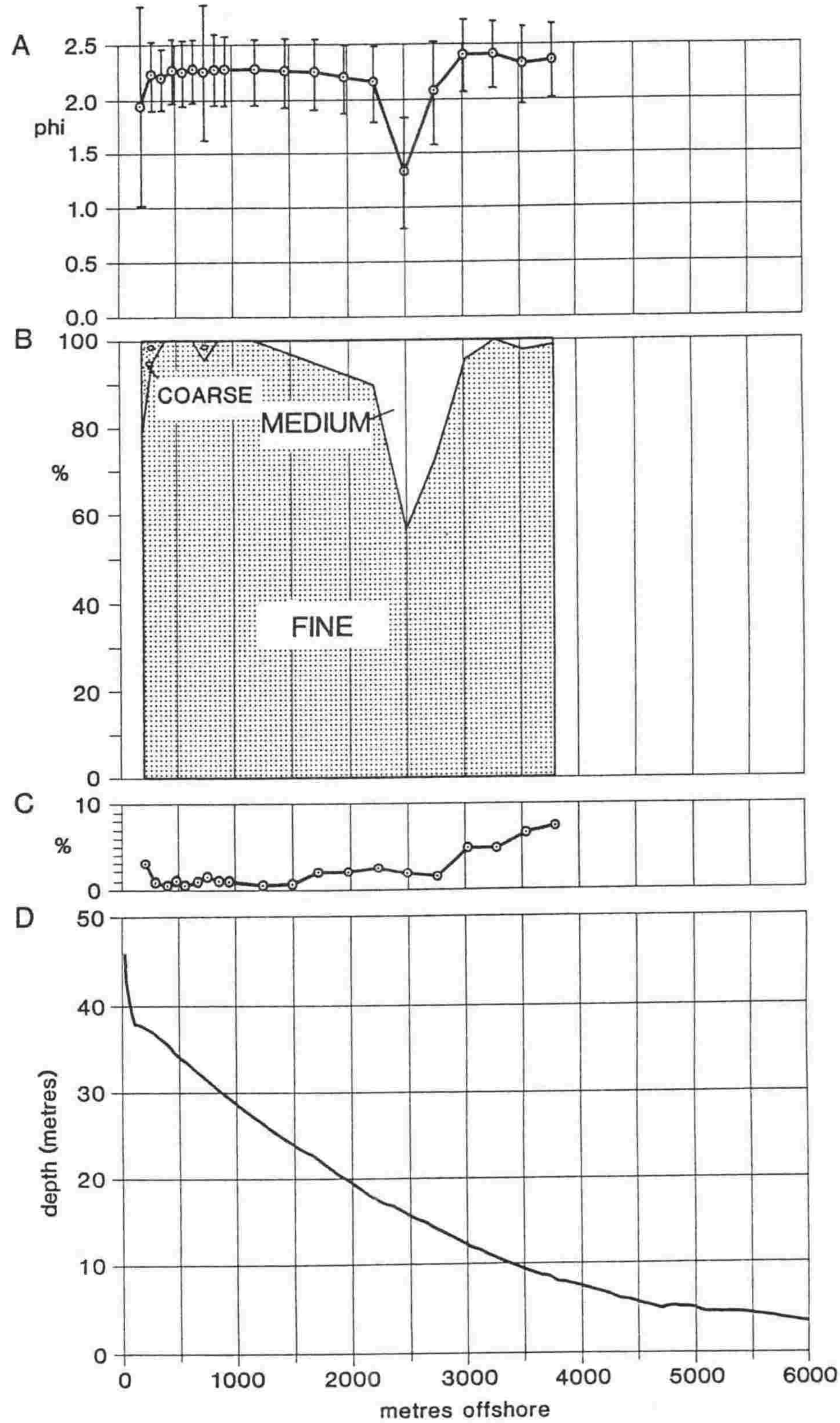



Figure 3.18 Variation in (A) mean grain size and sorting, (B) size grades and (C) percent mud across (D) Okakari transect

components that are characteristic of the northern transects are mostly absent, although there is a change in slope between what is inferred to be the inner shelf and the middle continental shelf. This juncture does not correspond to a marked change in sedimentology, however, and the transition from relatively coarse to very fine sand occurs much closer to shore in about 25 m of water. In many respects Matheson transect is intermediate between the sedimentological and morphological patterns across Okakari transect and the results obtained across the transects to the north.

## 3.3 Variations in Sediment Composition

### 3.3.1 Distribution of Carbonate Material

The carbonate fraction of the sediments is comprised mostly of fragments of the benthic macrofauna, which is predominantly of the phyla mollusca. The proportion of carbonate material in the surface sediments of the subtidal sediment body is not uniform throughout Pakiri Bay. The carbonate content increases, more or less regularly from transect to transect, in an offshore direction (Figure 3.19).

The proportion of carbonate material in the fine, very well-sorted sands of the upper shoreface is low, generally between 2 and 5 percent (Figure 3.19). The proportion of carbonate material steadily increases offshore across the shoreface and inner shelf, attaining maximum values of between 20 and 30 percent at the base of the inner shelf. The coarsest (mineral) sediments are thus also those that contain the most carbonate material. Immediately seaward of these coarse carbonate sediments there is an abrupt reduction, although concentrations tend to remain around 10 percent.

The analysis of multiple samples from Williams transect (Figure 3.20) shows the trend of increasing concentrations of carbonates across the shoreface and inner shelf is more regular than the (single sample, single station) transect data suggests. This is not surprising given the natural variability of carbonate material over

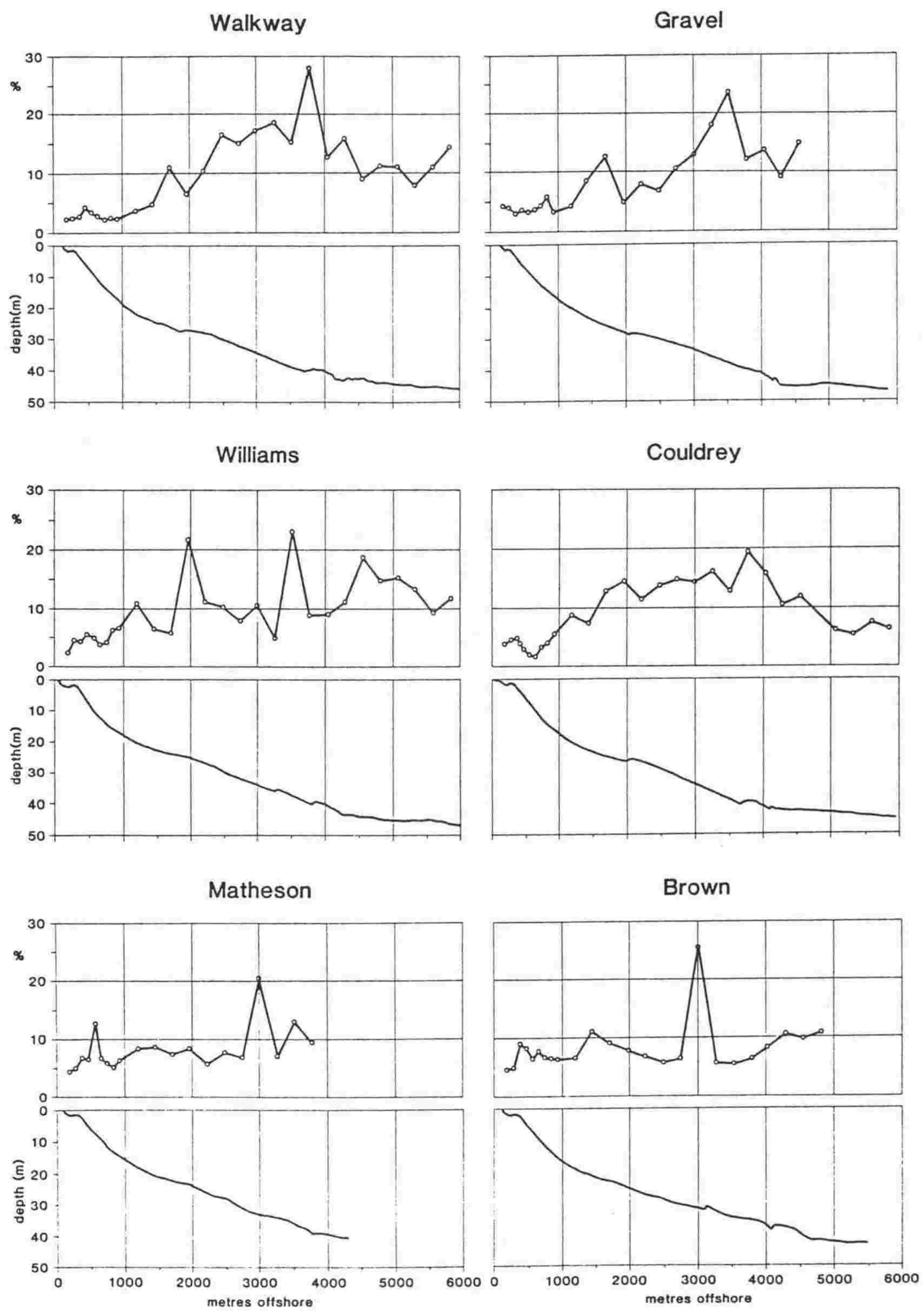



Figure 3.19 Variation in the proportion of carbonate material in the sediments across Walkway, Gravel, Couldrey, Williams, Matheson and Brown transects

small areas of seabed. In addition, the volume of sample analysed is only a small proportion of the original bulk sample, and the presence of a single large mollusc shell may significantly bias the carbonate estimates. The concentration of carbonate material in the troughs of megaripples may introduce further variability (Chapter Six).

The estimates of carbonate content across Williams transect are derived from four, five, six or eight samples obtained at each sample station (Figure 3.20). Samples obtained from the shoreface, in 15 m of water 800 m offshore, have the lowest variance. The most

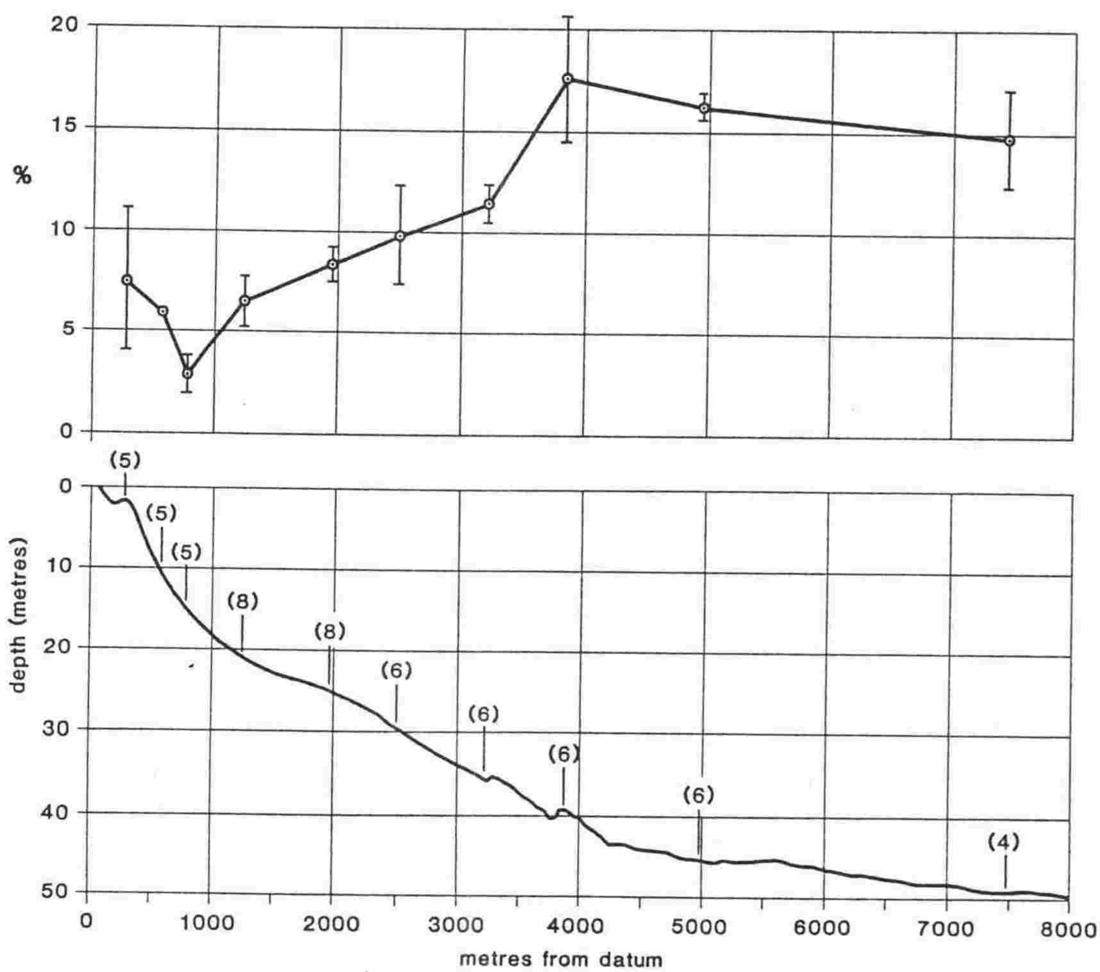



**Figure 3.20** Mean carbonate concentrations across Williams transect, derived from multiple sampling at each station (variance about means indicated by standard error bars)

variable are those samples from the alongshore trough, adjacent to Pakiri Beach, and from the base of the inner shelf. In the former case the variability results from the occasional presence of recently dead mollusca. In the latter case the high variability is more probably due to natural variations in the concentrations of long-dead mollusca in the sediments. Intra-station variance however, is relatively small compared to inter-station variance over the transect (3 to 17 percent). In general the concentration of carbonate material increases steadily across the lower shoreface and inner shelf, peaking at the base of the inner shelf, and remaining relatively high across that part of the middle shelf sampled. There is no pronounced alongshore pattern of carbonates in Pakiri Bay, although the isolines of percent carbonate tend to converge towards Okakari Point south of the Pakiri River (Figure 3.21).

The results of an initial study by Hilton and McLean (1984), and occasional diver observations during the present study, indicate the sediments of the inner shelf between Matheson transect and Cape Rodney become increasingly dominated by carbonate material. Maximum contents range from about 20 percent across Matheson to nearly 100 percent along the rocky coast south of Okakari Point. Where the carbonate content is less than 100 percent the balance often comprises locally-derived gravels. A typical selection of carbonate sediments, from highly comminuted calcareous sands near the coast to carbonate gravels further offshore may be found along Goat Island Bay transect (Figure 3.22).

The grain-size distribution of samples from Okakari and Walkway transects was determined prior to and following carbonate digestion. Living mollusca were removed prior to analysis, and the analysis undertaken using the settling tube technique. The retention of the carbonate fraction in the samples does not greatly affect the sample means (Figures 3.23 and 3.24). This is despite the carbonate content of the samples accounting for between 10 and 30 percent of the sample weight. Some experimental error may result from the different settling characteristics of shell fragments compared with mineral grains due to differences in shape, porosity and density.

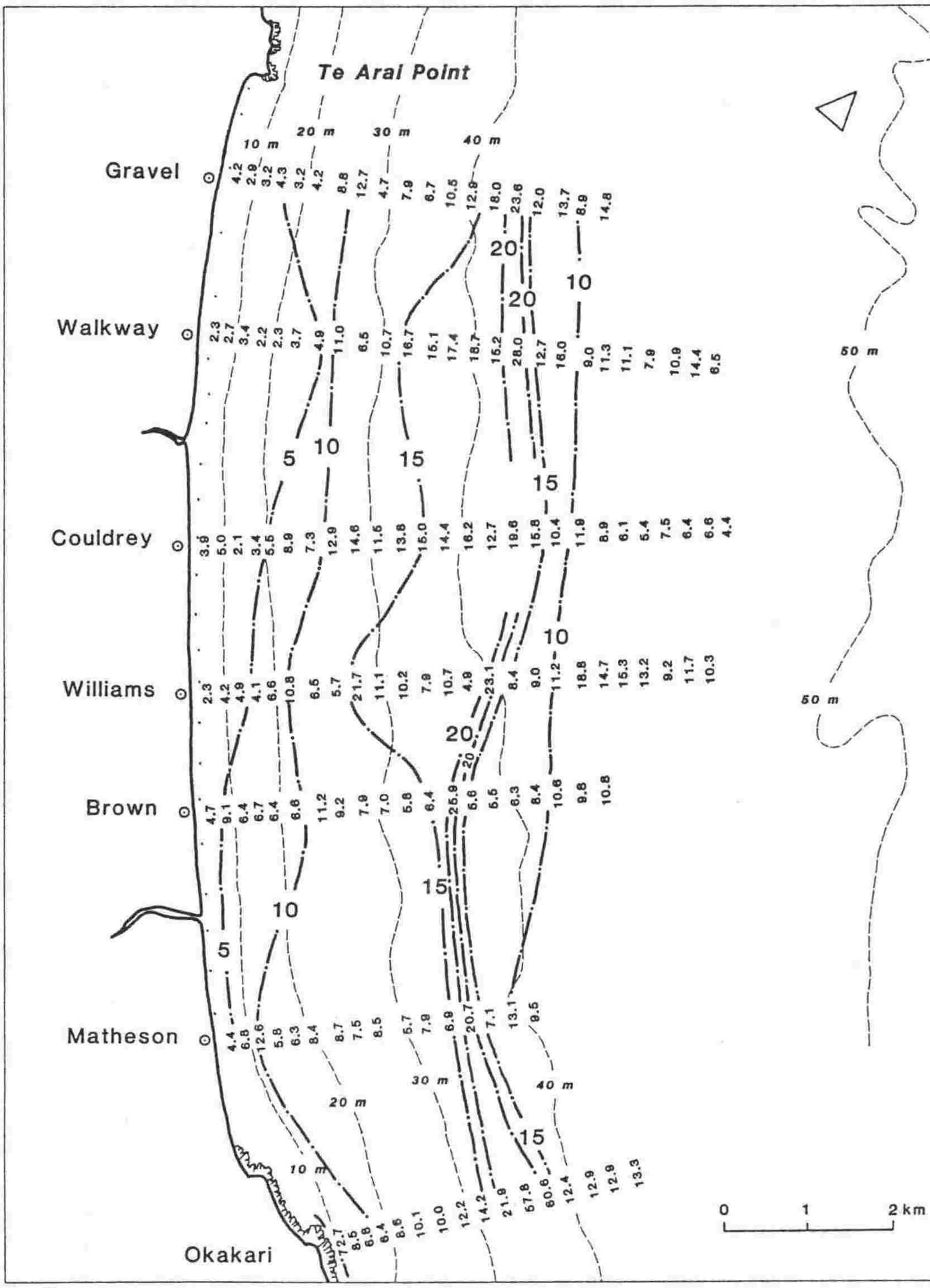
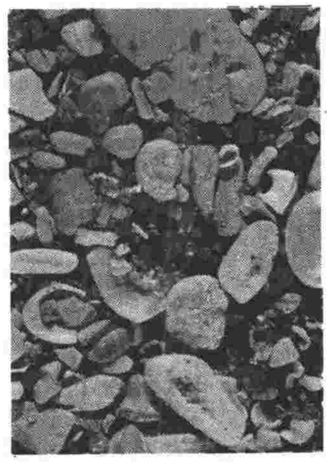



Figure 3.21 Isolines of carbonate concentration (percent), Pakiri Bay

**Figure 3.22** Photographs of bed sediments across Goat Island Bay transect, showing the predominance of carbonate sediment in samples from the inner shelf adjacent to the Cape Rodney to Okakari Point rocky coast (photoscale x3.5).

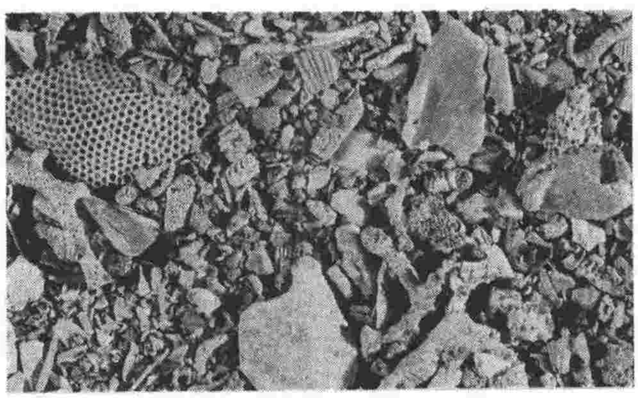
G.I.B. 1

G.I.B. 2



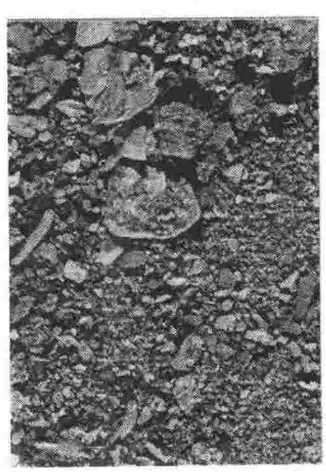
G.I.B. 3

G.I.B. 5

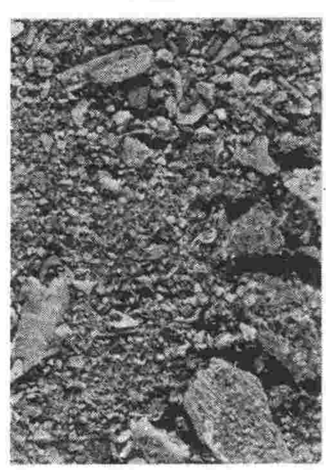


G.I.B. 4

G.I.B. 6



G.I.B. 7



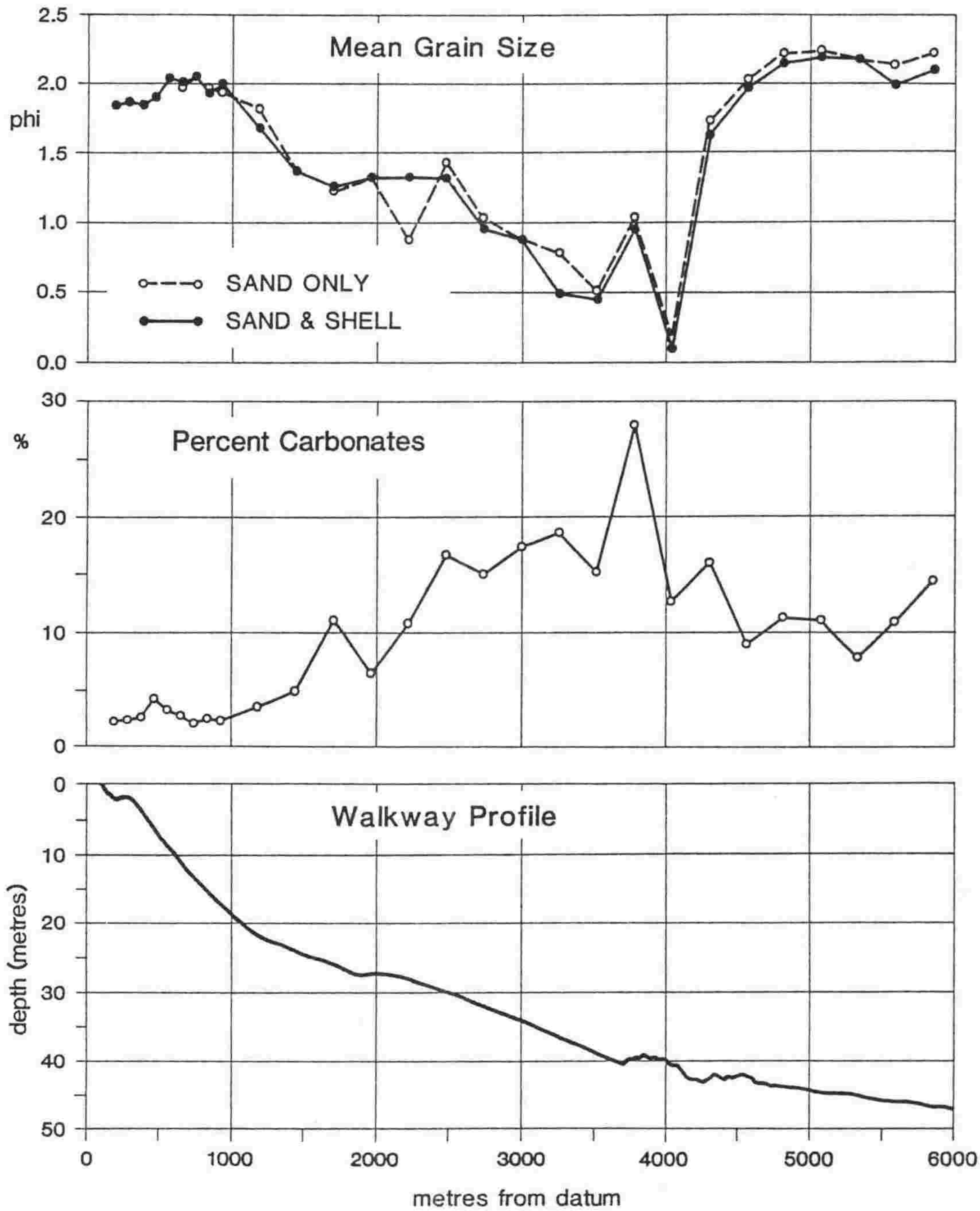



Figure 3.23 Variation in mean grain size for carbonate-digested and untreated samples and percent carbonate material across Walkway transect

However, the correlation between the carbonate-included and carbonate-excluded fractions is close for all sediment types encountered across the two transects. The major implication is that the size distribution of the carbonate fraction at any sample site is virtually the same as the size distribution of the non-carbonate sand grains.

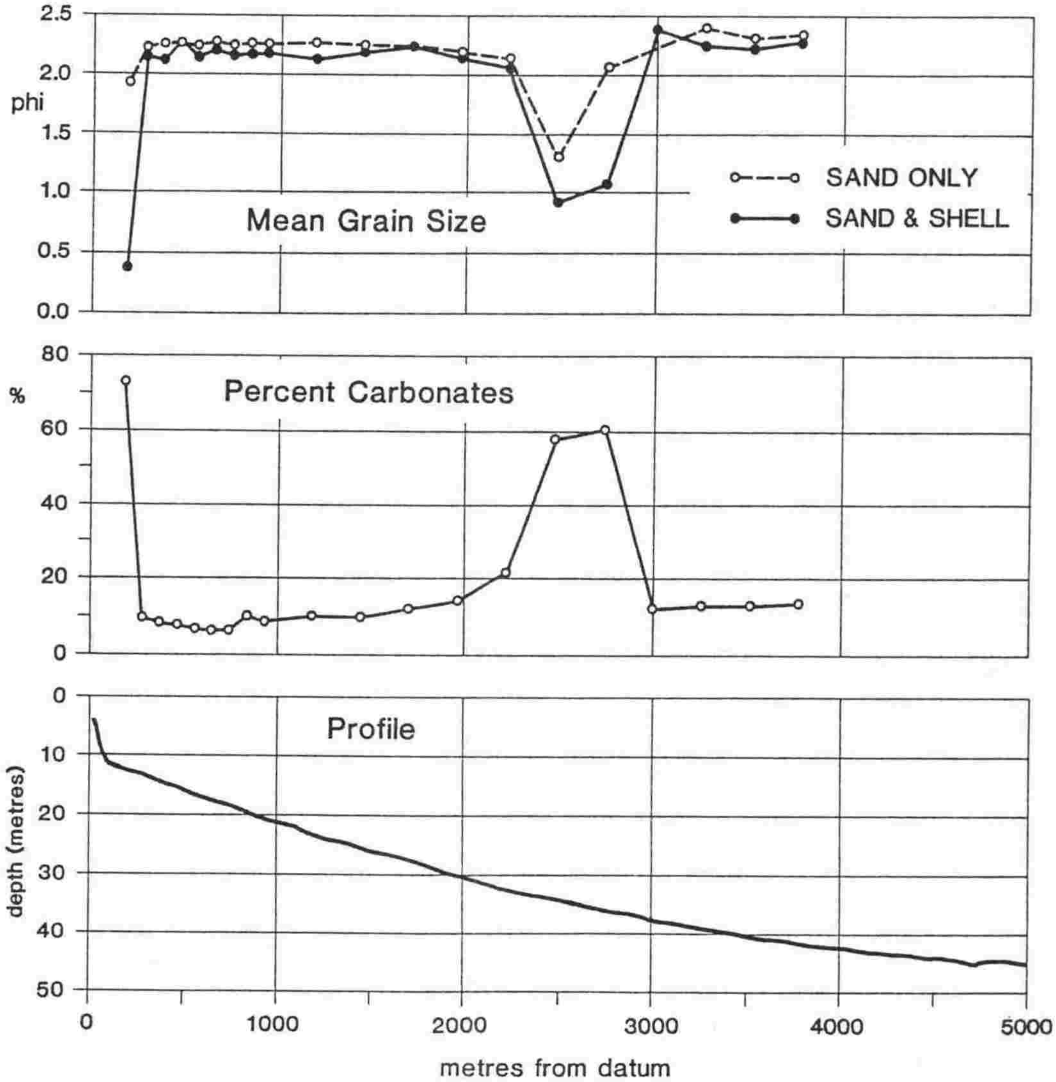



Figure 3.24 Variation in mean grain size for carbonate-digested and non-digested sediments, and percent carbonate material across Okakari transect

### 3.3.2 Variations in Mineralogy

The coastal and offshore mineral sediments of the Mangawhai-Pakiri embayment are broadly described as quartz-feldspathic sands (Schofield, 1970). Mineralogical studies by McCabe (1985) have confirmed the predominance of quartz (18 to 51 percent) and plagioclase feldspar (12 to 33 percent) in 25 beach and shoreface samples obtained between Bream Tail and Te Arai Point. Rock fragments are common in all samples. The heavy mineral assemblage (S.G.>2.65) is dominated by hypersthene (1 to 13 percent), with hornblende, magnetite, ilmenite, augite and zircon of much lesser importance. The carbonate content of the samples is mostly much less than 30 percent, except in the vicinity of the rocky Bream Tail coast, where concentrations are as high as 85 percent. These sediments are not thought by McCabe to be related to the Hauraki B Facies, but locally derived from the accumulation of carbonate skeletal material.

These results most likely have significance for the present investigation. There is some evidence, in the initial survey by Hilton and McLean (1984) and in the study by McCabe (1985) in Mangawhai Bay, to suggest the morphological and sedimentological patterns in Mangawhai Bay are a continuation of those described in Pakiri Bay. The offshore sediments are essentially part of the same sediment accumulation. At the extremes of the embayment high carbonate concentrations in the adjacent shelf sediments are almost certainly the result of local biogenic production. However, McCabe's (1985, p.172) conclusion that "the compositional variations of the inner shelf sediment zones did not appear to be related to the textural separation of mineral grains" is not consistent with analysis of some Pakiri samples. McCabe sampled to approximately the base of the shoreface (2300 m offshore in water depths of about 30 m). In Pakiri Bay significant changes in the proportion of heavy minerals in the sand fraction of the samples occurs over the mid to lower inner shelf, at somewhat greater depths than were sampled by McCabe (1985).

Samples from Walkway and Gravel transects were examined under an optical microscope to determine the variation in the proportion of heavy minerals across the transects. Samples were sieved at half phi intervals and the 1.0, 2.0 and 3.0 $\phi$ fractions examined. Estimates of the proportion of heavy minerals in each sample fraction are based on five slide counts of approximately 100 grains each. The difficulty in distinguishing dark rock fragments from discrete heavy minerals may result in the slight overestimation of heavy minerals. Examination of a wider range of phi fractions was initially attempted. However, the coarse fractions (0.0 to 1.5 $\phi$) comprise mostly rock fragments and, like the finer fractions (3 to 4 $\phi$) are of limited distribution. The 1.5 to 2.5 $\phi$ fractions are present in all samples across the transects and are therefore of most use for this study.

A large proportion (0 to 40 percent) of the 2 $\phi$ fraction across both Walkway and Gravel transects is comprised of heavy minerals (Figure 3.25). However, the proportion of heavy minerals across the transects is not constant, but varies in a regular fashion. The sediments of the mid to upper shoreface are primarily quartz and feldspars, with the low mafic content (2 to 5 percent), derived largely from the very fine sand fractions (3 to 4 $\phi$). The proportion of heavy minerals in these fractions declines, however, across the lower shoreface and inner shelf, while the proportion of heavy minerals in the 1.5 to 2.5 $\phi$ fractions increases. Concentrations in the latter size grades are greatest across the mid to lower inner shelf, becoming insignificant across the middle continental shelf. The heavy mineral fraction in the mid-shelf sands is largely due to the increased proportion of heavy minerals in the 3.0 to 4.0 $\phi$ fractions. This largely explains the blue-grey tone of these fine sediments, although staining due to certain biological processes may also contribute.

### 3.4 Implications For Sediment Transport

This chapter has described aspects of the texture of the surficial

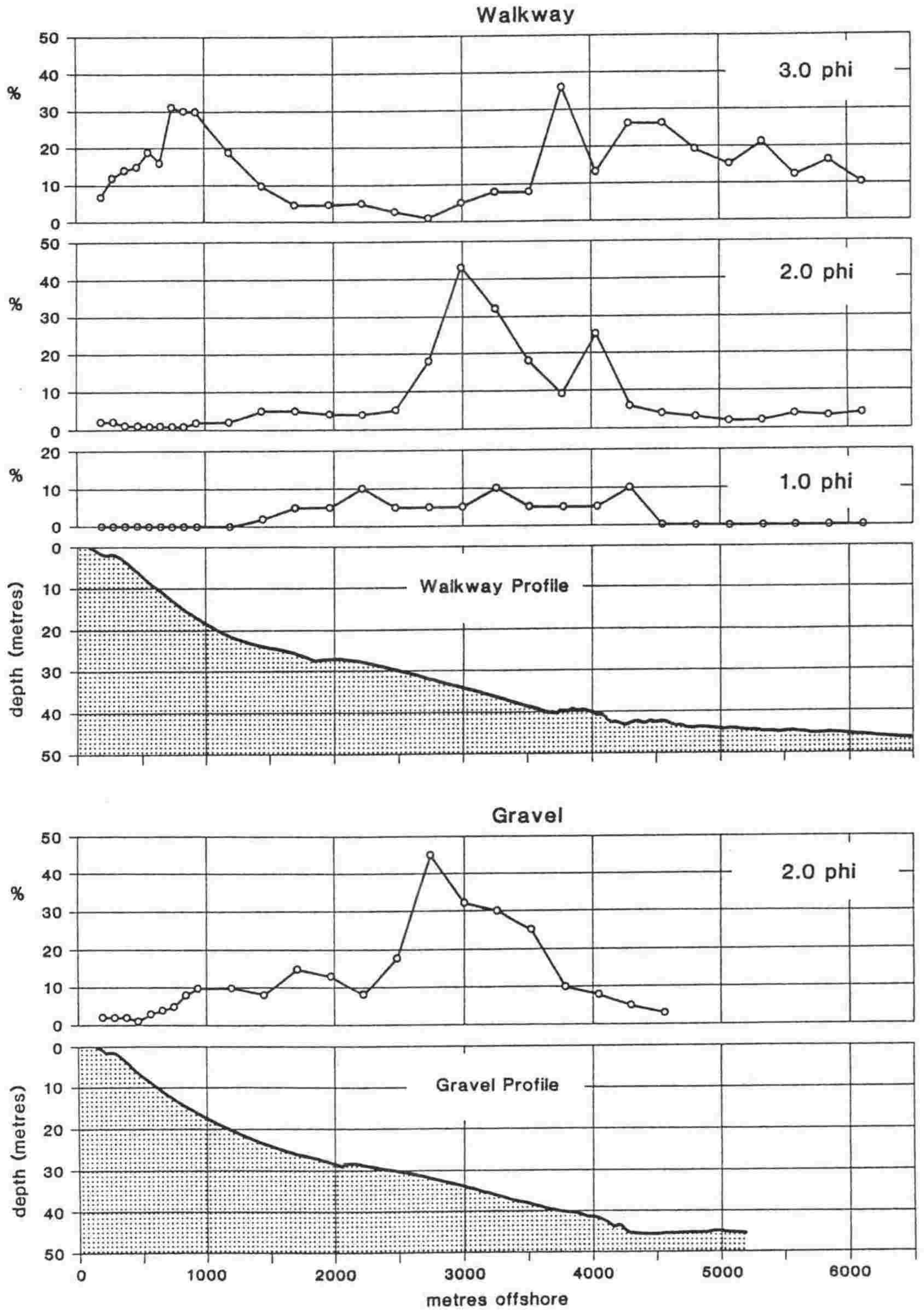



Figure 3.25 Variation in the proportion of heavy minerals in the 1, 2 and 3 phi fractions of samples obtained across Walkway and Gravel (2 phi) transects

sediments of the Pakiri sediment body. The following observations are consistent with a surface, comprised of unconsolidated sediments, which has at some time been exposed to processes of sediment transport and sorting.

(1) All of the samples obtained from Pakiri Bay are unconsolidated, with no evidence of aggregation or any form of insitu cementation.

(2) All the samples obtained are moderately well to very well sorted. Such a high degree of sorting would be expected where processes of sediment transport and deposition were intense and/or have operated over a long period.

(3) With one exception all the samples obtained are unimodal. This contrasts with the polymodal sediments of the middle continental shelf, described by Thompson (1975) from beyond the 70 m isobath, and supports the proposal that the sediments of the study area are a coastal derivative of the polymodal relict and palimpsest sediments of the Hauraki A Facies.

(4) The proportion of mud in samples obtained from the shoreface and inner shelf is nil or very low. This is in contrast with the relatively high mud content of the samples from the middle continental shelf. This dichotomy implies conditions on the mid shelf are conducive to the deposition of silt and clay, whereas disturbance of the shoreface and inner shelf seabed occurs too frequently to allow fines deposition.

(5) The seabed of the inner continental shelf is graded, both in terms of the grain size characteristics of the sediments, and to a lesser extent the mineralogical composition of the sediments. The arrangement of sediment types in Pakiri Bay is not haphazard, but exhibits pattern. Seaward of the medium to fine sands of the (lower) shoreface the sediments become progressively coarser. This trend culminates abruptly at the base of the inner shelf, with the very fine, muddy sands of the

mid shelf. This pattern could well result from intense and/or prolonged onshore/offshore sediment transport. Alongshore variations in sediment type are insignificant over most of Pakiri Bay, though with the variability discussed south of the Pakiri River mouth.

(6) The carbonate fraction of the sediments exhibits the same size gradation as that described for the bulk sample. This is especially true of the sediments of the inner and middle continental shelf. It seems improbable that such a pattern could result from authocthonous biogenic production of carbonates, and it is more likely that the grain-size characteristics of the carbonates across the transects reflects transport and resulting sorting of sediments, including the carbonate fraction.

## 3.5 Conclusions

The surficial sands of the study area comprise five shore-parallel bands of juxtaposed sediment types (Figure 3.26), two coastal (dune and foreshore/inshore) and three offshore (shoreface, inner shelf and mid shelf). This pattern of adjacent, shore-parallel, sediment types is persistent over the study period. Further, the results of repeat surveys across Williams transect in 1988 and Walkway transect in 1989, not presented here, concur with the above pattern.

The shore-normal pattern of grain size variation across the sediment body does not accord with the classic 'equilibrium' model of offshore sediment fining. Indeed, the reverse is the case. A pattern of offshore coarsening across the lower shoreface and inner continental shelf has been identified. This trend of progressive offshore coarsening culminates abruptly at the base of the inner shelf. Thereafter, as far as sampling extends, the sediments of the middle continental shelf are very fine, muddy sands. Nor are the patterns observed in Pakiri Bay readily reconcilable with the range of existing interpretations of present-day shelf profiles and

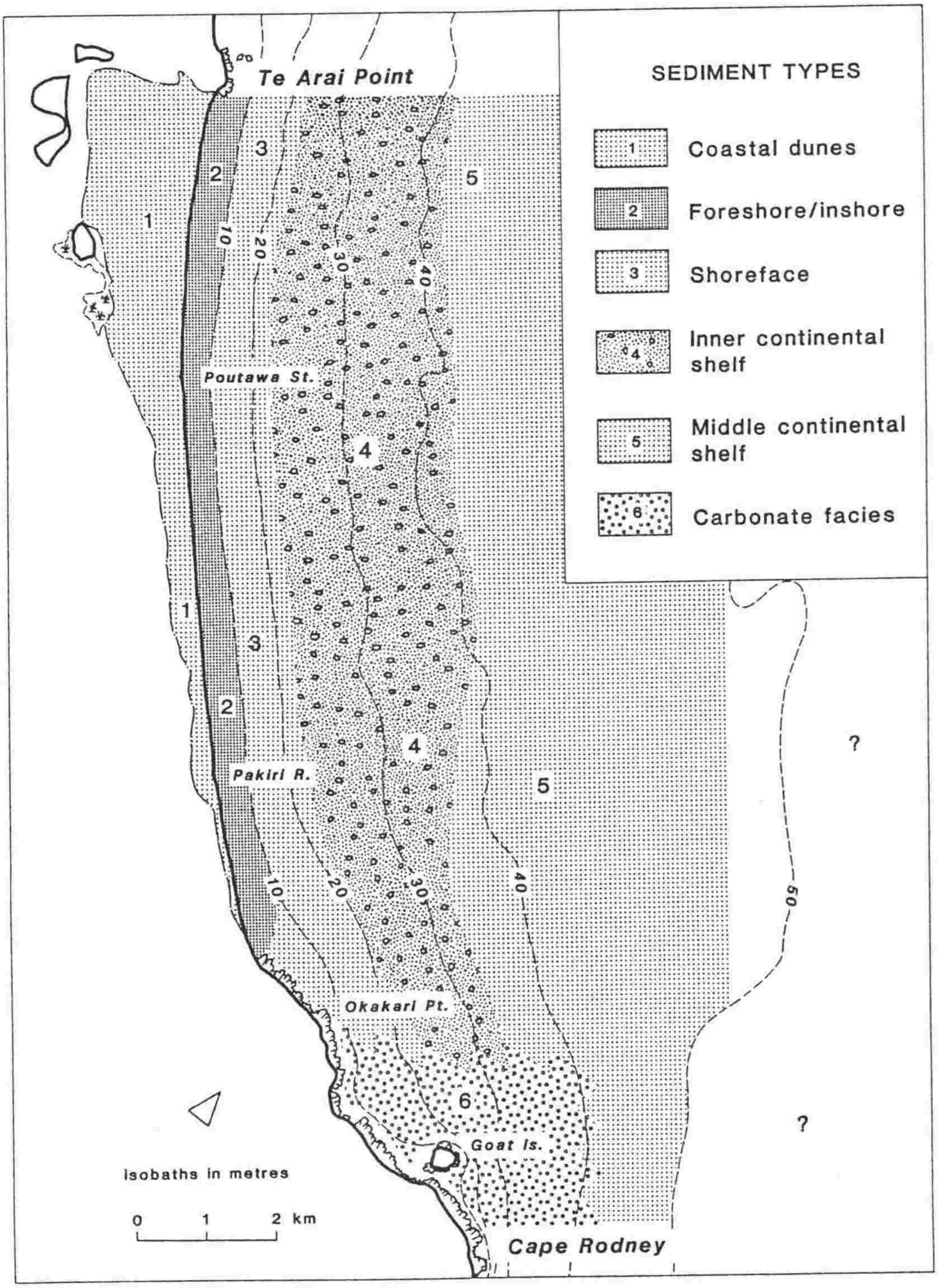



Figure 3.26 Sediment types of the Pakiri Bay sediment body and adjoining middle continental shelf

sediment covers (Figure 2.2).

Aspects of the Pakiri Bay pattern are described from other exposed, open coast locations. In particular, the juxtaposition of fine, well sorted shoreface sands and coarser offshore sands is described from Omaha Bay to the south of the study area (Schofield, 1979), and inferred from the results of Hilton and McLean (1984) to characterize Mangawhai Bay. The results from these two latter studies support the continuation of the Pakiri Bay sediment types north into Mangawhai Bay.

The offshore sequence of fine shoreface and coarse inner shelf sediments at Pakiri is broadly consistent with the results of studies reported by Bigham (1973), Cacchione _et al_. (1984) and Hunter _et al_. (1988). However, the detailed sequence of sediment types described at Pakiri is not documented elsewhere. With the exception of the local Omaha and Mangawhai studies the Pakiri sequence is perhaps most analogous to the sediment facies described from the New South Wales coast (Roy and Stephens, 1980; Roy and Crawford, 1980). In contrast to the Pakiri sediments however, the New South Wales inner shelf sediments are poorly sorted and polymodal. These latter sediments are interpreted to result from modern reworking of relict deposits to water depths of about 50 m. In this respect there is also evidence, summarized in the previous section, of sediment transport and subsequent textural and mineralogical sorting on the Pakiri inner shelf.

Carbonates comprise a high proportion of the samples in the study area. However, there is presently no readily applicable model of modern biogenic sedimentation to assist in their interpretation. The distribution of carbonates in the sediments shows a systematic increase offshore, with highest concentrations associated with the coarse sediments at the base of the inner shelf. That the grain-size distribution of the carbonates is analogous to that of the non-carbonate sand fraction suggests the two components are similarly affected by modern processes of physical sedimentation. Conversely, the carbonates may be autochthonous, and their concentrations and distribution in the sediments may reflect the actual distribution of contributing organisms. Accordingly, the high concentrations of carbonates at the base of the inner shelf may actually reflect the relatively high level of biological production and resultant accumulation of skeletal material at these water depths (40 to 45 m). In the following chapter patterns of carbonate material are investigated with respect to the activity and distribution of organisms and a model of modern carbonate sedimentation devised.

# Chapter 4

# CARBONATE SEDIMENTATION IN PAKIRI BAY

## 4.0 Introduction

Carbonates comprise up to 30 percent of shoreface and shelf sediments in Pakiri Bay. This result is consistent with the existing interpretation of sedimentation along the east coast of Northland. In this region biologically-derived sediments comprise a relatively high proportion of shelf sediments, due to a dearth of fluvial sediment inputs to the coast.

However, the distribution of carbonates in the surface sediments is not uniform. Investigations in the previous chapter have shown that carbonate content increases with increasing distance offshore. In addition, the carbonate fraction of the sediments shows the same size grading across the transects as the non-biogenic sediments.

This chapter describes and explains the characteristics and distribution of carbonate sediments in Pakiri Bay. Further, it seeks to answer the question of whether the patterns result directly from biological processes or are a product of the hydraulic regime. The approach employed involves comparing the patterns of modern shell production with the distribution, abundance and character of carbonates in the sediments. A model of the distribution and abundance of major shell producing benthos is derived by extensive and intensive sampling of the Pakiri Bay seabed. This model provides a means of differentiating modern and relict carbonate sediments as well as estimating modern levels of shell production.

The model of living benthos in Pakiri Bay also affords the opportunity to interpret aspects of depositional environments using known habitat preferences of individual species and communities. This approach provides a secondary method of differentiating the modern and relict component of carbonate sediments. It has been employed to distinguish relict from modern carbonates on the New Zealand shelf on the basis of, for example, anomalous depths of occurrence of species (Cullen, 1970; Gillie, 1981, Norris, 1972; Andrews, 1973).

### 4.1 General Concepts of Carbonate Sedimentation

There are fundamental differences in the origin of mineral and carbonate sediments. The former are allochthonous, derived from parent materials located some distance from the eventual environment of deposition. The characteristics of mineral sediment deposits is expressed as the sediment fabric and texture, as well as the sediment structures, and results from the interaction of the hydraulic regimen with the original sediment. In contrast, carbonate sediments are mostly autochthonous, born in, or close to, the environment of deposition. Hence, in addition to the purely physical sediment parameters used in the analysis of mineral sediments, the composition of carbonate particles themselves is important in characterizing the depositional environment (James, 1986).

The distribution and abundance of carbonate-producing organisms is closely related to marine environment. Temperature appears to be the main factor in determining organism distributions at a global or regional scale. However, local variations in environment are often closely related to increasing water depth. According to Rhoads (1974) increasing depth away from the coast is accompanied by (a) decreasing hydrodynamic energy, and therefore decreasing resuspension of bottom sediment and disturbance, (b) decreasing environmental variability, including annual, tidal and daily cycles, (c) a decreasing but more uniform supply of nutrients and (d) decreasing temperatures and increasing pressure. Organisms may also respond to the sediments themselves. Similar species are known to consistently occur on particular substrates. The grain size of the substrate is thought to be a major criteria, although secondary and related characteristics, such as porosity, fabric, permeability and interstitial volumes may also be important.

Benthic organisms may themselves affect the nature of the bed sediments, by (a) disturbance of the surface layer, (b) conversion of suspended solids into deposit faeces, (c) increasing particle sizes by faecal and mucus deposition, (d) circulation of interstitial water, (e) upward transport of particles, (f) deposition of mineral skeletons, (g) concentration of specific components of the sediment and (h) distribution and sorting of the sediment. Studies of bioturbation have shown that some of these processes tend to lower the critical erosion velocity of the sea bed sediments (Rhoads, 1974). In nearly all marine environments bioturbation is sufficiently active to significantly modify the nature of the sediments in the benthic boundary layer and their physical and chemical characteristics (Rhoads, 1974).

## 4.2 Carbonate Sedimentation on the East Coast of Northland

The coastal and shelf waters of the east coast of the Northland Peninsula ($34^{o}$ to $37^{o}$ Lat.S) are temperate, although with a subtropical influence resulting from the south flowing East Auckland Current. Measurements at the Leigh Marine Laboratory (1967-1985) indicate water temperatures (surface coastal) range between 20.5°C in summer and 14.0°C in winter (Evans and Ballantine, 1985). Sea surface salinities for the same period range between 34 and $36^{o}/_{oo}$. These conditions are not conducive to the development of colonial corals, however mollusca, bryozoa and foraminifera are relatively abundant.

Investigations of carbonate sedimentation in the Hauraki Gulf (Thompson, 1975), along the east coast of Northland (Schofield, 1970; Ballantine _et al_., 1973; Gillie, 1981) and in the Far North of New Zealand (Summerhayes, 1969 b) document the contribution biogenic shell production has made to coastal and shelf sediments. South of North Cape, for example, carbonates comprise as much as 75 percent of the sediment of the shelf (Summerhayes, 1969 b). They occur as biogenic skeletal debris, primarily molluscan and bryozoan fragments, with minor amounts of sponge spicules, echinoid and serpulid tube fragments, foraminifera and faecal pellets. Between Whangaroa Harbour and Bream Tail the sediments of the inner shelf contain high proportions of coarse (15 to 60 percent) and comminuted shell fragments (35 to 85 percent), in the coarse (>5mm) and fine (1-5mm) gravel fractions (Ritchie and Saul, 1974; Gillie, 1981).

Gillie (1981, p.162) considers the carbonates of the Northland shelf at the sites examined to be 'overwhelmingly modern', because the species composition of the carbonate detritus in the sediments accords with the species presently living on the inner shelf. He concludes that:-

> ...modifications of the original source characteristics of gravel in the deposits [by the addition of shell material] has occurred to such an extent that the original size distributions have been significantly changed. The deposits are thus considered to be palimpsest, and may be more correctly termed modern, because of the degree to which contemporary inner shelf processes are determining sediment characteristics.

However, where carbonate facies have been studied in detail on the New Zealand shelf (for example, McKnight 1969; Cullen, 1970) biogenic deposits are commonly a mixture of both relict and modern specimens.

Radiocarbon dating provides a means of absolutely dating and classifying shell material, however the risk of contamination of surface relict shell with more recently living animals is high. Evidence of post-depositional weathering provides a qualitative impression of the age of carbonate sediments, although little seems to be known of the endurance of shell material in differing marine environments. Thompson (1975) defined as relict any skeletal clast that exhibited (1) blackening, or similar discoloration; (2) extensive abrasion, resulting in a high degree of rounding and/or pitting; (3) evidence of extensive boring by gastropods, bryozoa, or similar; (4) infilling of pits, cavities or borings by glauconite, and; (5) encrustation by bryozoa or similar organisms. The classification of a carbonate sediment as relict on the basis of these criteria is clearly subjective. However, if the species presently lives in a different environment from that in which samples of the dead valves were obtained the interpretation can be made with additional confidence.

## 4.3 Investigations of Living Pakiri Bay Macrobenthos

### 4.3.1 Sampling Design

In the absence of existing data on the Pakiri Bay benthos an initial study was undertaken that involved four offshore surveys, two in Pakiri Bay and two offshore from the Cape Rodney rocky coast. These surveys were undertaken to provide some initial data on which to base a more extensive, and intensive, sampling programme. At the same time they provide information on the sedimentology of the bed offshore from the rocky coast, and an opportunity to determine the efficiency of the sampling device over a range of substrates. Since the results of the Pakiri Bay surveys are consistent with the subsequent, more thorough surveys, only the results for the initial rocky coast surveys are presented (section 4.3.3).

The four initial transect surveys, along Couldrey, Te Arai, Cape Rodney and Goat Island Bay transects, established the effectiveness of the sampling device in sandy substrates to water depths of around 50 m. The Pakiri Bay surveys revealed a greater diversity of live macrobenthos than had been captured during the rocky coast surveys, and greater overall numbers of living individuals (see Appendix H). These surveys also pointed to a pattern of shore-normal variation in species distribution, with the ranges of some species seemingly characterized by particular water depths and distances offshore.

Sample stations were therefore located across the same transects described previously so as to sample the range of substrates and marine environments known to be present. Three transects, Matheson, Williams and Walkway were sampled in March 1987, so as to provide as wide a coverage as possible of Pakiri Bay. Two of these, Williams and Walkway, were re-sampled nine months later, and Walkway was sampled a third time in May 1989. The location and date of Pakiri Bay benthos sample stations is shown in Figure 4.1. In terms of the intention to correlate benthos distribution with substrate type it was not considered necessary to re-sample bed sediments. The sedimentological patterns in Pakiri Bay are persistent over the sampling period and well documented.

### 4.3.2 Sampling Technique and Treatment of Samples

The method and limitations of the benthos sampling technique employed are outlined in Appendix F. The sampling device samples the macrobenthic epifauna and shallow living infauna, to an estimated depth of 10 cm. Organisms smaller than 1 cm diameter are unlikely to be retained in the dredge, excluding many small gastropod species in particular.

Initial analysis entailed the separation of the live macrobenthos from the carbonate detritus, and the identification and counting of live species. The presence of hermit crabs and the composition of the (non-living) shell residue was also determined. A reference collection to assist identification was established, and the systematics of Powell (1979) employed for all mollusca reported (Appendix G).

Estimates of biogenic production of shell are based on the dry shell weight of each of the most common Pakiri Bay species. This is calculated by multiplying the average weight of a dried shell of a mature specimen (without the animal) by the average number of that species captured at each station. The total dry shell weight of living benthos at each sample station is the sum of all the individual species weights in the sample. The total weight of shell (associated with living organisms) across each transect is the sum of the collective species weights at each sample station.

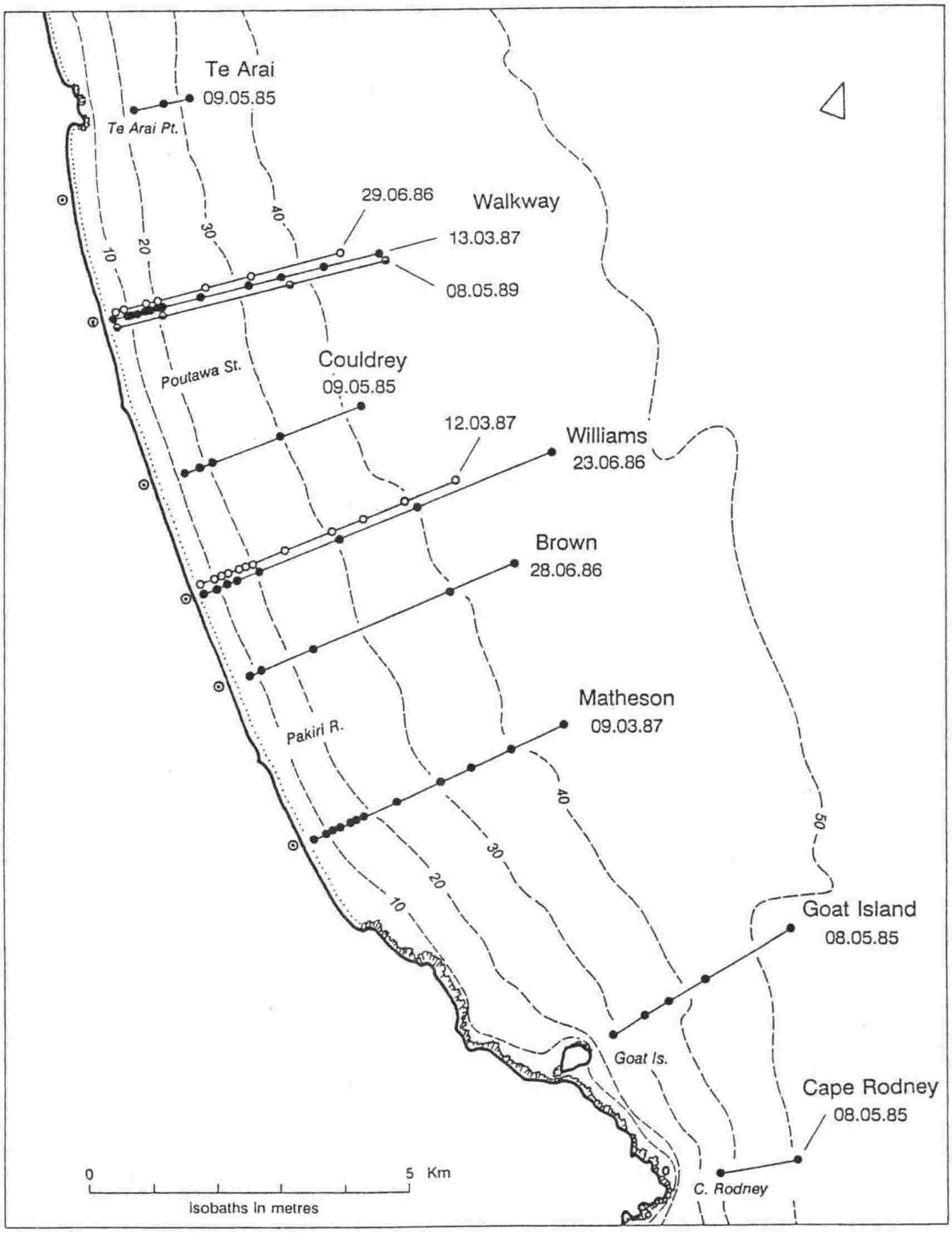



Figure 4.1 Location of initial benthos surveys (Te Arai, Couldrey, Goat Island and Cape Rodney transects) and subsequent Pakiri Bay transect surveys (Walkway, Williams, Matheson).

Samples obtained by pipe dredge from the base of the inner continental shelf during the sediment surveys of Pakiri Bay were analyzed for species composition and abundance. This work relied on the identification of as much of the carbonate fraction of the samples as possible, and involved the matching of fragments of shell against identified whole specimens. One or two samples of the lower shoreface carbonate-rich sediments were analyzed from each transect. The dry sediment was passed through a 0.5 cm sieve to separate the macrofauna from the terrigenous sediment and fine carbonate fragments. The coarse fraction was then, as far as possible, identified.

Because of the highly fragmented and degraded nature of much of the carbonate material at best 35 percent, and at worst 10 percent of the coarse shell fraction of the sample was able to be identified. Five 2 g sub-samples were obtained from the fine fraction of each sample. These were examined under a binocular microscope and the composition of the carbonate material determined. Together with the coarse carbonate fraction an estimate of the percent (by volume) of mollusca, foraminifera, brachipoda, bryozoa and scleractinia (stony corals) was made. An estimate of the relative abundance (as common, scarce or abundant) of different species in the coarse fraction was also made.

### 4.3.3 Cape Rodney to Okakari Point (Rocky Coast) Benthos

Sampling commenced at the top of the inner shelf, in water depths of about 30 m. Both live and 'recently-dead' (modern) specimens were identified from the samples, however no attempt was made to identify a large number of small (less than 1 cm) and immature gastropods, mostly of the Zeacolpus or Maoricolpus types, associated with the coarse shell sediments near the coast. The total weight of each sample, and the weight of the unidentified residue was then determined.

The sediments offshore from Cape Rodney and Goat Island transects are composed of large quantities of carbonate skeletal detritus. The terrigenous fraction is invariably coarse sands and gravels and commonly accounts for less than 10 percent of the sediments. The carbonate fragments are generally of coarse sand size and well-sorted (Figure 3.22). Adjacent to subtidal reefs and further offshore the carbonate content is less well sorted with a significant (non-biogenic) gravel component. Seaward of about the 45 m isobath the sediments are fine biogenic sands with a high (10 to 20 percent) mud content.

According to the criteria of Thompson (1975) only a small percentage of these sediments are comprised of whole mollusca that could be described as 'modern'. Between 55 and 75 percent of the Cape Rodney and Goat Island samples consisted of shell and echinoderm fragments. No live specimens were recovered from the two Cape Rodney stations, and only the bivalves **Corbula zelandica** and **Notocallista multistriata** were captured live from Goat Island stations. The dead 'modern' fauna consists mostly of **Corbula zelandica**, fan shells of the genus Chlamys, the dog cockle **Glycymeris laticostata**, **Tawera spissa**, **Notocallista multistriata**, **Venericardia purpurata**, and the gastropod **Zegalerus tenuis**. The species composition and abundance for these transects, live and dead, is listed in Appendix H.

### 4.3.4 Comparison of Pakiri Bay and Rocky Coast Phyla

Many of the dead and living species encountered during the rocky coast surveys are not recorded in Pakiri Bay. The solitary corals, echinoderm spines and spicules, barnacle and bryozoa fragments and the brachiopoda are absent, as is the large dog cockle (**Glycymeris laticostata**). The systematics of the relatively common (living) Pakiri Bay mollusc fauna, with an estimate of the relative abundance of individual species, is given in Appendix G. A total of 40 mollusca (19 bivalves and 21 gastropods) were found to occur relatively frequently across the four pilot study and three Pakiri Bay transects. Three echinoderms, the sand dollar **Fellasten zelandiae**, the heart urchin, **Echinocardium cordatum**, and the starfish **Luidia varia** were also relatively common. While many more species were occasionally encountered, the species listed account for about 95 percent of the total live shell weight recorded across the transects. However, apart from these, and very small quantities of foraminifera and bryozoa, the carbonate fauna is dominated by mollusca.

This pattern is modified towards the rocky shore of Cape Rodney where the foraminifera, bryozoa, brachiopoda and scleractinia all become more significant. Even then the mollusca account for 88 percent of the total (dead and living) carbonate content (by volume) dredged. Near the Cape Rodney rocky coast the solitary stony corals **Flabellum rubrum** and **Culicia rubeola**, and a brachiopod, **Terebratella inconspicua** are also present. In general the species that comprise the carbonate rich sands and gravels of the Okakari Point to Cape Rodney coast are closely related to living species that characterize the existing fauna of the rocky coast.

### 4.3.5 Species Composition, Abundance and Distribution

The results of the benthic surveys are presented as kite diagrams of species distribution and absolute abundance across the transects. Each diagram combines the results of one, two or three surveys in the case of Williams (Figure 4.2), Matheson (Figure 4.3) and Walkway (Figure 4.4) transects, respectively. The location of the sample stations and the variations in sediment grade and the percent mud content across the transects are also portrayed. The margins of the shaded areas thus enclose the maximum abundance and widest distribution of each species across the transects. Only those species that were most frequently captured (live) on the surveyed transects are represented in the diagrams. These few species are relatively abundant and collectively account for almost all shell production in Pakiri Bay.

The distribution of macrobenthos in Pakiri Bay is not haphazard. Certain species, such as **Umbonium zelandicum**, are consistently

Figure 4.2 (a) Summary of distribution and abundance of the most commonly captured macrobenthos, (b) variation in sediment size grades and (c) sample locations and variation in percent mud, across Williams transect, June 1986 and March 1987.

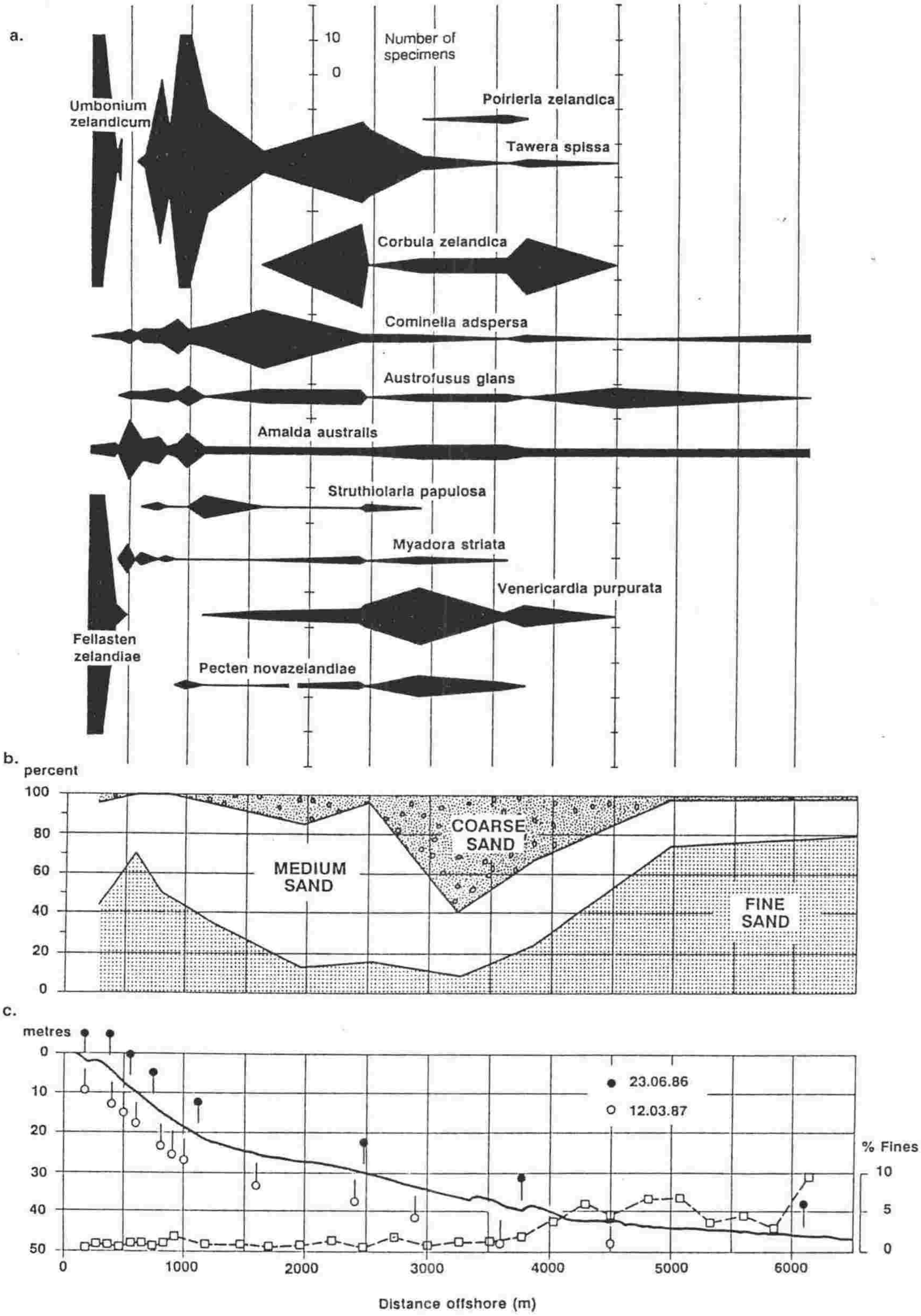

a.
10
0
Number of specimens
Umbonium zelandicum
Poirieria zelandica
Tawera spissa
Corbula zelandica
Cominella adspersa
Austrofusus glans
Amalda australis
Struthiolaria papulosa
Myadora striata
Venericardia purpurata
Fellasten zelandiae
Pecten novazelandiae
b.
percent
100
80
60
40
20
0
COARSE SAND
MEDIUM SAND
FINE SAND
c.
metres
0
10
20
30
40
50
23.06.86
12.03.87
% Fines
10
5
0
0
1000
2000
3000
4000
5000
6000
Distance offshore (m)

Figure 4.3 (a) Summary of distribution and abundance of the most commonly captured macrobenthos, (b) variation in sediment size grades and (c) sample locations and variation in percent mud, across Matheson transect, 9 March 1987.

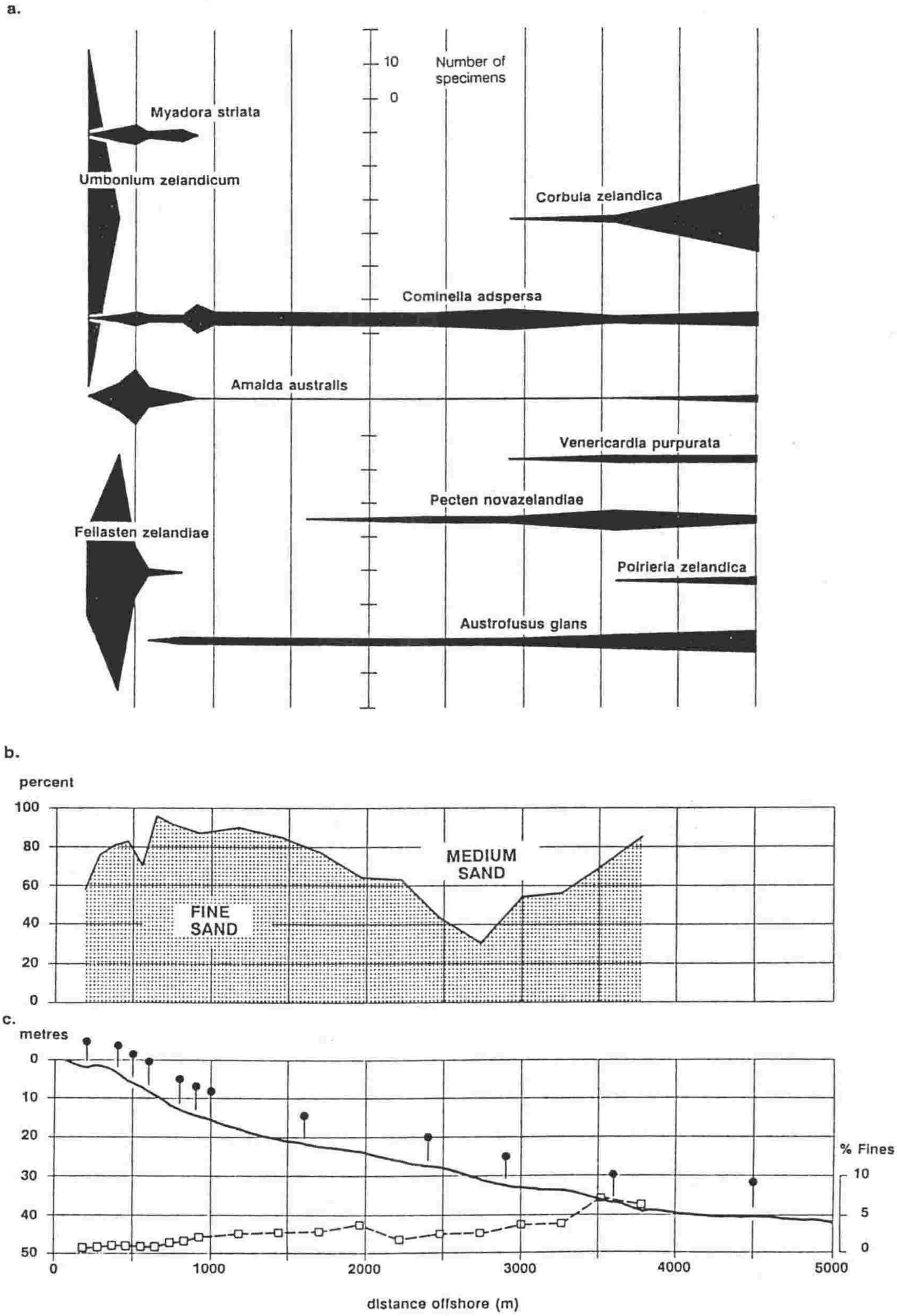
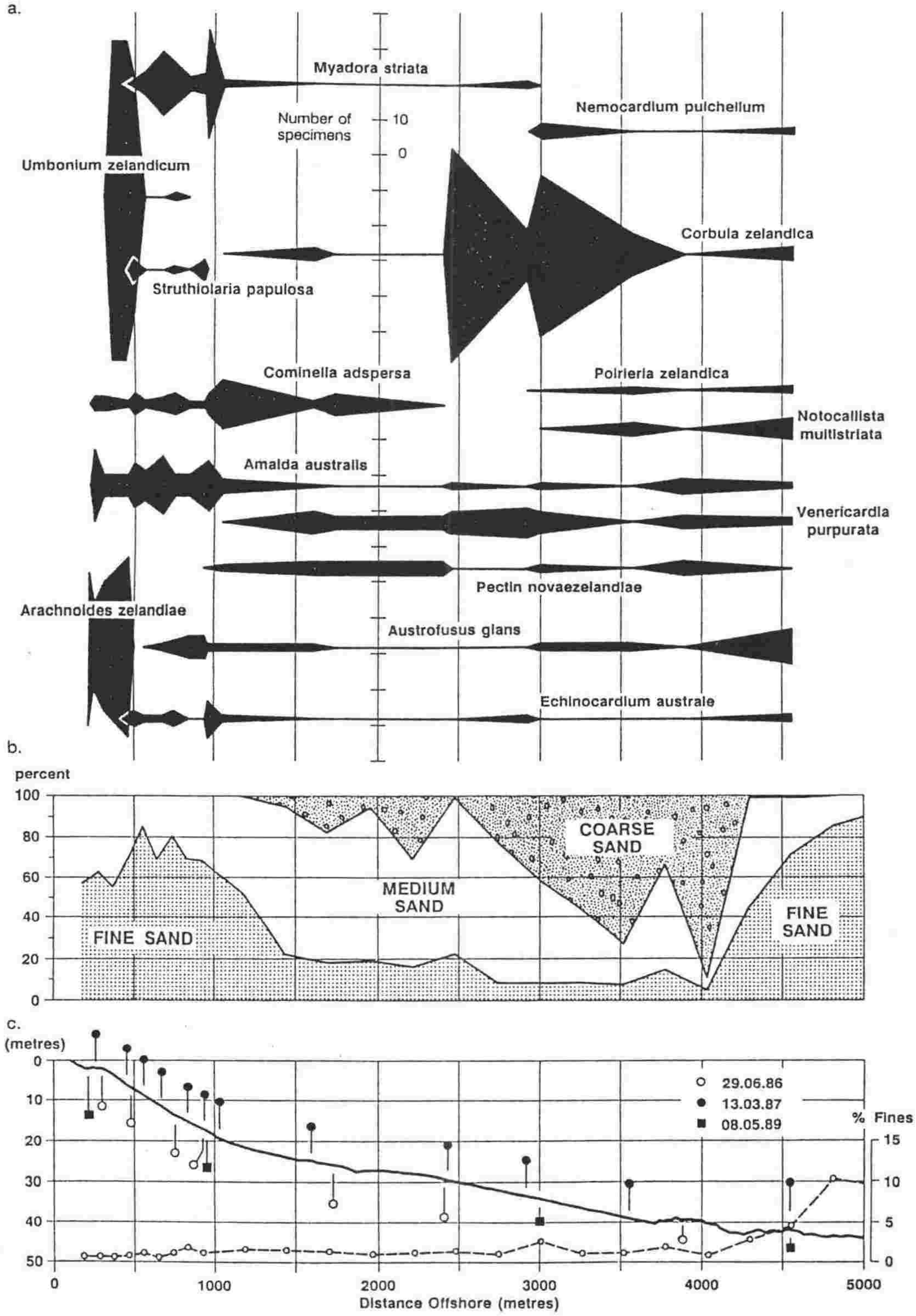

a.
10
0
Number of specimens
Myadora striata
Umbonium zelandicum
Corbula zelandica
Cominella adspersa
Amalda australis
Venericardia purpurata
Pecten novazelandiae
Fellasten zelandiae
Poirieria zelandica
Austrofusus glans
b.
percent
100
80
60
40
20
0
FINE SAND
MEDIUM SAND
c.
metres
0
10
20
30
40
50
% Fines
10
5
0
0
1000
2000
3000
4000
5000
distance offshore (m)

Figure 4.4 (a) Summary of distribution and abundance of the most commonly captured macrobenthos (b) variation in sediment size grades and (c) sample locations and variation in percent mud, across Walkway transect, June 1986, March 1987 and May 1989.


a.
Myadora striata
Number of specimens
10
0
Nemocardium pulchellum
Umbonium zelandicum
Corbula zelandica
Struthiolaria papulosa
Cominella adspersa
Poirieria zelandica
Notocallista multistriata
Amalda australis
Venericardia purpurata
Pectin novaezelandiae
Arachnoides zelandiae
Austrofusus glans
Echinocardium australe
b.
percent
100
80
60
40
20
0
FINE SAND
MEDIUM SAND
COARSE SAND
FINE SAND
c.
(metres)
0
10
20
30
40
50
29.06.86
13.03.87
08.05.89
% Fines
15
10
5
0
0
1000
2000
3000
4000
5000
Distance Offshore (metres)

captured from a particular area of shoreface or shelf seabed. Other species, including **Myadora striata** and **Tawera spissa**, are distributed more widely, but are relatively abundant over only part of their range. Figure 4.5 interprets and summarizes the results of the March 1987 Pakiri Bay benthos surveys. The benthos patterns are depicted relative to a representative shoreface and continental shelf profile and the sediment types identified in the previous chapter. This model has successfully predicted the outcome of benthos surveys, employing the same techniques, on three subsequent occasions. Subsequently sampling has been undertaken across Couldrey transect (May, 1988), Walkway transect (May 1989), and across a randomly selected transect 100 m south of Brown transect (bearing 030$^{o}$ north) in June 1988.

Four associations of species are recognized and, although there is overlap between them, each is characteristic of a particular area of seabed in Pakiri Bay. The boundaries between the four associations accord, more or less, with the spatial limits of the morphological components and sediment types described (Figure 3.13). The 'inshore-upper shoreface' association, for example, is dominated by two species **Umbonium zelandicum** and **Fellasten zelandiae**, that are found nowhere else in the study area. Although other species, such as **Cominella adspersa**, **Echinocardium cordatum** and **Amalda australis**, may also be present in low numbers. This association extends offshore 250 to 500 m, in 3 to 8 m water depth. The remaining three groupings of species are associated with the mid and lower shoreface, the inner shelf and the middle continental shelf (Table 4.1).

The number of species in each association is variable, as is the abundance of individuals within an association. For example, the benthic macrofauna of the 'inshore-upper shoreface' is dominated by just two species, whereas the number of species recorded from the shoreface is much greater. However, in terms of the abundance of animals on the seafloor in these environments, greatest densities occur in the former. For example, **Umbonium zelandicum** and **Fellasten zelandiae** occur in maximum densities of $10^2$ to $10^4$ individuals/m$^2$

Figure 4.5 (a) Interpretation of the relative abundance and distribution of the most commonly captured macrobenthos, showing the distribution of recognized associations of species, and (b) morphological and sedimentological variations across a representative shore normal profile.

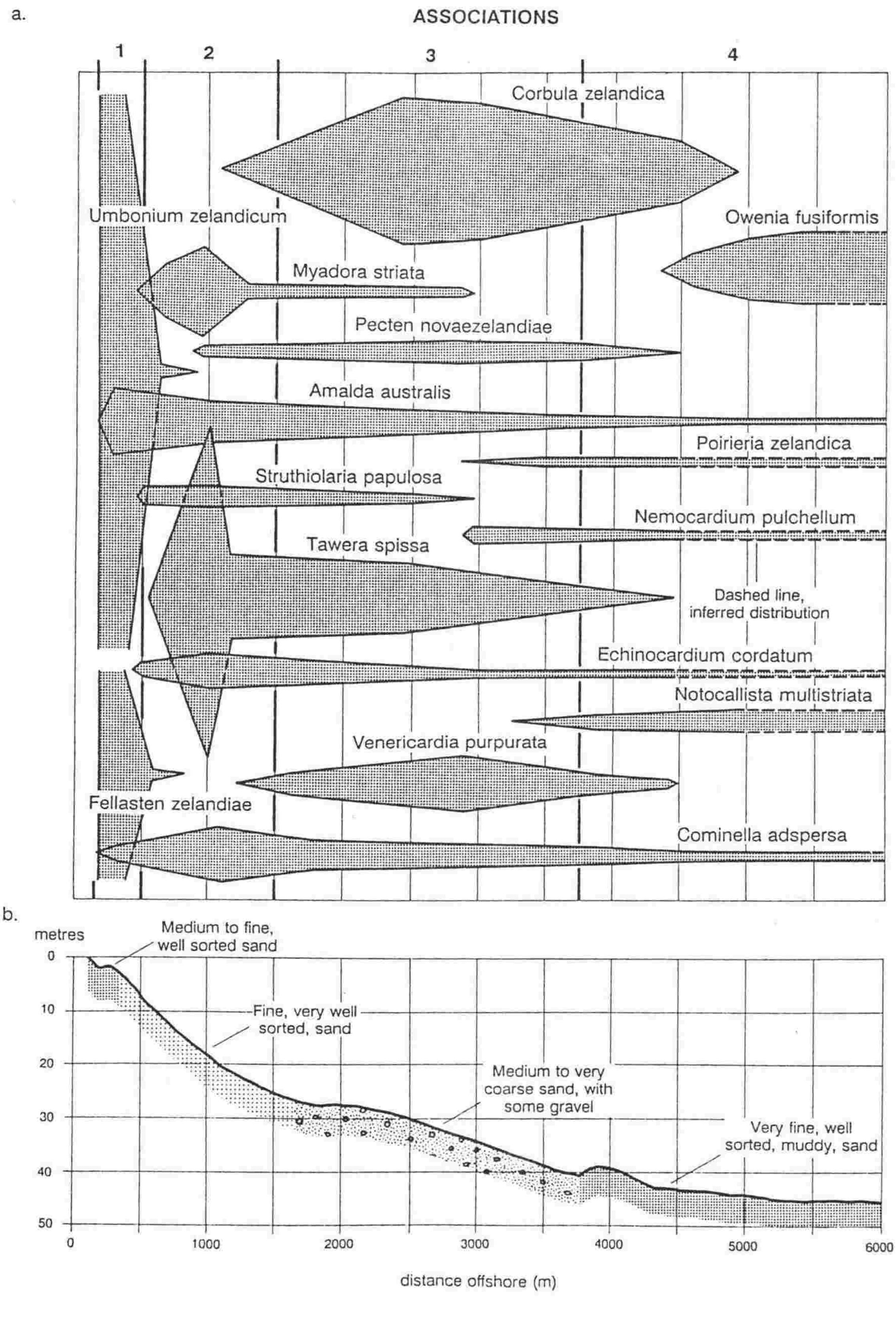

a.
ASSOCIATIONS
1
2
3
4
Corbula zelandica
Umbonium zelandicum
Owenia fusiformis
Myadora striata
Pecten novaezelandiae
Amalda australis
Poirieria zelandica
Struthiolaria papulosa
Nemocardium pulchellum
Tawera spissa
Dashed line, inferred distribution
Echinocardium cordatum
Notocallista multistriata
Venericardia purpurata
Fellasten zelandiae
Cominella adspersa
b.
metres
Medium to fine, well sorted sand
Fine, very well sorted, sand
Medium to very coarse sand, with some gravel
Very fine, well sorted, muddy, sand
0
10
20
30
40
50
0
1000
2000
3000
4000
5000
6000
distance offshore (m)

Table 4.1 Species Associations, Densities and Environmental Circumstances

| ASSOCIATION/<br>Species Composition | Density<br>No./$m^2$ | Distance<br>Offshore<br>(m) | Water<br>Depth<br>(m) | Substrate<br>Type |
|---|---|---|---|---|
| INSHORE - UPPER SHOREFACE | | 250-500 | 3-8 | Medium to fine, well sorted sand |
| Umbonium zelandicum | $10^3$ - $10^4$ | | | |
| Fellasten zelandiae | $10^1$ - $10^2$ | | | |
| (with) | | | | |
| Cominella adspersa | $10^0$ | | | |
| Echinocardium cordatum | $10^1$ | | | |
| Amalda australis | $10^0$ | | | |
| SHOREFACE | | 500-1500 | 8-25 | Fine, very well sorted sand |
| Tawera spissa | $10^1$ - $10^2$ | | | |
| Cominella adspersa | $10^0$ | | | |
| Myadora striata | $10^0$ - $10^1$ | | | |
| Amalda australis | $10^0$ - $10^1$ | | | |
| Struthiolaria papulosa | $10^0$ | | | |
| Echinocardium cordatum | $10^0$ | | | |
| INNER SHELF | | 1500-3750 | 25-42 | Medium to very coarse sand, with some gravel |
| Corbula zelandica | $10^1$ - $10^2$ | | | |
| Venericardia purpurata | $10^1$ | | | |
| Pecten novazelandiae | $10^0$ | | | |
| (with) | | | | |
| Tawera spissa | $10^1$ | | | |
| MIDDLE SHELF | | 3750- | 42- | Very fine, muddy sand |
| Notocallista multistriata | $10^{-1}$ | | | |
| Diplodonta globus | $10^{-1}$ | | | |
| Nemocardium pulchellum | $10^{-1}$ | | | |
| Poirieria zelandica | $10^{-1}$ | | | |
| Xenophora neozelandica | $10^{-1}$ | | | |

respectively. In contrast, maximum densities of species on the inner shelf are $10^1$ to $10^2/m^2$ and on the middle continental shelf $10^{-1}/m^2$. Estimates of the densities of species are based on the estimated area of seabed sampled (see Appendix F).

## 4.4 Modern Shell Production

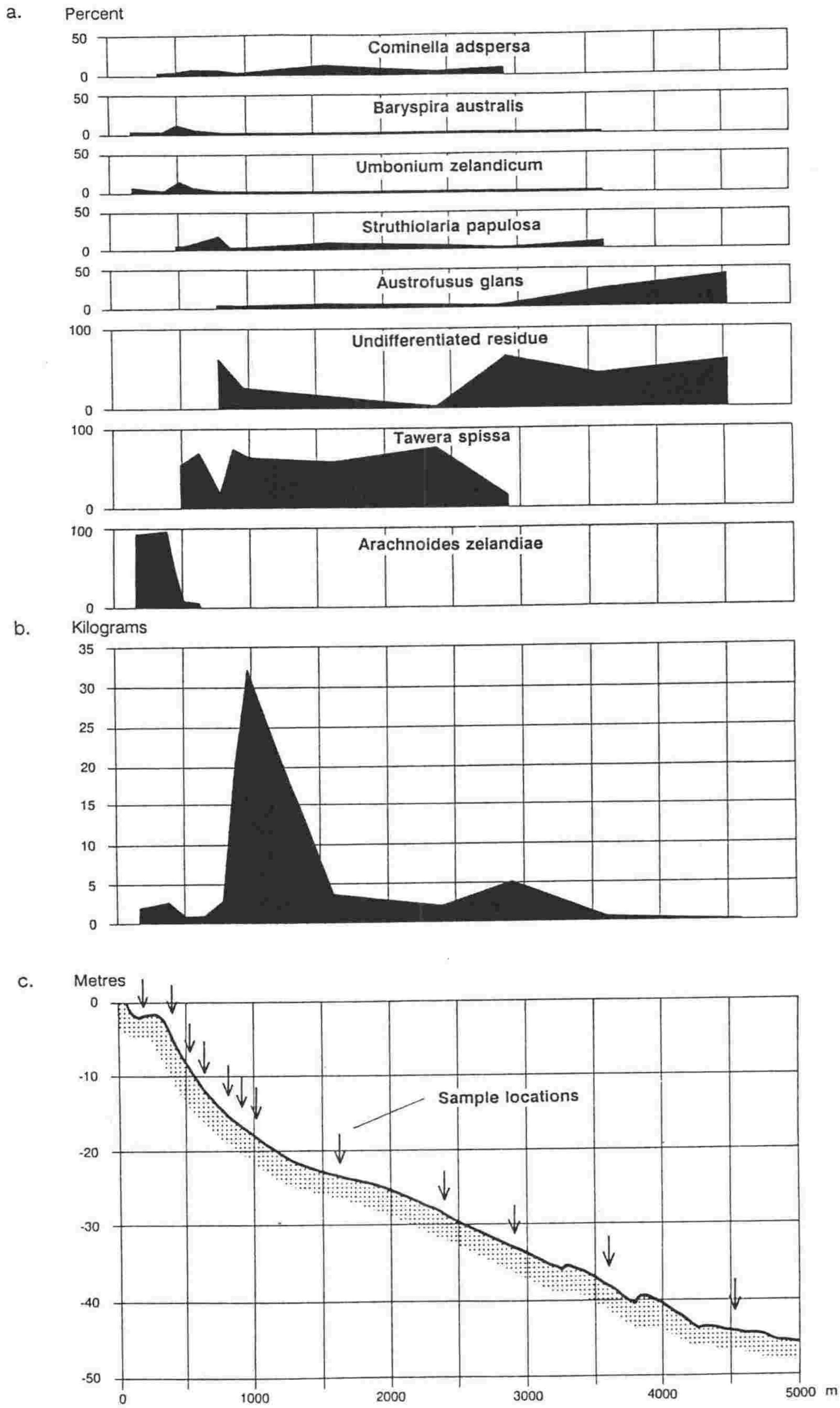
The interpretation of species distribution and abundance (Figure 4.5) allows the potential contribution of living (shell producing) organisms to the carbonate fraction of the sediments to be estimated. Weight is used as a convenient measure of shell production, and calculated at each sample station according to the procedure outlined in section 4.3.2.

The calculated weight of shell material at the sample stations across Matheson, Williams and Walkway transects ranges between a few grams and 30 kg. The variation in (live) shell weight across Williams transect is representative of the results obtained across each transect (Figure 4.6). The highest concentrations of shell occur near the base of the shoreface, 1000 to 1500 m offshore in about 20 m water depth. Lowest concentrations are found in sediments from the (lower) inner shelf and middle continental shelf, seaward of the mid shoreface.

Comparatively few species contribute most of the shell material. The actual contribution of any one species depends upon the number of individuals present, and the size and mass of that species' test. Hence, while **Umbonium zelandicum** are numerically most abundant, **Tawera spissa**, which has relatively more massive valves, contributes much more to total shell weight. **Struthiolaria papulosa**, **Pecten novazelandiae** and **Tawera spissa** collectively account for almost all the weight of shell across the (lower) shoreface and (upper) inner shelf.

The results of the macrobenthos surveys across the three transects are averaged to derive the mean concentration of (live) shell at

Figure 4.6 (a) Variation in the percentage of the total shell weight at each station contributed by the most commonly captured species, and (b) estimates of the total (live) shell weight at each station, across (c) Williams transect (12.03.87).


a.
Percent
50
0
Cominella adspersa
Baryspira australis
Umbonium zelandicum
Struthiolaria papulosa
Austrofusus glans
100
Undifferentiated residue
Tawera spissa
Arachnoides zelandiae
b.
Kilograms
35
30
25
20
15
10
5
c.
Metres
-10
-20
-30
-40
-50
Sample locations
1000
2000
3000
4000
5000 m

each sample station. The results are extrapolated between stations and the resulting curve integrated to calculate the total amount of shell material across the transect. This amounts to 17,556 kg of shell.

However, the estimates of shell weight at each station are not based on spot samples, but alongshore trawls that sample a finite area of seabed. Given a trawl speed of 2.5 knots, trawl time of 60 s and basket dredge width of 0.55 m the length and area of seabed sampled is 77 m and 42 $m^2$ respectively. Multiplying the above weight (17,556 kg) by the reciprocal of 0.55 standardizes the integration of the curve as kg/m. The amount (weight) of shell present actually represents the amount recovered from the top 5-10 cm of seabed in a swath of seabed (centred on the transect) 77 m wide and 4300 m long ($3.3 \times 10^5$ $m^2$). The actual weight of shell across the transect is therefore:-

$$17{,}556 \text{ kg}/0.55 \text{ m} \times 1.818 = 31{,}917 \text{ kg}/3.3 \times 10^5 \text{ m}^2$$

The pattern of live carbonate-producing benthos has been found to be consistent alongshore over the three year sampling period. Assuming that the averaged March 1987 data is representative within Pakiri Bay (length 13,000 m), the total weight of (live) shell across the shoreface and inner continental shelf is therefore:-

$$31{,}917 \text{ (kg}/3.3 \times 10^5 \text{ m}^2) \times \frac{1.3 \times 10^4 \text{ m}}{77 \text{ m}} = 5.3 \times 10^6 \text{ kg}$$

Given the area of seabed in Pakiri Bay, comprising the shoreface and inner continental shelf, is $5.46 \times 10^7$ $m^2$, the average concentration of shell over the Bay is $9.7 \times 10^{-2}$ kg/$m^2$ (97 g/$m^2$).

This figure has significance when compared with the actual weight of carbonate material in the sediments. This calculation is based on the estimates of carbonate material in the sediments across Williams transect, derived by averaging the results of multiple samples (Figure 3.20). Given that the weight of carbonate material has been determined for a 1 l sample of the bed by digestion, the weight of carbonate over an area of bed of 100 x 100 x 10 cm is simply the weight in 1 l multiplied by 100 (there being 100 l of sediment in a volume of 100 x 100 x 10 cm). The calculated weights of carbonate matter in this volume varies over the transect as the weight of carbonates in each litre sample analyzed varies. Calculated weights range from maximum concentrations at the base of the inner shelf of 450 g per 0.10 $m^3$ to the lowest values on the upper shoreface of 150 g per 0.10 $m^3$. Given the average weight of (live) shell over the seabed of Pakiri Bay is 97 $g/m^2$, modern biogenic production of shell clearly has the potential to significantly contribute to the bulk of the sediments of the study area.

The biogenic production of shell over time, the mass of shell added to the sediment body over a given period, may also be calculated. The maximum life span of the most abundant bivalve encountered **Tawera spissa** is thought to be about ten years (pers comm., Professor John Morton, Department of Zoology, University of Auckland). If the number of live **Tawera spissa** is stable, and an equal number of individuals recruit each year to replace those that die, the total amount of shell material will increase by 10 percent each year. Assuming the lifespan of 10 years is applicable to other Pakiri Bay mollusca, and there is no loss of shell by weathering or transport out of the system, the calculated existing weight of shell material of $5.3 \times 10^3$ tonnes would increase to $73 \times 10^6$ tonnes after 100 years, and approximately $1.7 \times 10^{40}$ tonnes after 1000 years.

### 4.5 Comparison of the Patterns of Modern Shell Production and Carbonate Concentration in the Sediments of Pakiri Bay

Investigations in the previous chapter (section 3.3.1) document variations in the proportion of carbonate in the sediments in Pakiri Bay. The location of sediments containing the highest carbonate concentrations does not correlate with the areas of highest contemporary shell production. In fact, as the comparison between the two characteristics shows across Williams transect, the converse is true. Production of shell as a result of contemporary biogenic activity occurs mostly across the lower shoreface (Figure 4.7 a), whereas carbonate concentrations in the sediments peak around the base of the inner shelf, approximately 3000 m seaward (Figure 4.7 b).

This discordancy is repeated across all the transects surveyed, and on all occasions. Figure 4.8 presents the mean (live) shell weight, derived from the three transect surveys, and the mean carbonate content at each sample station, derived from all seven Pakiri Bay transects. Initial concentrations of live shell, 200 to 400 m offshore reflect the presence of just two species, **Umbonium zelandicum** and **Fellasten zelandiae**, and the paucity of shell 400 to 800 m offshore the absence of any species in large numbers. The subsequent rapid increase in shell weight is due to the relative abundance of **Cominella adspersa**, **Myadora striata**, **Tawera spissa**, **Struthiolaria papulosa** and **Baryspira australis**. The subsequent decline in shell weight across the inner shelf reflects the reduction in numbers or absence of these species, and the presence of fewer and less abundant species (especially **Corbula zelandica** and **Venericardia purpurata**). This trend of diminishing shell production with increasing distance offshore culminates in the relatively sparse fauna of the mid continental shelf.

The relationship between the carbonate concentration of the sediments and contemporary shell production can be further investigated by determining the species composition of the carbonate rich sediments of the lower inner shelf, according to the procedure outlined in section 4.3.2. Table 4.2 lists the species most commonly identified in these sediments and their relative abundance. Most of the species that comprise the carbonate-rich sediments are relatively common across the Pakiri Bay transects. Live specimens of **Nucula hartvigiana**, a small inequivalve bivalve of the family Nuculidae, were observed for the first time - probably because of the coarse mesh of the basket dredge excludes capture. However, **Corbula zelandica** and **Venericardia purpurata** are well known from the lower inner shelf. The remainder of the fauna, with the exception

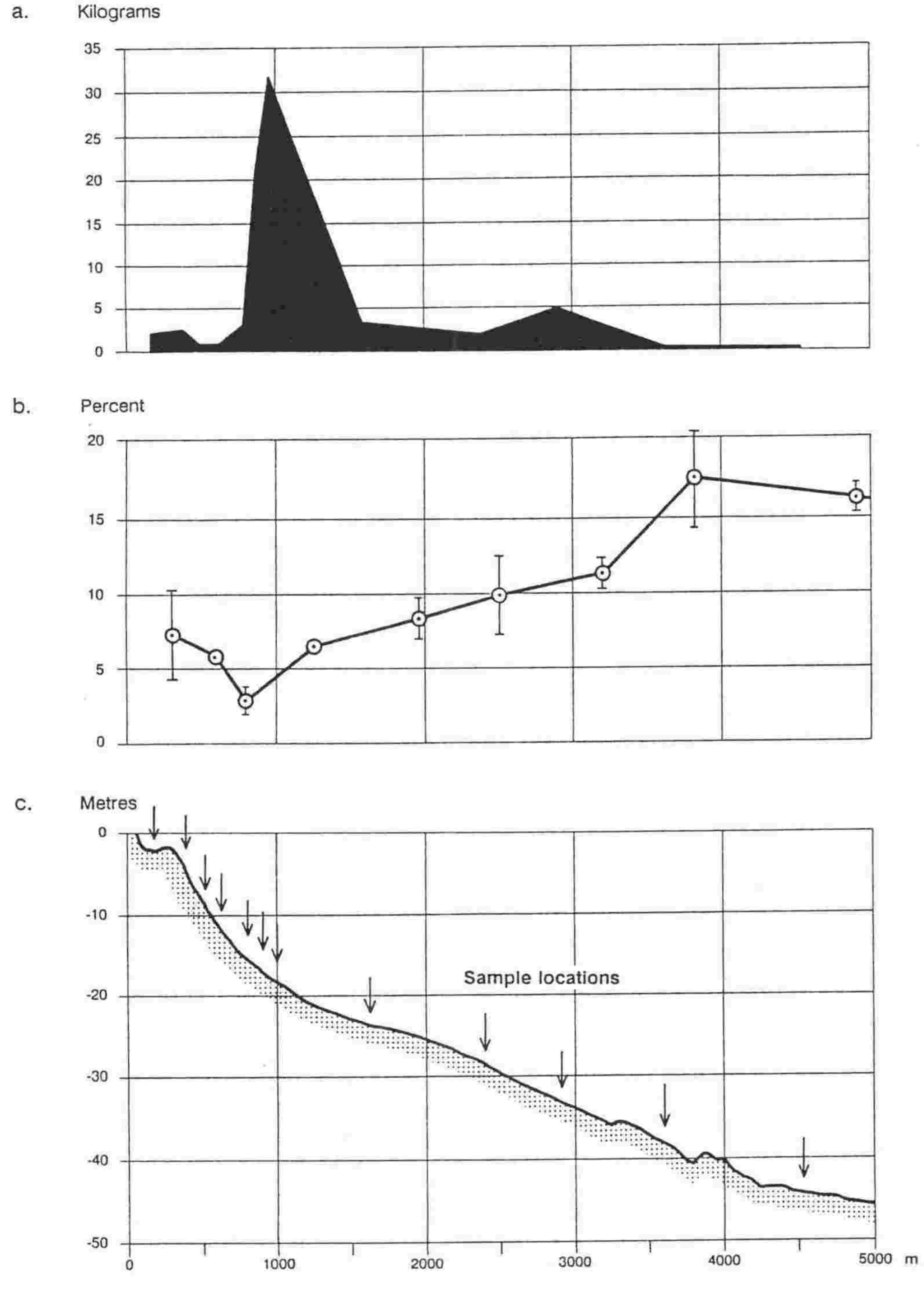
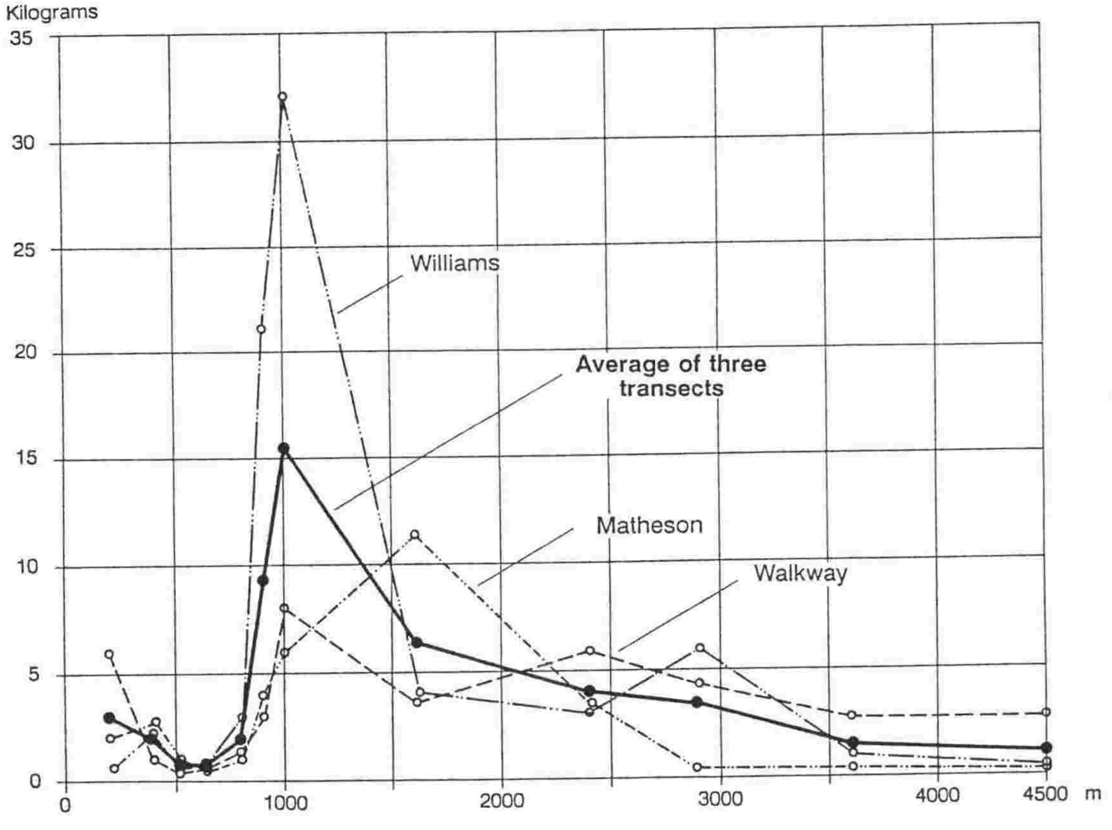



**Figure 4.7** Variation in (a) estimated (live) shell weight and (b) carbonate content of the sediment, across (c) Williams transect (12.03.87).

a.




b.

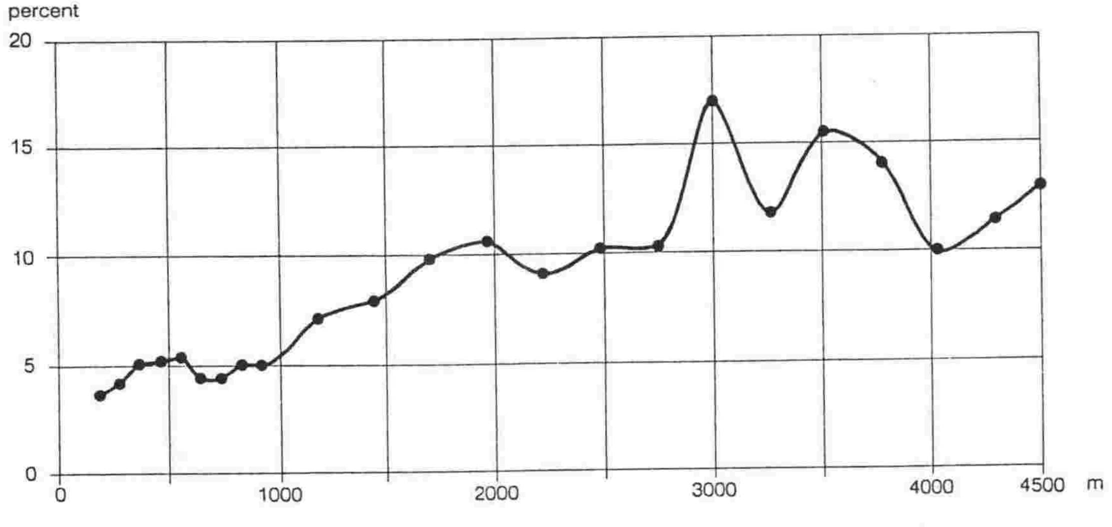



**Figure 4.8** (a) Offshore variation in (live) shell weight (March 1987 - average of three transects) and, (b) percent carbonate concentration in sediments (best fit curve of mean station values for all seven Pakiri Bay transects)

Table 4.2 Species Composition of (Lower) Inner Shelf, Carbonate-Rich Sediments, Pakiri Bay

| Transect | Gravel | | Walkway | | Couldrey | Williams | | Brown | Matheson | Okakari |
|---|---|---|---|---|---|---|---|---|---|---|
| Sample # | 18 | 19 | 66 | 67 | 20 | 19 | 21 | 4 | 80 | 16 |
| Species | Relative Abundance | | | | | | | | | |
| Corbula zelandica ..... | C | - | - | S | C | C | C | C | S | - |
| Diplodonta globus | - | S | - | - | S | - | - | - | - | - |
| Divaricella huttoniana .... | - | - | - | - | S | - | - | - | S | - |
| Dosinia anus ... | - | - | S | - | - | - | - | S | - | - |
| GENUS Chlamys .. | S | - | - | - | S | - | - | - | S | - |
| Glycymeris modesta ....... | - | S | - | - | - | S | - | - | - | - |
| Longimactra elongata ...... | S | - | - | - | S | - | - | S | - | C |
| Myadora striata | S | - | S | C | - | - | - | - | - | - |
| Nucula hartvigiana ... | C | - | - | - | C | - | S | - | C | S |
| Pecten novazelandiae . | - | S | C | S | - | - | - | C | - | - |
| Tawera spissa .. | S | - | - | C | - | C | S | C | - | - |
| Venericardia purpurata ..... | S | - | S | C | - | - | C | A | S | - |
| Zegalerus tenuis | C | - | C | - | C | S | - | - | - | - |
| Percentage of sample identified | 22 | 19 | 17 | 21 | 13 | 21 | 25 | 10 | 29 | 10 |

Phyla Composition of Carbonate Fraction of Sediments

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| % Mollusca | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 99 | 95 |
| % Foraminifera | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | <1 | 5 |
| % Bryozoa | 1 | <1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | <1 |

of **Pecten novazelandiae**, **Diplodonta globus** and **Divaricella huttoniana** are not recorded in significant numbers at these depths. Up to 90 percent of some samples are comprised of fragments, usually less that 5 mm maximum diameter, of biodegraded and discoloured shell. This fraction could not be identified - though it includes both juvenile and adult shell thicknesses. **Tawera spissa** and **Dosinia anus** comprise most of the identifiable shell fragments in the samples examined. Fragments of fan shells (Genus Chlamys), **Zegalerus tenuis** and **Pecten novazelandiae** were also common.

These results support the hypothesis that the high carbonate contents in the sediments of the inner shelf are not the result of insitu biogenic production. Only **Venericardia purpurata**, **Nucula hartvigiana** and **Corbula zelandica**, species that favour coarse sand and shell-gravel substrates, are commonly captured in the carbonate-rich sediments of the (lower) inner continental shelf. A large proportion of these sediments are comprised of species that inhabit the environments of the lower shoreface and inner continental shelf. In addition, the major proportion of these carbonate sediments is made up of weathered shell fragments, rather than whole valves in fresh condition which would be expected if the shell material had been derived insitu. In contrast, the carbonates are mostly present as fragments that exhibit signs of abrasion and biodegradation.

The high carbonate concentrations in the sediments of the lower inner shelf are not the result of insitu biogenic shell production. If the carbonate-rich sediments of the (lower) inner shelf are the result of modern production the tests of the dead mollusca must be transported either down-slope across the shoreface and inner shelf, or onshore from some unknown source on the middle continental shelf.

### 4.6 Environmental Interpretation of Pakiri Bay Macrobenthos

The species that characterize the macrobenthos of Pakiri Bay are described from other east coast and shelf locations. Enough is known about their ecology to infer certain characteristics about the environment from which they are captured. It is proposed that species composition, distribution and abundance in Pakiri Bay is primarily a response to one of two environmental factors - the grain size characteristics of the bed and the degree of disturbance of the bed (incorporating sediment transport and water circulation).

The previous chapter has described the range of sediment types present in Pakiri Bay, and results reported in the present chapter have documented the apparent relationships between these variations and associations of species (Table 4.1). Some of these relationships are well known. For example, both Venericardia purpurata and Corbula zelandica favour coarse sand and/or gravel substrates. In the latter case this is related to its system of anchoring by a single byssal thread (Yange and Thompson, 1976).

In most other cases however, the relationship between species distribution and abundance and substrate type is probably of secondary importance to the frequency and magnitude of bed disturbance and the flow conditions in the benthic boundary layer. The macrofauna of the extreme upper shoreface, for example, is dominated by the relatively abundant Umbonium zelandicum and Fellasten zelandiae, with Amalda australis also present. These species are described offshore from sandy beaches along the Northland coast in water depths less than 10 m, in moderate to high energy environments where they are thought to experience frequent sediment movement and disturbance. The urchin has a morphology, internal structure and behaviour that serves to reduce drag on the test, allowing it to inhabit areas affected by strong currents (Telford and Mooi, 1987). Both species favour or can tolerate habitats where the water flows are severe and burial as a result of sand movement commonplace.

In contrast the middle continental shelf contains a sparse but distinctive deep water fauna of mollusca and polychaetes including Nemocardium pulchellum, Notocallista multistriata, Austrofusus glans, Poirieria zelandica and Xenophora neozelandica. Many of these species are reported from other east coast locations, typically in water depths exceeding 40 m on very fine sandy substrates, with mud contents up to 20 percent (Grace and Hayward, 1980; Hayward et al., 1982; Hayward et al., 1984). Disturbance due to waves, tidal or other currents in these environments is considered to be nil or very low and many of the species are specifically adapted to such environments. The bivalve **Nemocardium pulchellum** for example, has very thin fragile valves that require it to live below the area 'affected by wave action' (Morton and Miller, 1968 p.569). The species of polychaete most commonly captured on the mid shelf in Pakiri Bay is also considered characteristic of low energy environments. Masses of imbricated tubes of the species **Owenia fusiformis** were dredged from stations on the mid shelf along all transects. This species is widespread on the continental shelf around New Zealand, and is thought to locate in areas of minimal bed disturbance (pers comm., Dr Ushi Kaly, Department of Zoology, University of Auckland).

Many species that inhabit the shoreface and inner shelf in Pakiri Bay are reported from environments intermediate between the extremes of high and low disturbance on the upper shoreface and the middle continental shelf respectively. **Tawera spissa** for example, because it buries itself only 1 or 2 cm below the sediment surface, is susceptible to erosion. It prefers relatively stable substrates, but is not reported from muddy sediments that are associated with very low energy environments elsewhere (Grace, 1972). At Pakiri it is most common between water depths of 20 and 35 m.

## 4.7 Summary and Conclusions

The fauna recorded from Pakiri Bay is dominated by molluscs. All other phyla combined, including the bryozoa and foraminifera, account for less than 1 percent of carbonate material at stations on the shoreface and inner shelf. Offshore from the Cape Rodney rocky coast this pattern is slightly modified, with brachiopods, solitary stony corals and bryozoas collectively comprising as much as 5 percent of samples. These results concur with other benthos and carbonate surveys along the east coast of Northland. The contribution of bryozoan fragments, foraminifera and other constituents of carbonate sediment are of minor importance compared with molluscan debris (Summerhayes, 1969 b; Thompson, 1975; Gillie, 1981).

The distribution and abundance of the major shell-producing benthos has been shown to be predictable. The pattern of species distribution is not haphazard, but shows a regular pattern whereby certain species are associated only (or most abundantly) with certain areas of the Pakiri Bay seabed. The two mollusc communities described from the western Hauraki Gulf by McKnight (1969), **Tawera spissa - Venericardia purpurata** and **Nemocardium pulchellum-Venericardia purpurata**, are similar to the inner shelf and mid shelf associations (respectively) identified in Pakiri Bay. The major difference is the absence of **Venericardia purpurata** in the mid shelf association, and the relatively sparse occurrence of Glycymeris in the Pakiri inner shelf samples. These inconsistencies may reflect real differences in the spatial and temporal occurrence of the communities, or simply be an artifact of the differing sampling techniques and strategies employed. Absent from the Pakiri Bay results are several large, deep-burrowing bivalves, including **Dosinia anus, Zenatia acinaces** and **Panopea zelandica** that are known from strandline and diver observations to be present in Pakiri Bay.

The pattern of increasing carbonate concentration in the sediments with increasing distance offshore in Pakiri Bay does not accord with the pattern of modern biogenic production. Most shell production occurs across the shoreface whereas the highest carbonate contents in the sediments occur over the (lower) inner continental shelf. The following scenarios that might explain this dichotomy are considered.

The carbonates of the lower inner shelf may not be related to the contemporary benthos, but rather some former depositional environment, or phase of biological activity. However, the species identified in these carbonates are not diagnostic of shallow-water species of either exposed sandy coasts, that presently occur along the Pakiri coast, or sheltered (lagoonal or estuarine) marine environments. The carbonate sediments at the base of the inner shelf are comprised of species that presently inhabit the shoreface and inner shelf. Further, the diversity of species in these sediments is greater than is presently observed in any one association of species recognized. This might result if carbonates were transported and concentrated during a lower sea level phase, however such a deposit would most probably be reworked and incorporated into sediments resulting from the last transgression, rather than left as a concentrated relict deposit.

A second scenario envisages the accumulation of biogenic detritus at the base of the inner shelf as the product of contemporary processes of sediment transport. The carbonates of the lower shelf would thus be an accumulation of skeletal debris derived from biogenic production of shell landward or seaward of the lower inner shelf. The comminuted nature of the carbonate material in the surface sediments, paucity of species and the very low rates of biogenic shell production on the middle continental shelf precludes the latter as a contemporary source of shell. This hypothesis is consistent the sedimentological characteristics of the inner shelf, which indicate the action of intense processes of sediment transport and sorting of sediments across the lower shoreface and inner shelf. The equally graded nature of both the biogenic and non-biogenic component of the inner shelf sediments is consistent with these processes occurring sometime after sea level approximated its present position.

The disparity between the low concentrations of carbonate in the sediments near the coast and the high concentrations of the lower inner shelf may also result from transport of the non-biogenic fraction of the sediments. Areas of seabed with high concentrations of carbonates can be interpreted as lag deposits from which the non-biogenic fraction has been preferentially removed, whereas areas with low concentrations of carbonate result from the dilution of the shell material due to comparatively high rates of non-biogenic sediment deposition. If this scenario is correct it would imply sediment is being preferentially eroded from the inner shelf at Pakiri and deposited on the shoreface. Assuming smaller particles are more easily transported this hypothesis is consistent with the observations of the size-graded bed of the inner shelf. At the same time carbonate fragments in the sediments of the shoreface are probably subjected to higher levels of disturbance and hence greater abrasion.

Many of the species captured in the study area are known to inhabit particular marine environments at other locations along the Northland coast and shelf. The pattern of fauna in Pakiri Bay accords with an onshore-offshore environmental gradient of decreasing bed disturbance with increasing distance offshore, with substrate type of much less importance. In particular there is a marked contrast between the species of the shoreface and inner shelf and those of the middle continental shelf. The latter are widely interpreted as diagnostic of low energy environments where disturbance of the bed by currents is minimal. It seems likely therefore that whatever physical processes of sedimentation are affecting the inner shelf do not act to the same extent on the middle continental shelf.

# Chapter 5

# MORPHOLOGY AND MORPHODYNAMICS OF THE PAKIRI SHOREFACE AND CONTINENTAL SHELF

## 5.0 Introduction

Investigations reported in the preceding chapters document characteristic sediment and benthos patterns in Pakiri Bay. The sediment types are defined in terms of the texture and composition of the bed, and segregated from adjacent types where there is a marked sedimentological discontinuity. These discontinuities are apparently closely related to the boundaries of the morphologic components that comprise the subtidal Pakiri sediment body (Figure 3.13). This chapter investigates the character of these components, and the nature of the relationship between the morphology and sedimentology of the sediment body.

The combined morphology of the shoreface and continental shelf is discussed, and interpreted in terms of external factors that might influence its configuration. In particular, the results of an investigation of the sub-strata of the sediment body, using a sub-bottom sonar device, are described.

Historic records of the morphology of the coast, shoreface and continental shelf are examined, and compared with survey data obtained during the present study. These morphodynamic studies are based on a 10 year time series of beach and offshore surveys from 1978 to 1988. These data are relevant in so much as they provide evidence of sediment transport in Pakiri Bay. Immediately prior to the commencement of these surveys the east coast experienced a severe storm that eroded the exposed sandy coasts of Bream Bay, Omaha and Pakiri. The implications of this storm for understanding sediment transport on the shoreface are examined.

## 5.1 Survey Techniques

### 5.1.1 Onshore and Echosound Survey Techniques

Interpretations of the morphology of features in Pakiri Bay are based on field investigations involving echo-sound, sub-bottom and side-scan surveys. Onshore dune and foreshore profiles were surveyed using dumpy level or theodolite instruments. Two types of offshore echosound survey were employed - single surveys using a Furuno echosounder mounted on the University of Auckland's research vessel, R.V. Proteus, and repeated surveys along the same transects, using a Furuno FE-450 sounder mounted in an Avon (hard-bottomed) inflatable. These techniques are described in Appendix I.

Table 5.1 lists the offshore surveys undertaken during the present investigation, as well as a hydrographic survey conducted by the Royal New Zealand Navy in 1964, and two sets of surveys conducted during a previous study supported by the Marine Division of the Ministry of Transport and the Auckland Regional Water Board (Hilton and McLean, 1984).

Backshore and foreshore surveys have been conducted at Pakiri since 1978, initially by the Auckland Regional Water Board (1978-1983), and later as part of the present investigation (1984-1988). Since 1988 six-monthly surveys have once again been undertaken by the Water Board, with additional surveys by the Department of Conservation (Coastal and Marine Division, Auckland Conservancy). All surveys were reduced to a common datum, and have been conducted over the same transects. Collectively this data set comprises a time series of observations of the position, configuration and morphology of the Pakiri Bay coast of ten years (Table 5.2).

Surveys were undertaken along the transects located and described in Appendix D, and conducted following storm events, during very calm conditions in conjunction with offshore echosound surveys, or when the availability of personnel allowed. Distances and elevations are calculated relative to datum (mean sea level Auckland), and

Table 5.1 Pakiri Offshore Surveys

| | Transects[1] | | | | | | | | | Method[2] | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Date | Ma | 2971 | Br | Wi | Co | Wa | Gr | Pi | 2941 | UC | SC | FC |
| 1964[3] | closely spaced echosound profiles | | | | | | | | | | * | |
| 21.11.78[4] | - | x | x | x | x | x | x | x | x | | | * |
| 03.07.84 | - | x | x | x | x | x | x | x | x | | * | |
| 23.04.85[5] | x2 | - | x | x | x | x | x | x | x | | | * |
| 24.07.85 | x2 | - | x2 | x2 | x2 | - | - | - | - | * | | |
| 01.10.85 | - | - | x4 | x3 | x | - | - | - | - | | | * |
| 28.10.85 | - | - | x2 | x | x | - | - | - | - | Co | | * |
| 29.10.85 | - | - | - | - | - | x | x | - | - | | * | |
| 14.01.86 | x | - | x | x | - | - | - | - | - | | * | |
| 08.04.86 | x | - | x | x | x | x | x | - | - | | * | |
| 15.07.86 | - | - | x2 | x | - | x | x | - | - | | | * |
| 03.02.87 | x2 | - | - | - | - | - | - | - | - | | | * |
| 03.04.87[6] | x | - | x | x | x | x | x | - | - | | * | |
| 26.03.88 | - | - | - | x | - | x | x | - | - | * | | |
| 08.05.89 | - | - | - | - | - | x | - | - | - | | * | |

1. Ma - Matheson, Br - Brown, Wi - Williams, Co - Couldrey, Wa - Walkway, Gr - Gravel, Pi - Picnic, 2971/2941 - Auckland Regional Water Board datums (1978).

2. Echosound survey method (see Appendix I) UC - uncontrolled, SC - semi-controlled, FC - fully controlled.

3. Derived from fair chart, Royal New Zealand Navy, Hydrographic Office.

4. Surveyed by Murray North Ltd (Auckland).

5. In addition, Te Rere Bay and Te Arai Point surveys.

6. Also Te Arai Point, Cape Rodney, Goat Island, Okakari Point.

Table 5.2 Pakiri Beach Surveys (1978 to 1988)

| Date | Matheson | Brown | Transects Williams | Couldrey | Walkway | Gravel |
|---|---|---|---|---|---|---|
| 12.09.78[1] | - | - | - | - | * | * |
| 17.10.78 | - | - | * | * | - | - |
| 24.10.78 | - | * | - | - | - | - |
| 21.11.78 | - | * | * | * | * | - |
| 14.12.78 | - | * | - | * | * | * |
| 24.03.79 | - | * | * | * | * | * |
| 14.08.81 | - | * | * | * | * | * |
| 16.09.82 | - | * | * | * | * | * |
| 28.01.83 | - | * | * | * | * | - |
| 20.10.83 | - | * | * | * | * | * |
| 13.11.84 | - | * | * | * | * | - |
| 06.12.84 | - | * | * | * | - | - |
| 26.01.85 | - | - | - | * | * | * |
| 04.02.85 | * | - | - | - | - | - |
| 19.03.85 | * | * | * | * | - | - |
| 09.04.85 | * | * | * | * | - | - |
| 11/12.06.85[2] | */- | */- | -/* | */- | -/* | -/* |
| 03.07.85 | - | * | * | - | - | - |
| 13.08.85 | - | * | * | - | - | - |
| 30.08.85 | - | * | * | * | - | - |
| 04.09.85 | - | * | * | - | - | - |
| 11/12.09.85 | - | -/* | -/* | -/* | */- | */- |
| 17.09.85 | - | * | - | - | - | - |
| 20/21.09.85 | - | */- | -/* | -/* | - | - |
| 28/29.09.85 | - | -/* | -/* | - | */- | */- |
| 01/02.10.85 | - | */- | -/* | -/* | - | - |
| 13/15.10.85 | - | */- | */- | */- | -/* | -/* |
| 28/29.10.85 | - | - | * | * | -/* | - |
| 26/28.11.85 | - | -/* | -/* | -/* | */- | */- |
| 14/15.12.85 | - | */- | */- | */- | -/* | -/* |
| 26.12.85 | - | - | - | * | - | - |
| 15/16.01.86 | */* | */* | */* | -/* | -/* | -/* |
| 29/30.01.86 | -/* | -/* | -/* | */- | */- | */- |
| 09/10.06.86 | -/* | -/* | -/* | */- | */- | */- |
| 16/17.07.86 | - | */- | - | - | -/* | -/* |
| 11/12.09.86 | */- | - | */- | - | - | -/* |
| 02/03.12.86 | -/* | -/* | -/* | */- | */- | - |
| 12.12.86 | - | - | - | * | - | * |
| 15.01.87 | - | - | - | - | * | * |
| 17.03.88 | - | * | * | * | * | * |

Note: 1. 1978-1983 Auckland Regional Water Board surveys.

2. Survey occurs on day(s) marked with an asterisk for each set of surveys.

expressed as both distance/elevation plots relative to datum, and as excursion distance coordinates, after the method of McLean and Thom (1975).

There are some omissions in the overall Pakiri-Mangawhai survey record. This investigation has been little concerned with the Mangawhai Beach transects (2941 and Picnic). The Regional Water Board's 2971 transect, immediately south of the Pakiri River mouth was abandoned, and an adjacent transect (Matheson) established in 1985, relative to auxiliary datum 2971 $S_2$. Nevertheless, the surveys are continuous for Brown, Williams, Couldrey, Walkway (SB2) and Gravel (SB1) transects - and the 1978/1988 surveys by the Water Board permit comparison of the net change at all Mangawhai and Pakiri transects over a 10 year period.

### 5.1.2 Side-scan Sonar Technique

The specifications and operating parameters of the Klein 500 sidescan sonar deployed at Pakiri are given in Appendix J. The survey was undertaken with the assistance of the Defence Scientific Establishment of the Royal New Zealand Navy on 15 March 1987. The resolution of the survey, given the relatively narrow horizontal sound beam employed (1.2$^{o}$) and pulse length (100 milliseconds) over the 100 m range is thought to be 10 cm, or better. Ripples, of wavelength less than 1 m and amplitude of less than 10 cm, were continually detected along the second leg of the survey.

Approximately 22 km of seabed were surveyed using simultaneous sidescan and sub-bottom sonar. Four transects were surveyed, two alongshore lines that followed (approximately) the 25 and 45 m isobaths, and intersecting shore-normal lines (Figure 5.1). Location of survey stations was accomplished by periodic radar triangulation.

The side-scan sonar method and principle of operation is described by Tucker (1966) and Belderson <u>et</u> <u>al</u>. (1972). These writers provide

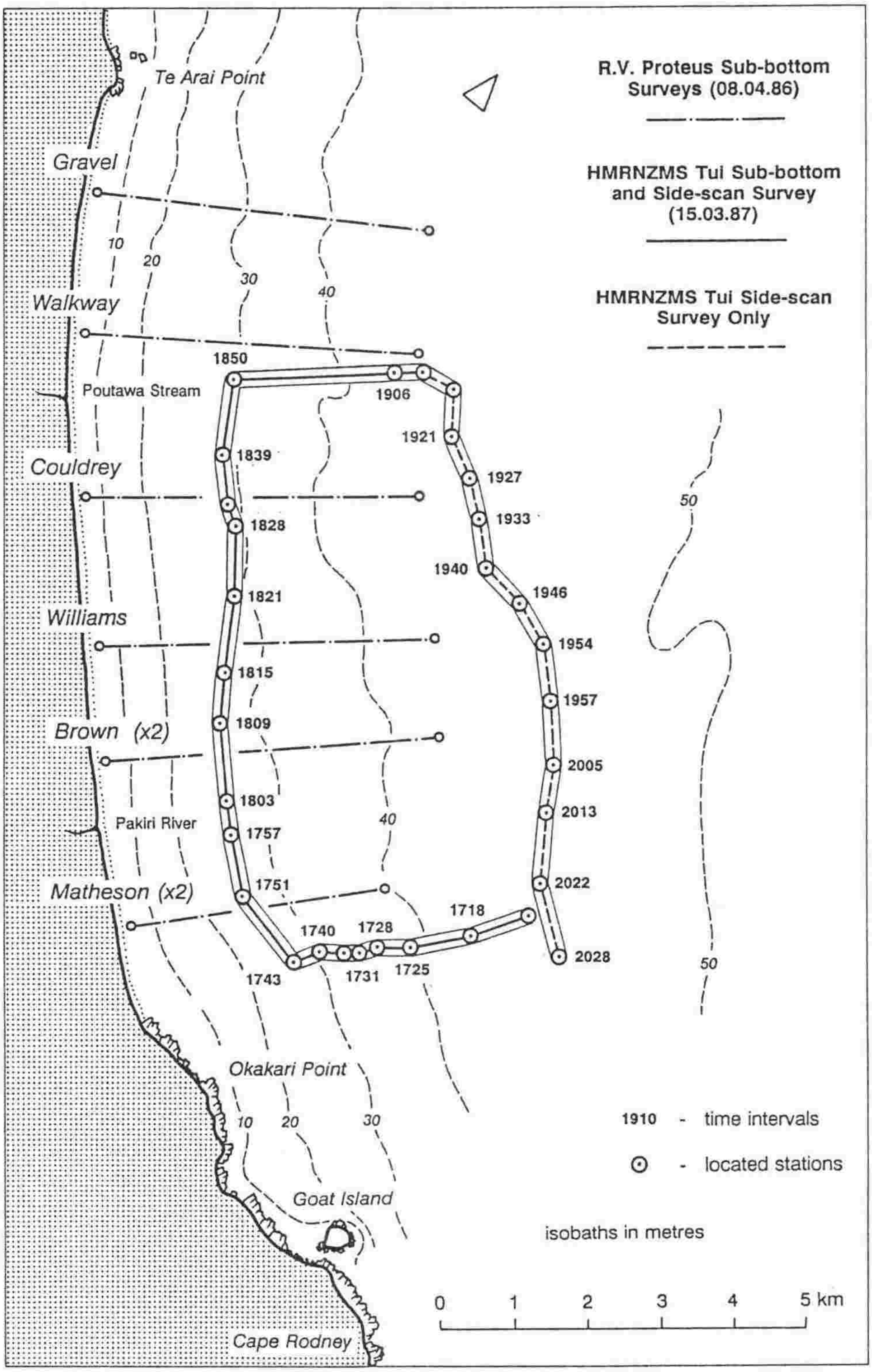



**Figure 5.1** Area of seabed surveyed by (a) side-scan sonar and sub-bottom transect surveys (15 March 1987) by H.M.S. Tui, and (b) sub-bottom transect surveys (April, 1986).

numerous interpretations of sonographs of various bedforms and substrate types from shallow marine environments. These are consistent with those of recent investigations of inner shelf environments (for example, Karl, 1980; Hunter et al., 1982; Cacchione et al., 1984; Hunter et al., 1988). In terms of the sedimentology of the seabed the coarser the texture the greater the reflectance, and hence the darker the paper image. Sands and muds appear in fainter tones. Sand ribbons, sand waves and various types of ripples are well documented in the above literature, and show consistency of record from place to place. The troughs or depressions associated with these features generally show up as darker tones.

### 5.1.3 Sub-bottom Sonar Technique

The principles of continuous sub-bottom seismic reflection profiling are outlined in McQuillin and Andrews (1977). Reflection of seismic waves takes place at a boundary between layers of contrasting acoustic impedance (seismic velocity x density), such that the reflection strength depends on the impedance contrast.

The sub-bottom work was undertaken using an ORE sub-bottom sonar system, deployed from the R.V. Proteus. Profiles were surveyed along Gravel, Walkway, Couldrey, Williams, Brown and Matheson transects to distances of approximately 4500 m offshore. An additional alongshore and shore-normal sub-bottom survey was undertaken for this study by the Defence Scientific Establishment of the Royal New Zealand Navy (Figure 5.1), using a different instrument (though at the same frequency). The specifications of the instruments deployed are described in Appendix J.

Surveys were undertaken along the transects delineated in the field by alignment of shore markers, as per the method described in Appendix B. The R.V. Proteus surveys were located along the transect by radar range-finder and the Navy survey by range-finder triangulation. Shore-normal surveys extended from (about) the crest of the nearshore bar to water depths of approximately 46 m, a variable distance seaward of the inferred inner-mid shelf boundary.

## 5.2 Morphologic Components of the Study Area

The major morphologic components of the Pakiri Bay sediment body were identified in Chapter Three. These comprise the sand dunes of the backshore, the foreshore (beach and berm face) and low tide terrace, the alongshore trough and alongshore bar association, shoreface, inner continental shelf and the middle continental shelf (Figure 3.13). This section discusses in greater detail the nature of the subtidal components of the sediment body. Aspects of the geomorphology of the coast are described in section 5.4.

### 5.2.1 Shoreface

In accordance with the original definition by Johnson (1919), and recent work by Shipp (1984) and Niedoroda et al. (1984), the shoreface is interpreted in Pakiri Bay as the relatively steeply sloping concave segment of seabed between the alongshore bar and the inner continental shelf. Between 1500 and 2000 m offshore, in water depths of 20 to 25 m, there is a transition from the lower concave slope of the shoreface to the convex surface of the inner continental shelf.

The transition from the (concave) lower shoreface to the (convex) inner shelf is preceded by a lessening of the gradient of the seabed. At the base of the shoreface typical slope angles for the Pakiri Bay profiles are $0.5^{0}$, compared with about $1.0^{0}$ 1000 m offshore, and $1.5\text{-}2.0^{0}$ 500 m offshore. This last angle, representing the mean slope across a width of profile 50 m either side of sample point, is the steepest measured at any point on the profiles (Figure 5.2 a-g). In marked contrast, the gradient of the inner shelf near the juncture with the shoreface is close to $0.0^{0}$. When superimposed all of the Pakiri Bay profiles show remarkable

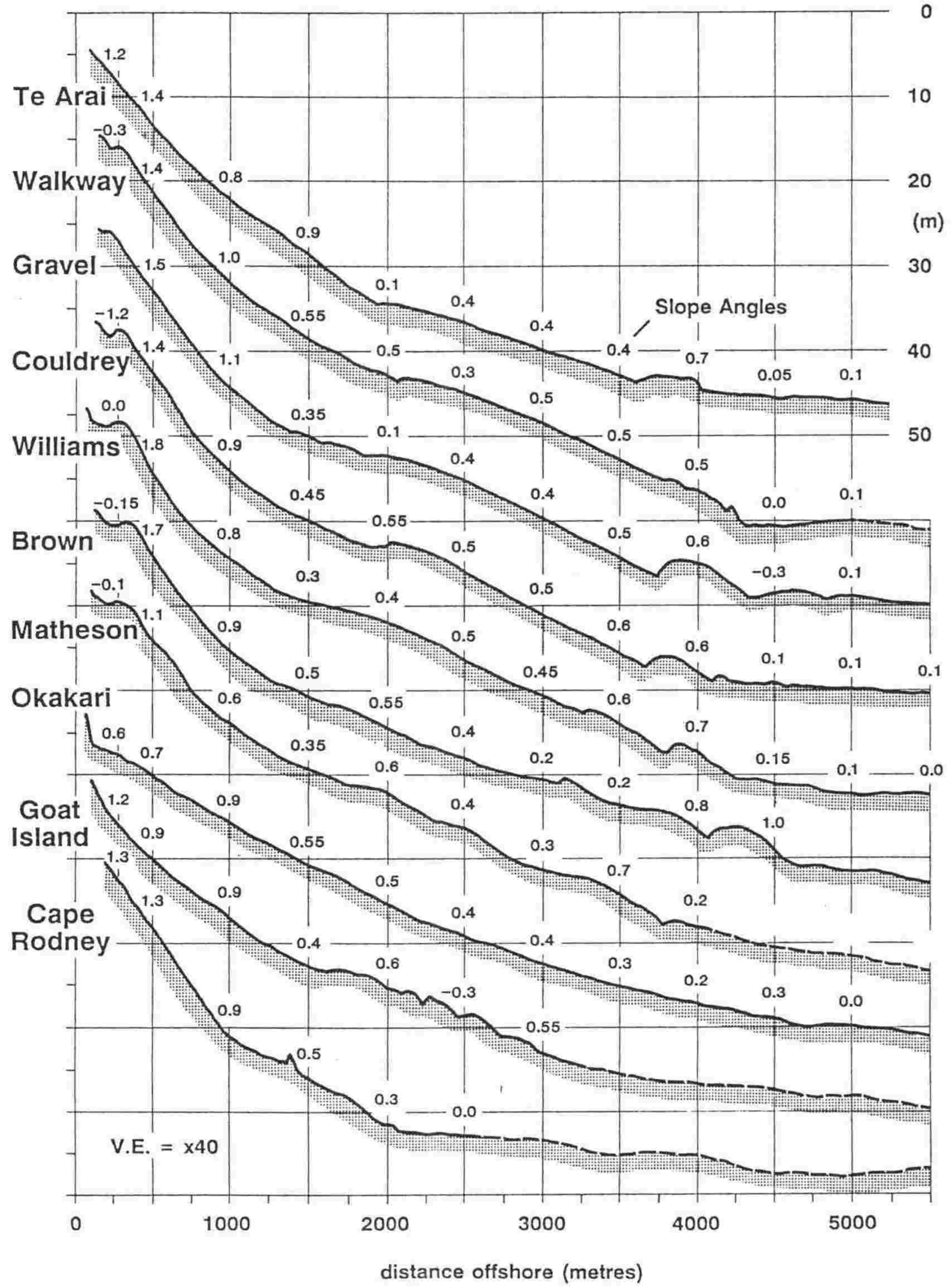



Figure 5.2 Comparison of 1986 shore-normal profiles, Te Arai Point to Cape Rodney, showing seabed slope angles at 500 m intervals (dashed segments derived from RNZN hydrographic chart, 1974)

consistency. However, in terms of its configuration and bathymetric range the shoreface is the most consistent morphologic feature recognized, with a width of about 1700 m, and a depth range of 3 to 25-28 m below mean sea level (Figure 5.3).

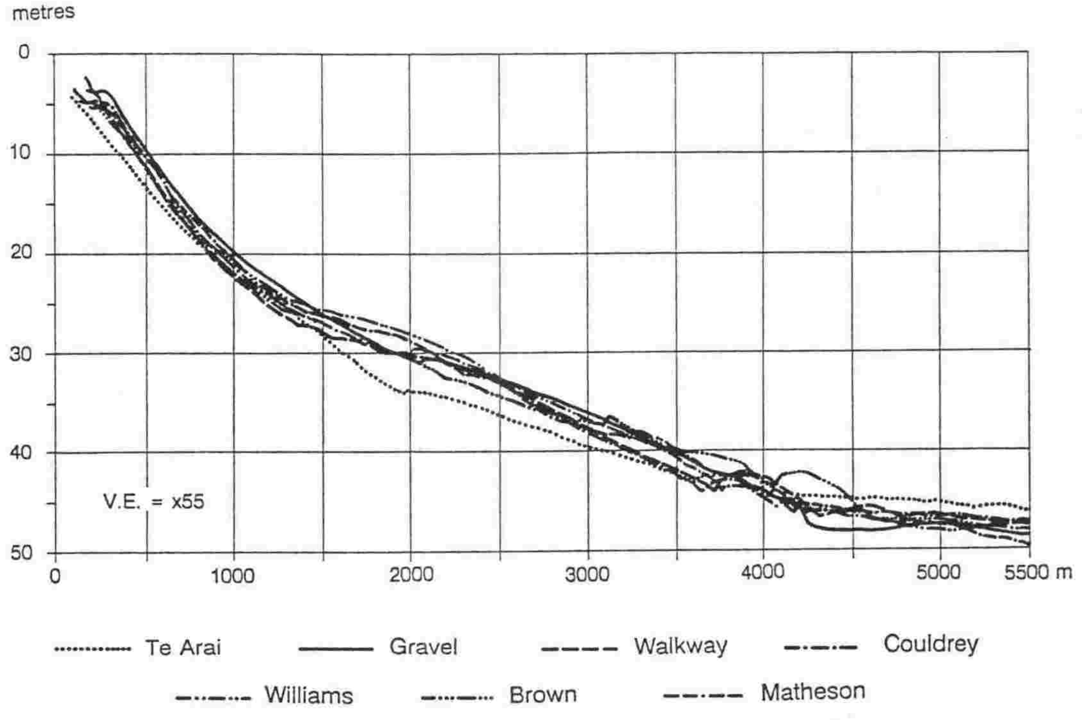
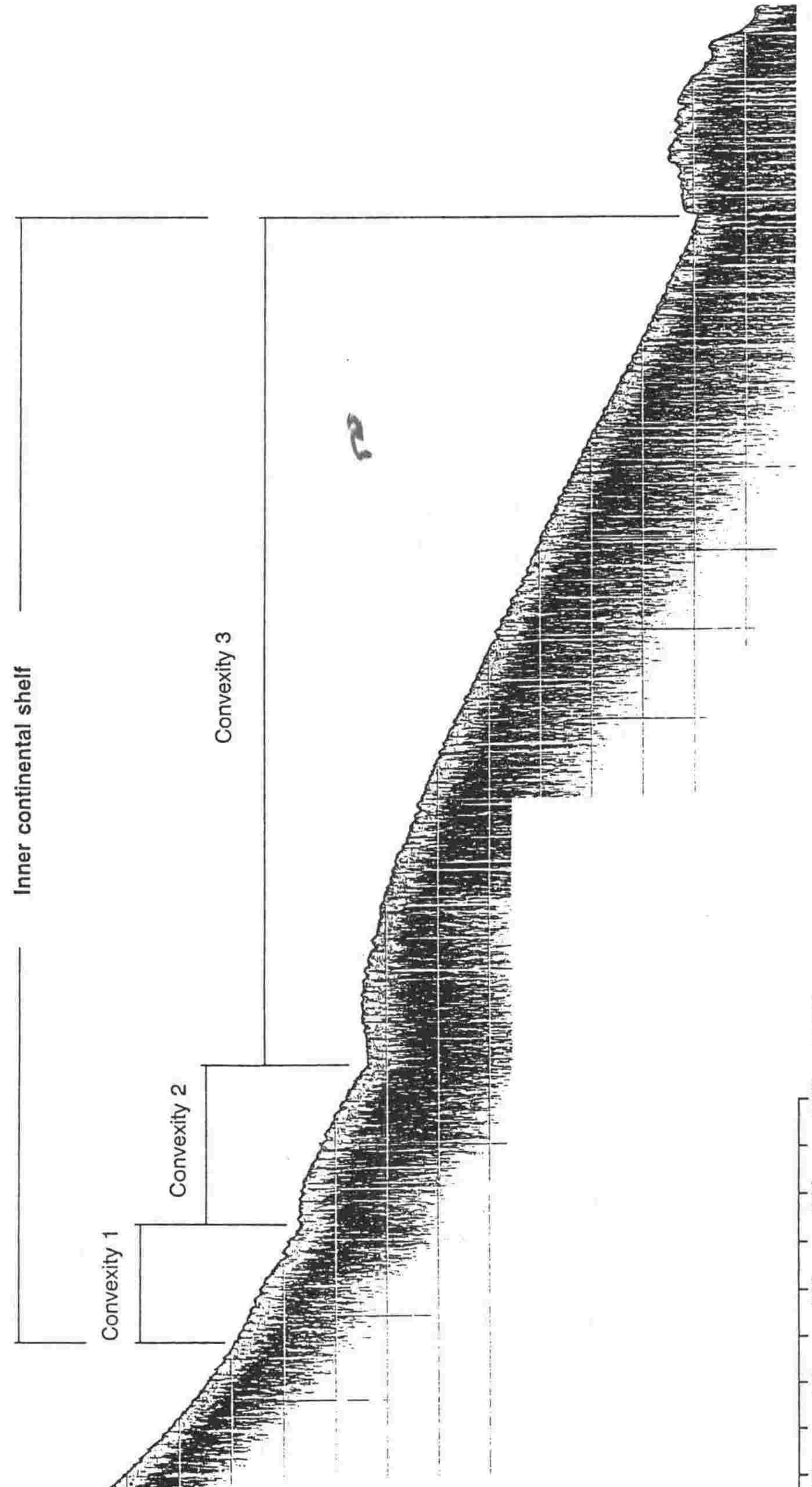



**Figure 5.3** Superimposition of 1987 Pakiri Bay shoreface and continental shelf profiles

### 5.2.2 Inner Continental Shelf

Across most transects the inner continental shelf is comprised of a single curvilinear convexity, although on some profiles one or two adjoining convexities may also be present landward of the main convexity. Across Walkway transect two smaller convexities are present (Figure 5.4). Collectively these comprise a sequence of adjoining curvilinear slope components, the overall dimensions of which increase in a seaward direction. In the case of Walkway transect the seaward, middle and landward convexities have plan widths of 1870, 352 and 241 m respectively. The relief of the two


Inner continental shelf
Convexity 1
Convexity 2
Convexity 3
(metres)
20
18
16
14
12
10
8
6
4
2
0
0
200
400
600
800
1000
metres

smaller convexities, measured from the crests to the two intervening swales is low compared with the major convexity of the inner shelf. These have depth ranges of approximately 1 and 15 m respectively.

Across Te Arai, Gravel, Walkway and Couldrey transects the inner shelf is comprised of two or three curvilinear elements (Figure 5.5). Across Williams and Brown transects, however, the surface of the inner shelf is less uniform, although convexities of several hundred metres length are still present seaward of the shoreface on both profiles.

### 5.2.3 Hummocks

Across most of the transects the transition from the inner shelf to the middle continental shelf accords with the presence of one or more convexities, termed hummocks (Figure 5.6 a-f). These occur 3600 to 4600 m offshore, immediately seaward of the inner shelf, with a mean distance of 4085 m (Table 5.3). The landward edge of the hummocks occurs in 40 to 45 m water depth. They are broad features. The average width of those observed on the transect echosound records is about 440 m, but with maximum heights of only 3 to 4 m (measured from the crest of the hummock to the level of the juncture point with the middle continental shelf, Figure 5.6 c). The largest example, recorded from Walkway transect, has a length of about 600 m and an amplitude of about 4 m.

The hummocks are absent across Okakari transect. Convexities are present across the shoreface and inner shelf of Matheson transect, but these are subdued, ambiguous, features compared with those observed at the base of the inner shelf across transects to the north (for example, Couldrey Figure 5.6 d). These examples have well-defined landward and seaward margins, with abrupt changes in the gradient of the bed. Most are asymmetrical in section, skewed toward the coast, with a steep landward face and relatively gentle seaward face. The example(s) on Gravel transect (Figure 5.6 b) represents something of an exception.

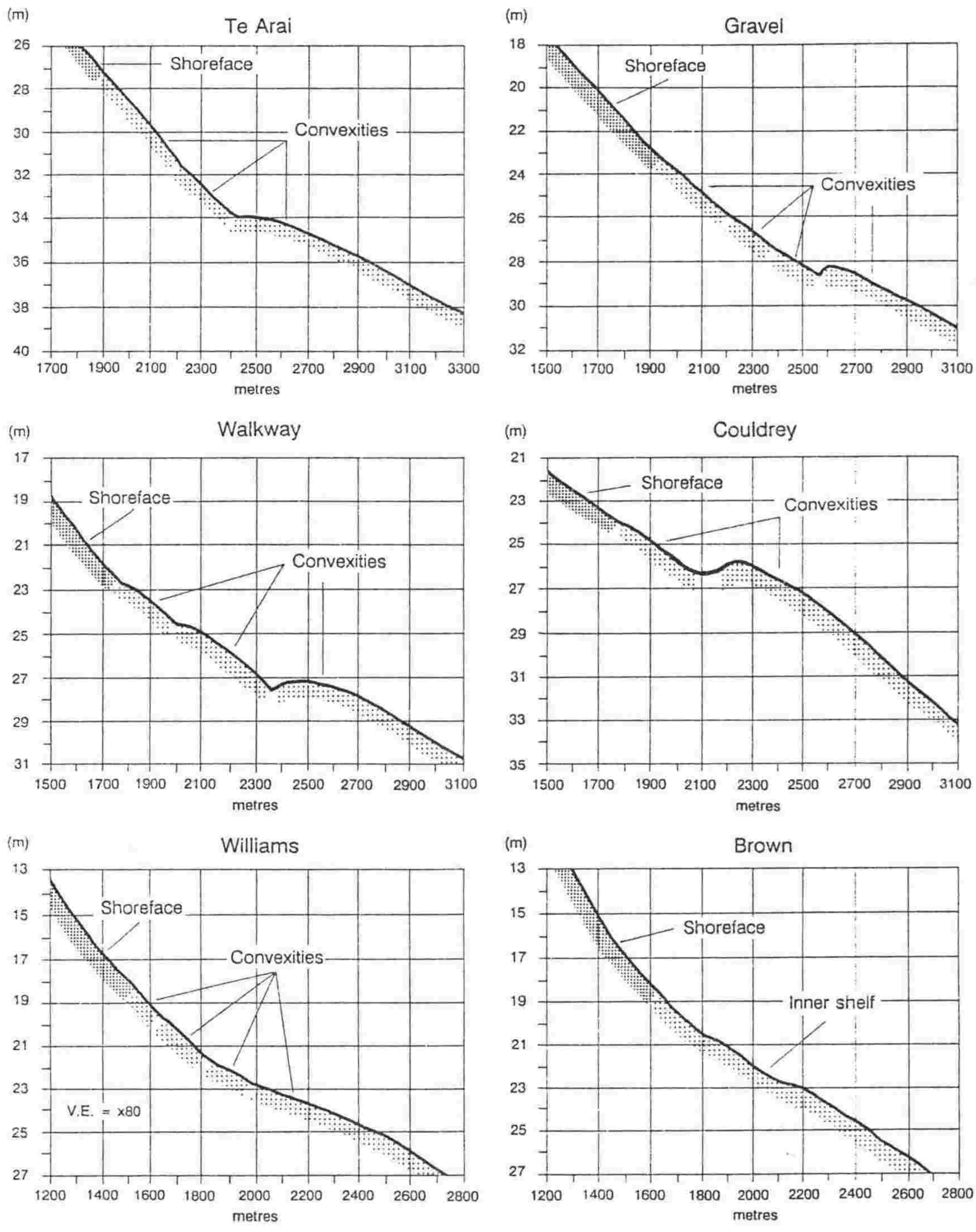



Figure 5.5 Segments of the Pakiri Bay transect profiles showing the transition zone between the shoreface and the inner continental shelf, and the location of minor convexities.

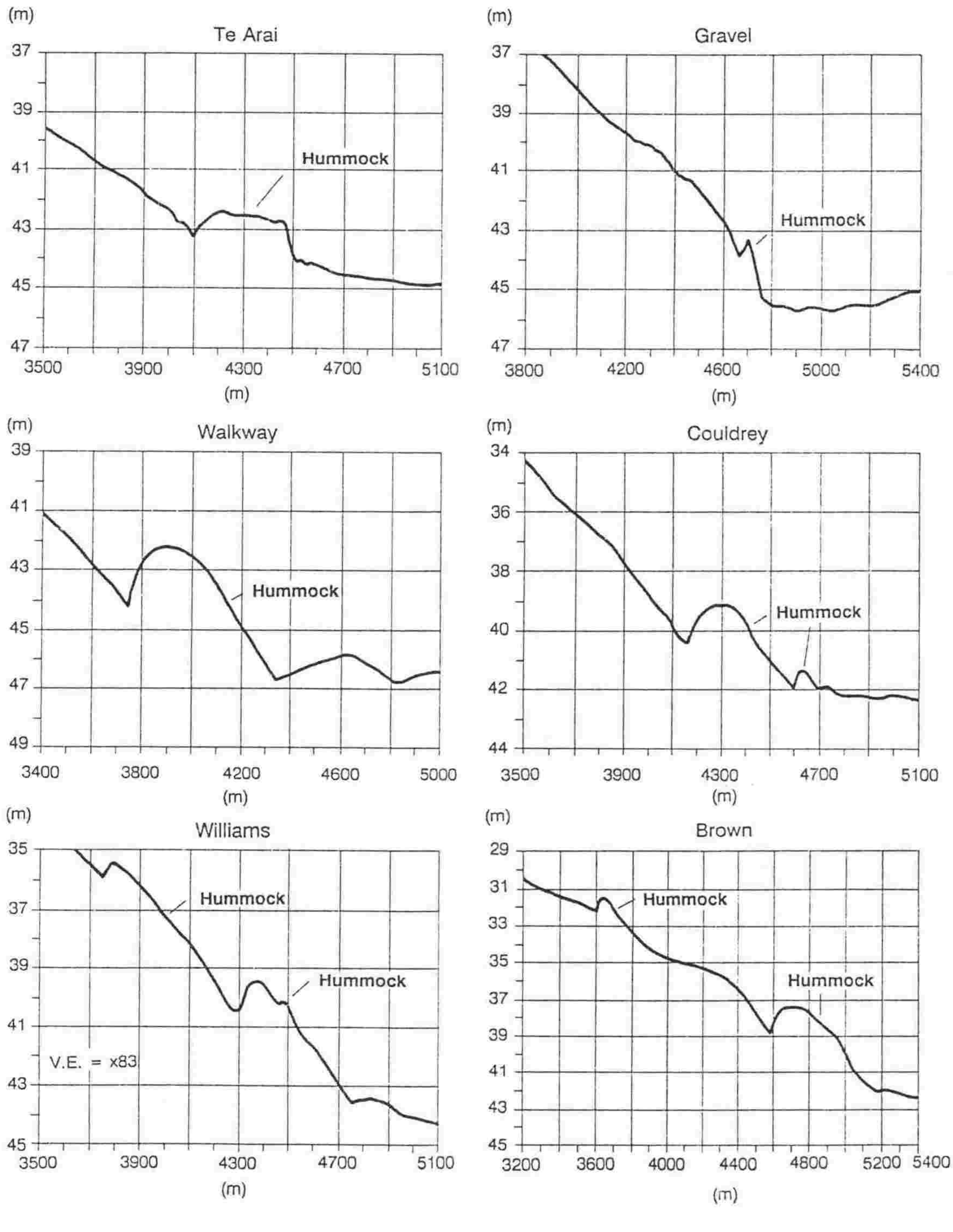



**Figure 5.6** Segments of the Pakiri Bay transect profiles, showing the transition zone between the inner and middle continental shelf, and the location and geometry of the hummocks.

**Table 5.3 Location and Dimensions of Hummocks**

| Transect | # of Hummocks | Distance Offshore (m) | Water Depth (m) | Length[1] (m) | Amplitude[2] (m) |
|---|---|---|---|---|---|
| Te Arai | 1 | 4100 | 43 | 400 | 1.5 |
| Gravel | 1(2) | 4200 | 40 | 450 | 4.5 |
| Walkway | 1 | 3800 | 44 | 550 | 4.5 |
| Couldrey | 2 | 4100<br>4600 | 41<br>42 | 450<br>100 | 3.0<br>0.7 |
| Williams | 2 | 3800<br>4300 | 36<br>40 | 500<br>450 | 4.8<br>4.1 |
| Brown | 2 | 3600<br>4600 | 32<br>39 | 400?<br>600 | 3.5?<br>4.7 |
| Matheson | 1 | 3750 | 38 | 500? | 3.0? |

Notes: 1. Measured from points of inflection on landward and seaward sides (see Figure 5.6).
2. Measured from crest of hummock to level of lowest point of inflection (see Figure 5.6).

A distinction can be drawn between the northern three transects, Te Arai, Gravel and Walkway, which are characterized by a single hummock and the transects to the south, Couldrey, Williams and Brown, which have two hummocks. These latter occurrences are smaller, but collectively cover a greater width of the inner shelf profile. Where two hummocks are present the landward-most is superimposed on the inner shelf. With the exception of Te Arai profile the hummocks exhibit the same general cross-sectional morphology, with a relatively steep onshore (stoss-like) face and more gradually sloping offshore face.

The side-scan sonar records provide an indication of the alongshore morphology of the hummocks. These records also suggest the nature of the transition between the inner and mid continental shelf sediment types, and the relationship between this sedimentological discontinuity and the location of the hummocks. The survey line traces the southern margin of Pakiri Bay, in an area of relatively uniform bathymetry between Matheson and Okakari transects. Consistent with echosound surveys across Matheson and Okakari transects there is no evidence of hummocks on the side-scan record. However, there is clear evidence of a marked change in the sedimentology of the seabed, about 3500 m offshore, in water depths of 38 m (Station 1731, Figure 5.1). There is an abrupt change in sonar signal that is characteristic of a contact between a coarse and relatively fine sediment. This is interpreted as the contact between the inner shelf and mid shelf sediment types. The transition from the very coarse sands of the former (dark tones) and the very fine, muddy sands of the latter (light tones) occurs as a continuous line (Figure 5.7).

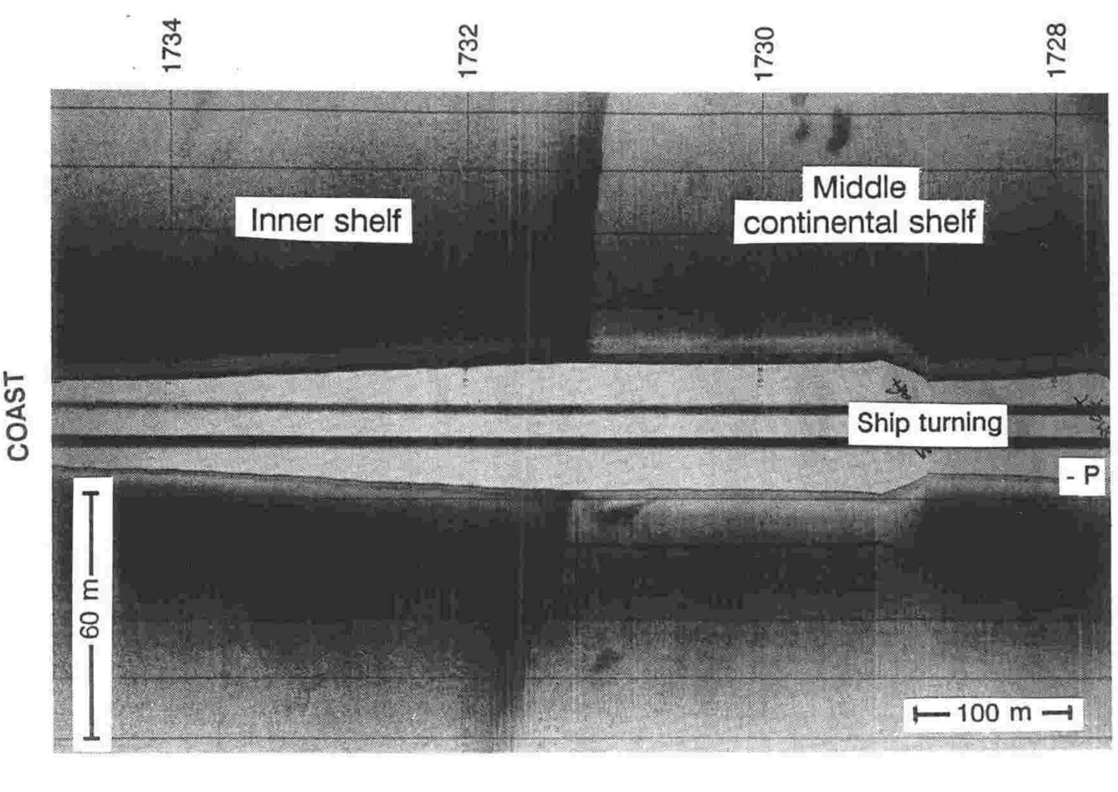



Figure 5.7 Interpretation of side-scan record, showing transition from mid shelf to inner shelf sediment types, station 1728-1734.

The results of the sediment surveys presented in Chapter Three indicated that the transition from the inner shelf to mid shelf sediment types must occur over a swath of seabed of the order of tens of metres wide. It appears that the juncture between the disparate sediments of the inner and mid shelves occurs along a line of contact. There is no gradation from one type to the other, rather the contact is abrupt.

The northern shore-normal leg of the sidescan survey is located immediately south of Walkway transect, in an area from which the major morphological components identified (see Figure 3.13) are most pronounced. The transition from mid shelf and inner shelf is again evidenced by an abrupt change from relatively fine sediments (light tones) to coarse sediments (dark tones) respectively (Figure 5.8). This occurs on the side-scan record 4500 m offshore, a location that closely agrees with the results of the known distribution of sediments across Walkway transect (Figure 3.3).

The side-scan records from the area of seabed at the base of the inner shelf indicate a more complex pattern of sediment types than was present on the southern side-scan survey. Accumulations of fine sediment are present on the inner shelf within 300 m of the continuous inner shelf/mid shelf sediment boundary (Figure 5.8). These deposits have an approximately elliptical plan form with acute extremities and are elevated relative to the surrounding bed. In cross section these features have an elevation of 2 to 3 m, and their long axis is oriented approximately parallel to the coast. They are adjacent to the hummocks described from the base of the inner shelf.

The side scan sonar surveys did not extend over the exact same areas of seabed from which the hummocks have been described from echosound data. Nevertheless the location and relative relief of the fine sediment deposits evident on the side scan records is consistent with their interpretation as the forementioned hummocks. The scenario envisaged therefore is of large, convex accumulations of sediment (the hummocks) lying seaward of the base of the inner

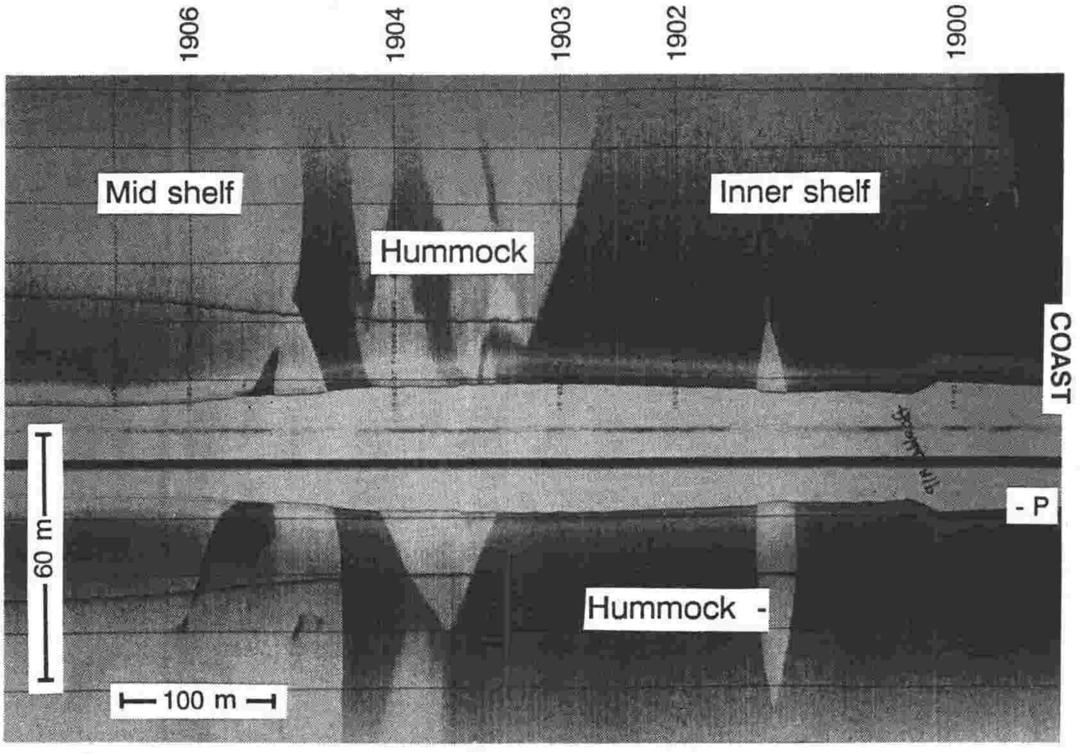



**Figure 5.8** Interpretation of side-scan sonar record of the area of contact between the inner shelf (dark) and mid shelf (light) sediment types, and the presence of large-scale bedforms (hummocks), stations 1900-1906.

shelf. These features are comprised of the mid shelf sediment type. The transition between the very fine, muddy sands of the mid shelf and the very coarse sands of the lower inner shelf occurs along the landward margin of these features. Further landward, in water depths of around 40 m, discrete and isolated accumulations of the mid shelf sediment type form elliptical bedforms on the (lower) inner shelf (Figure 5.6 e, for example). These are interpreted as smaller variations of the hummocks. They may represent quantities of very fine sand that have transgressed the inner shelf-mid shelf juncture, forming large-scale bedforms.

Large bedforms are described from continental shelf environments in a range of locations (for example, Flemming, 1978, 1980; Morang and McMaster, 1980), although most of these are of the smaller sand wave type. Hunter et al. (1982) describe lobate sand patches from the inner shelf in the north-east Bering Sea that share many characteristics with the hummocks (and mounds) observed at Pakiri. These include the overall morphology (lobate, convex section) and dimensions of the bedforms (10-500 m), and the textural distinction between the relatively fine sediments of the bedform and the surrounding coarse sediments. The Bering sea features are inferred to result from processes of sediment transport in a wave-dominated environment, however the exact mechanism by which they form is not known.

If the hummocks are indeed transgressive features their form and location at the base of the inner shelf may be explicable in terms of the abrupt change in gradient of the seabed at the inner shelf-mid shelf juncture. The slope of the bed increases from about 0 to 0.5°. This may be sufficient to slow or inhibit further onshore movement of sediment, and/or result in the modification of the form of the mound-type bedforms as they transgress the mid continental shelf surface. Alternatively, hydraulic conditions on the inner shelf may be such as to prevent the aggregation of very fine sands as bedforms, and hence transport may occur (if at all) in some other way. The morphology of the hummocks may, in addition, represent an equilibrium response to the hydraulic regime. That these features are in some way related to the present hydraulic regime is inferred from the abrupt nature of their textural segregation from the surrounding coarse sediment.

The location of hummocks on the lower inner shelf on Williams, Brown and perhaps Matheson transects almost certainly has implications for interpreting the results of the sediment surveys reported in Chapter Three. Across Williams, Couldrey, Walkway and Gravel transects, the textural transition between the inner shelf and mid shelf sediment types occurs at the landward margin of the hummocks. Across the transects to the south the transition occurs in conjunction with the landward-most hummock, some distance across the inner shelf. The variability in grain size results obtained across Brown transect for example (Figure 3.5), may result where samples of the fine (hummock) sands are obtained, although the surrounding (and most probably underlying) bed is composed of very coarse sands and fine gravels.

### 5.2.4 Middle Continental Shelf

Compared with the graded bed of the inner shelf the sedimentology and bathymetry of the mid shelf is relatively uniform, at least as far offshore as the surveys extended (8000 m). Seaward of the hummocks at the base of the inner shelf the seafloor slopes gently at an angle of about $0.1^{\circ}$. Bathymetric variations across the surface of the shelf tend to be less than 1 to 2 m.

The side-scan results indicate that most of the area of mid shelf surveyed is comprised of the same type of sediment. These are inferred to be very fine, muddy sands. This sediment was commonly recovered from the mid shelf during sediment sampling. However, the results also show a recurring pattern of sedimentological and associated morphological variation. An 8500 m long (160 m wide) strip of mid shelf seabed was surveyed between 5500 and 7000 m offshore, in water depths of about 45 to 48 m. Evidence of textural differentiation of sediments occurs as accumulations of relatively fine sediment separated by bands of coarser sediment. The former is almost certainly the very fine, muddy sands described. The latter are most probably medium to fine sands, samples of which were, on occasion, dredged from the mid shelf (across Williams transect, for example, Figure 3.6). That the darker toned sediments are in fact coarser is also suggested by their occasional association with large, linear-crested ripples. At other locations in the study area such ripples are invariably found in conjunction with coarse or very coarse sands (Chapter Six).

The relatively fine and coarse sediments of the middle continental shelf are associated with elevated areas of the sea bed (termed mounds) and depressions respectively. The plan configuration of the mounds is variable, but commonly exhibits an elongated configuration, with the long axis oriented approximately normal to the Pakiri coast. The landward margin is frequently broad and crenated, with the seaward end being more acute (Figure 5.9). The contrast between the fine sediments of the bedforms and the surrounding coarse sediments of the depressions is more pronounced along the seaward margin of these features than along the landward edge.

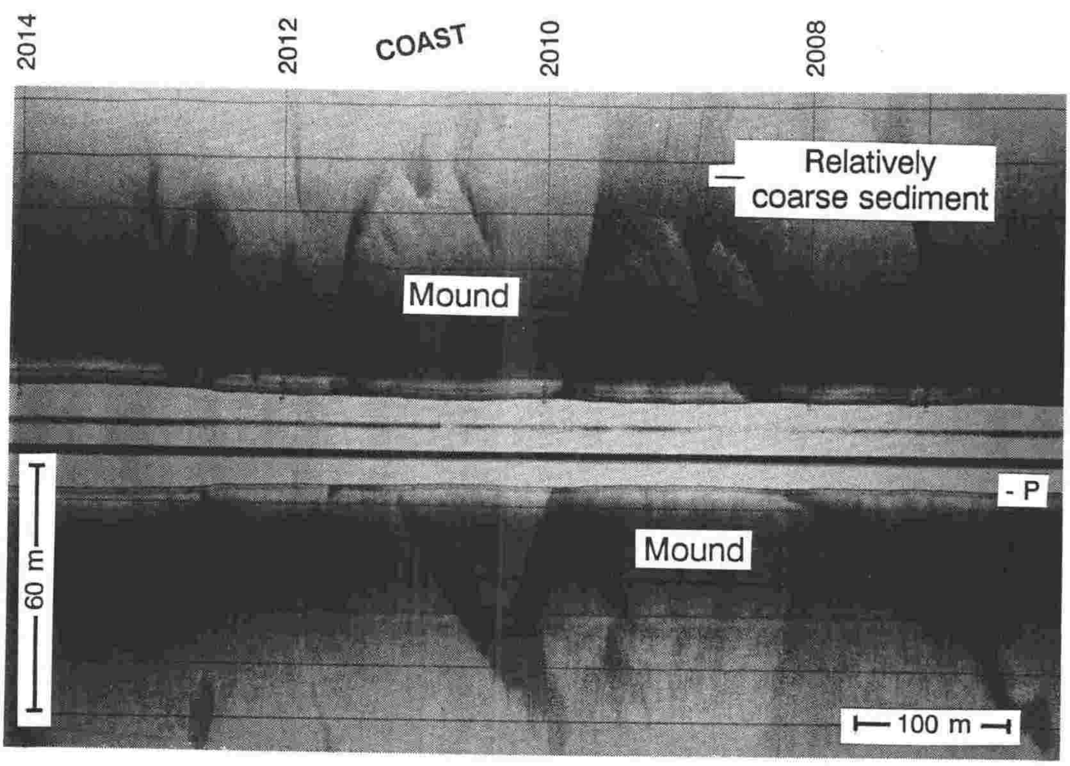



**Figure 5.9** Interpretation of side-scan sonar record showing large-scale bedforms (mounds) on the middle continental shelf (station 2006-2014, Figure 5.1).

The mounds of the mid shelf are bedforms of considerable size. The example in Figure 5.9 has a length of 330 m and maximum width of 125 m. Their form and alignment relative to the coast contrasts with the hummocks described from the surface and base of the inner shelf. The long axis of these latter features is orientated parallel rather than normal to shore. In other respects however, the mounds of the mid shelf and the larger hummocks of the inner shelf-mid shelf transition share several intrinsic characteristics. They are both comprised of relatively fine sediments, have an amplitude of less than 4 m, and are long and broad relative to their width.

The extent to which the mounds and hummocks of the continental shelf result from contemporary physical processes of sedimentation is problematic. The side-scan evidence of textural differentiation associated with both indicates that at some time these features have formed as a result of sediment transport. The abrupt nature of the contact between the fine sediments of these features and the coarser sediments of the depressions, in the case of the mid shelf mounds, and the adjoining coarse sediments in the case of the hummocks, suggests this process may be ongoing. If this is so the configuration of the mounds is most consistent with shore-normal sediment transport, an interpretation that is supported by the orientation of large ripples in the relatively coarse sediments of the depressions (see section 6.4.1).

## 5.3 Alongshore Variations in Subtidal and Coastal Geomorphology

The nature and arrangement of shoreface, inner shelf and mid shelf morphologic components is consistent over most of Pakiri Bay, although variations within units have been described. There are, however, some alongshore variations on the classic pattern summarized in Figure 3.13. Across both Brown and Matheson transects the convex form of the inner shelf is less pronounced, and the profile generally less regular. South of Brown transect the boundaries between the shoreface, inner shelf, hummocks (if present) and the mid continental shelf become progressively more subtle, and the morphological components less distinguishable. This alongshore trend culminates in the almost featureless profile of Okakari transect. There is a change in slope 4750 m offshore, in water depths of 40 m, which is interpreted as the seaward margin of the inner shelf. Landward of this point however the shore-normal profile comprises a curvilinear arc as the seabed shoals to the base of the high tide rock platform. In contrast the components are readily delineated across the transects north of the Pakiri River (Figure 5.2).

South of Okakari Point the profiles are morphologically more complex, with the juncture between the inner shelf and the middle continental shelf becoming less pronounced. The concave shoreface is interrupted across Okakari, Goat Island and Cape Rodney transects (Figure 5.2 h,i,j) by the presence of subtidal rock platforms and the subaqueous exposure of the rocky (cliffed) coast. In many respects the sedimentological characteristics and geomorphology of the coast and seabed south of Okakari Point differs from that of Pakiri Bay (and most likely Mangawhai Bay to the north). A detailed examination of this area is beyond the scope of the present investigation. However, the sedimentology and morphology of the inner shelf offshore from the rocky coast appears to have close parallels with the seabed adjacent to Bream Tail, the northern headland of the Pakiri-Mangawhai embayment described by McCabe (1985). Common features include a cliffed coast, rocky foreshore and extensive subtidal platforms and an abundance of locally-derived coarse carbonate sands and gravels on the inner shelf. Seaward of these sediments, however, the sediments of the mid shelf appear to be essentially the same as those described from the Pakiri Bay mid shelf.

### 5.4 Coastal, Shoreface and Inner Shelf Stability

The historic records of coastal and bathymetric changes provide evidence of the stability, or otherwise, of the morphological components in Pakiri Bay. These data have relevance to the present study in so much as they may indicate directions and volumes of sediment transport, and hence the origin and destination of particular sediments. One of the major objectives of the following discussion of coastal and seabed morphodynamics is to assess the extent to which sediments of the coast may contribute sand to the shoreface.

### 5.4.1 Coastal Dunes

Sand dune development has not been uniform alongshore within Pakiri Bay. The mean elevation and width of the unconsolidated sands of the dune field bordering the coast increases to the north as far as Te Arai Point, and beyond to Mangawhai Harbour. There is no (especially pedological) evidence, however, to suggest the most recent phase of dune development did not occur simultaneously alongshore.

Apart from areas of historic foredune disturbance and related blowouts, especially bordering the stream mouths, the dunefield is densely vegetated. A programme of afforestation in the 1960s has effectively vegetated and stabilized the formerly mobile sands of this most recent phase of dune activity.

Three dune types are recognized (Figure 1.4). South of the Pakiri River mouth the dunes comprise an irregular surface less than 50 m wide and 15 m high (Type 1). Between the Pakiri and Poutawa Streams the dunes maintain a uniform elevation and width, averaging 25 to 30 m above mean sea level and 2-300 m in width (Type 2). A typical dune cross-section shows a seaward facing scarp, approximately 7 m high, which was eroded during the exceptionally severe storms of July, 1978. Seaward of this scarp a low (2-3 m high) incipient foredune is periodically formed and eroded. The surface topography of the dune field is hummocky and irregular with numerous active and stabilized parabolic blowouts, a legacy of past and present episodes of dune mobility and revegetation. On the landward side of the dunes the surface slopes steeply to the alluvial plains. As a result of foredune disturbance blowouts up to 500 m wide have formed in several places, one transgressing the full width of the dune field. The third dune type equates to the boundaries of Mangawhai

State Forest, and represents the area of most massive sand dune development (Figure 1.4). Along this section of coast the dunefield attains widths of 2000 m and elevations of 50 m.

A consequence of human activity along the coast has been to deplete the volume of sands contained in the foredunes bordering the coast. A former dune surface, 3 to 5 m higher than the degraded 'foredune' levels, is evidenced by pedestals of Holocene sand capped by Maori midden and tephra deposits near Couldrey and Williams transects (Anderson, 1985). These are invariably associated with the large blowouts south of the Poutawa Stream. In addition, foredune 'reconstruction' north of the Poutawa Stream, by the New Zealand Forest Service in the 1960s, has largely transformed the original dune topography (Wishnowsky, 1981). Irregularities in the original dune surface were removed, and a strip of land bordering the coast some 200 m wide leveled by excavation, prior to the construction of an artificial foredune. Both these impacts, in addition to mining and afforestation, represent a loss of sand further inland from the immediate backshore, and hence from the active coastal sediment system.

Scarping of the backshore is a relatively frequent occurrence, especially south of the Poutawa Stream, where an eroded face 5 to 8 m high extends between the beach and the stabilised dune surface. There is clearly the potential, given the presence of a backshore scarp and the absence of a foredune along much of the Pakiri Bay coast, for eolian dune sands to be incorporated in the sediments of the beach as a result of backshore erosion, and from there to be transported offshore to contribute to the sediments of the inshore and shoreface.

### 5.4.2 Beach and Inshore Morphodynamics

The most frequently-occurring foreshore morphologies show features of Wright and Short's (1983) 'intermediate' beach states - since no true dissipative or reflective variations were observed. In general there is a cyclic pattern of beach development between relatively featureless lowered storm profiles, in which the berm and occasionally the foredune toe are eroded, and non-storm profiles in which the berm and a rhythmic ridge and runnel topography is well developed.

The inshore topography is persistently characterized by a trough/bar complex, extending as a subtidal ledge approximately 250 m offshore. The bar is usually present as a single, alongshore ridge, rising 2 to 3 m higher than the trough to landward, however a much smaller second bar is occasionally noted within the broader trough. Echosound traverses between 1984 and 1988 indicate that, at least in this time period, the alongshore bar is a feature of the inshore-upper shoreface along all transects (see Appendix I, Figure 2, for example).

The bar also appears to be persistent alongshore, although the elevation of the crest of the bar relative to the trough tends to be greater north of the Poutawa Stream. This continuity is most evident during periods of high wave activity (Figure 5.10) during which times the waves break over the crest of the bar.

### 5.4.3 Historical Fluctuations in Shoreline Position

As part of an investigation of historical changes in the position of the backshore along the east coast Lees (1982) compared aerial photographs of the Pakiri coast covering the period 1942 to 1981. The results and methods employed are discussed fully in Appendix K. In summary, this study revealed no strong trend in coastal development over the 39 year period, although the interpretation is limited by the variable quality and coverage of the photographic data, some methodological problems and a lack of data related to the effects of the 1978 storms. However, the results do evidence the dynamic nature of the Pakiri coast with phases of erosion and deposition associated with rates of change of up to 5 m per year.

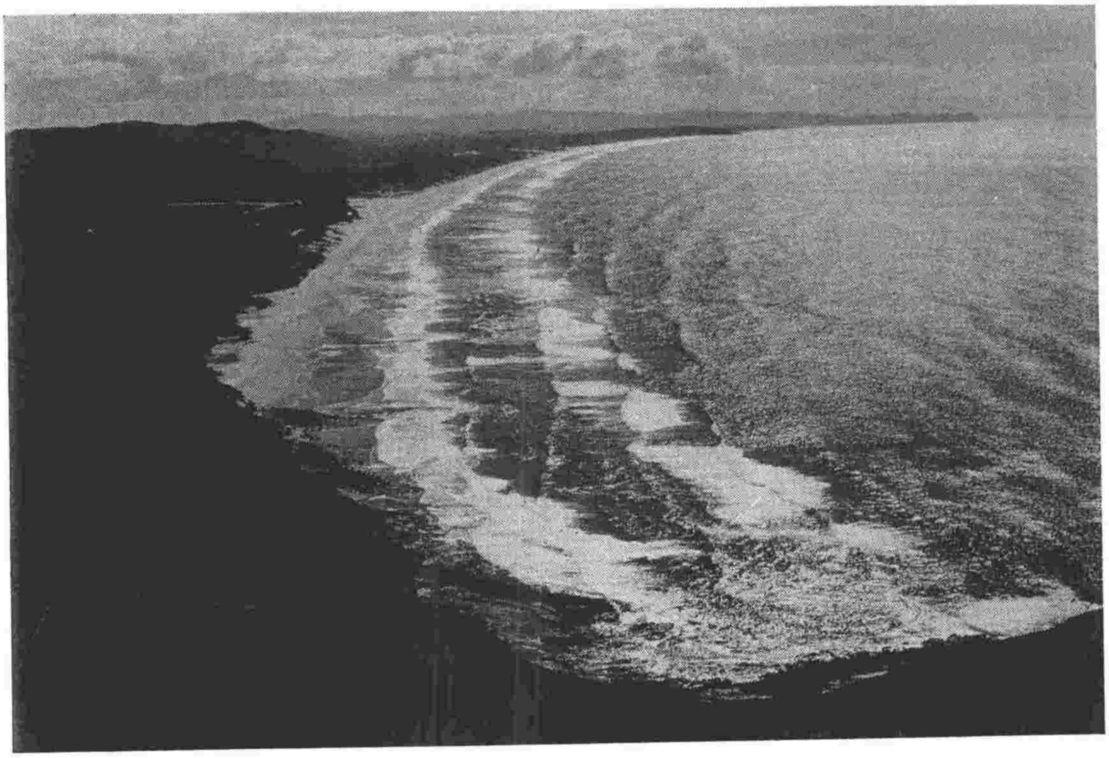


**Figure 5.10** Photograph of Pakiri Bay (looking north from above Okakari Point) in moderate wave conditions (height=2 m), illustrating the continuity of the alongshore trough and bar system.

Beach surveys initiated in 1978 provide a less equivocal record of coastal development over the last 10 years. The surveys commenced soon after a devastating storm in July 1978, following a series of lesser onshore (easterly) storms in May and June. The July event resulted in severe erosion of the sandy coasts immediately to the south and north of the Pakiri-Mangawhai embayment. The foreshore was eroded 40 and 5 m at Omaha and Bream Bay respectively (Hume, 1979). The magnitude of foreshore retreat at Pakiri is not known, since the beach surveys commenced after the storm. An estimate of 20 m, based on a comparison of oblique photographs of the Pakiri coast, is probably reasonable. The scarp produced by this episode of erosion extends between Brown and Williams transects, the only stretch of coast relatively unaltered by recent human activities.

The results for Brown transect are representative of the fluctuations in beach configuration and backshore position during this time (Figure 5.11). The excursion distance analysis indicates net change in shoreline position over this time interval has been negligible. Since 1978, however, the foreshore has fluctuated considerably within an envelope of change, reaching maximum volumes in the summer of 1983, and minimum volumes in September 1985 following periods of prolonged offshore and onshore winds respectively. Comparison of 1978 and 1988 backshore and foreshore profiles, for both Mangawhai and Pakiri Beaches, indicates the net change in the elevation and position of the foreshore and backshore has been virtually nil (Figure 5.12). Apparent increases in the elevation of the backshore at Gravel, Walkway and Picnic profiles are in fact the result of foredune construction by the New Zealand Forest Service.

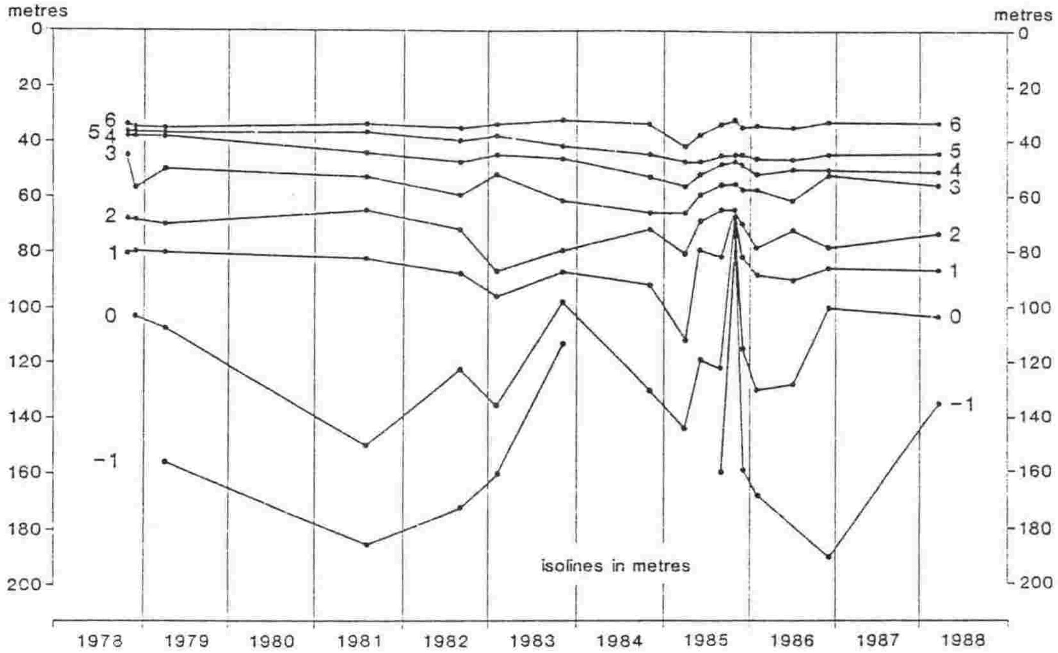



Figure 5.11 Excursion distance analysis of a time series of beach surveys (1978 to 1988), Brown transect (source of 1978 to 1983 data, Auckland Regional Authority).

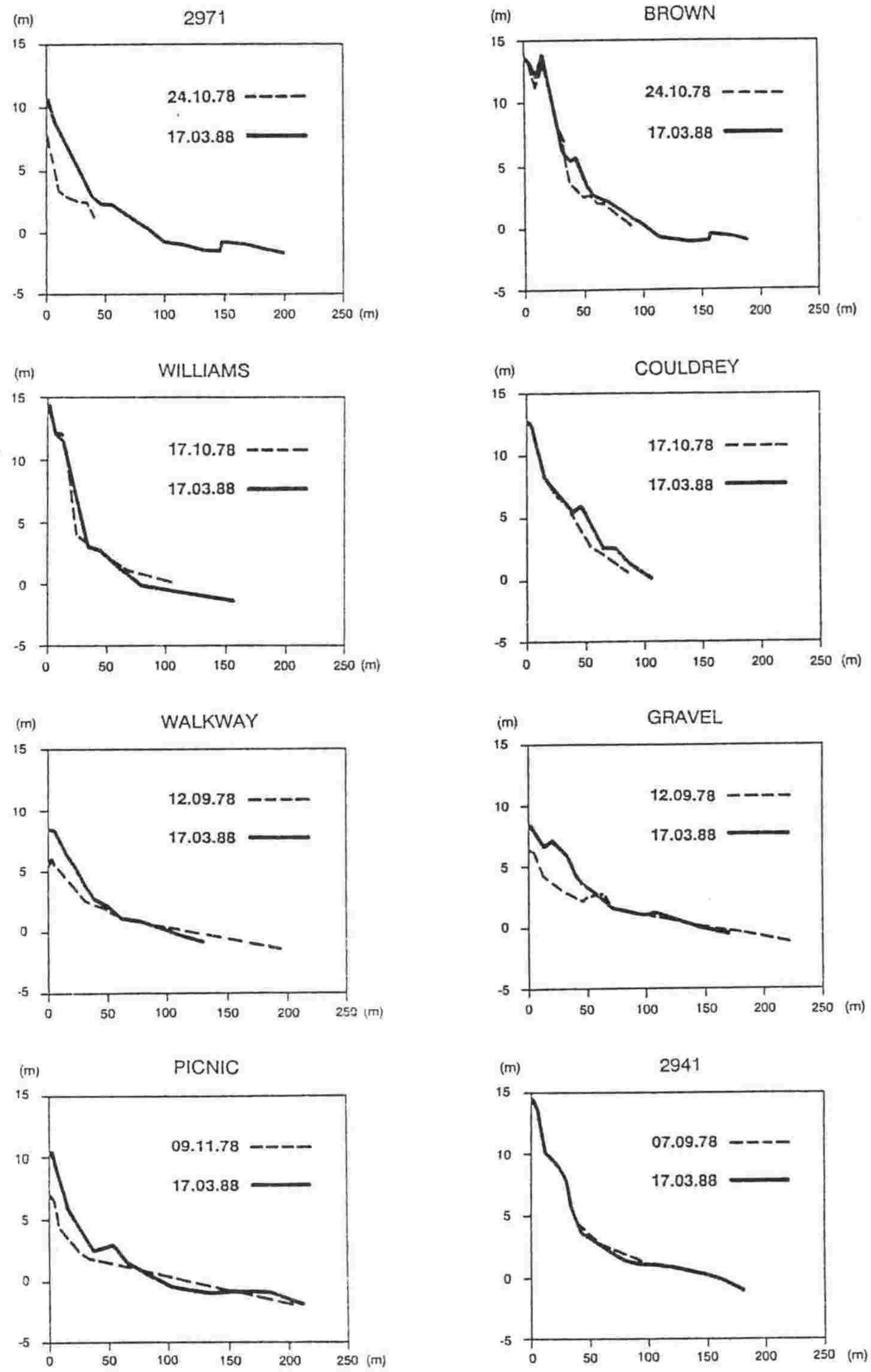



**Figure 5.12** Comparison of 1978 and 1988 beach surveys, Pakiri Bay and Mangawhai Bay transects (see Appendix D for location). Survey data supplied by the Auckland Regional Authority.

The major implication of these results is that whatever sand was eroded from the backshore to form the existing scarp during the 1978 storms, has not in the following ten years, been returned and incorporated into a new foredune complex. On the contrary, segments of coast along which foredune reconstruction has not occurred display characteristics, such as a narrow or absent berm at high tide, and a scarped backshore, that are typical of eroding coasts.

### 5.4.4 Evidence of Shoreface and Inner Shelf Morphodynamics

The bathymetry of the Pakiri inner continental shelf was first surveyed by the Hydrographic Office of the Royal New Zealand Navy in 1964. Offshore profiles have been derived using water depths from the original fair charts, approximately along the shore normal lines of the transects employed in the present investigation. These are compared with offshore profiles surveyed in 1987 in Figures 5.13. The process of comparing profiles derived by different techniques entails a significant error margin. Added confidence is gained in the results, however, given the consistent, albeit approximate, alongshore agreement between the two data sets.

The comparisons provide no basis for arguing for any trend in the direction of development of the shoreface or continental shelf. The gross configuration of the shore-normal profile, and relative dimensions of the morphological components, has changed little over the 23 year period. While the detail of the modern components is not evident on the 1964 profiles, the changes in gradient at the base of the shoreface and between the inner and mid shelf are consistent with existing profiles. The concordance between the two sets of profiles is greatest closest to shore, indicating that the intrinsic character, and position, of the Pakiri shoreface has not changed significantly during the period.

Periodic offshore echosound surveys were undertaken between 1984 and 1988, to investigate the stability of the morphologic components identified in Pakiri Bay. Together with the surveys undertaken by

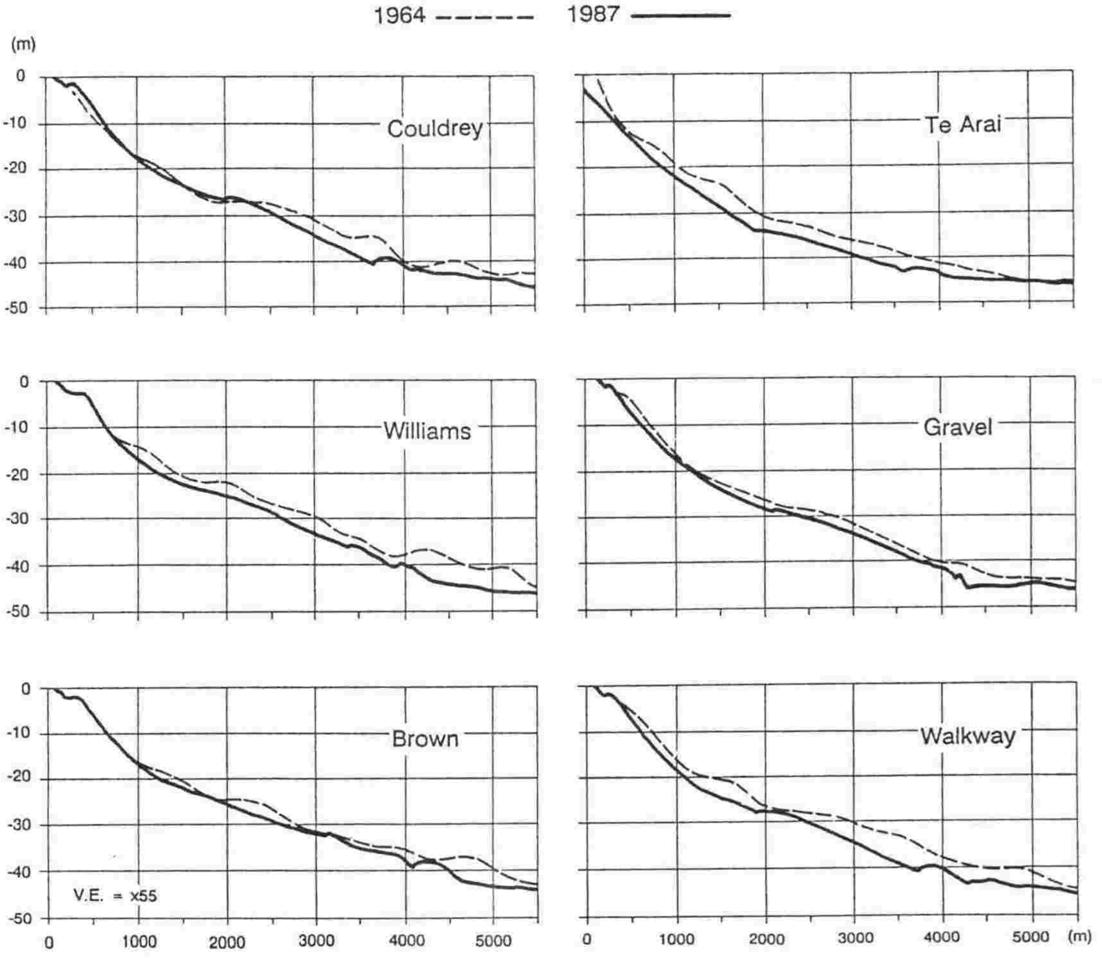



**Figure 5.13** Comparison of 1964 Royal New Zealand Navy fair chart and 1987 echosound surveys, Pakiri Bay transects.

the Auckland Regional Water Board in November 1978, four months after the storms referred to previously, they constitute a time series of bathymetric data of 10 years duration. The errors associated with bathymetric surveys have been discussed (Appendix I). However it should be reiterated that comparison of surveyed profiles obtained using different methods (and instruments), in different conditions by different people must be undertaken with caution.

Over the 10 year interval for which survey data is available the morphology of the shoreface has varied between two forms. The

November 1978 and July 1984 surveys reveal a convex bulge, extending up to 1000 m from datum, to water depths of about 12 m (Figure 5.14 a). The inshore platform is broader, steeper and deeper and there is no alongshore bar and trough system evident in the survey immediately following the 1978 storm. This configuration is less pronounced in July 1984 survey and since April 1985 the profiles have exhibited the more characteristic concave shoreface profile (Figure 5.14 b, for example).

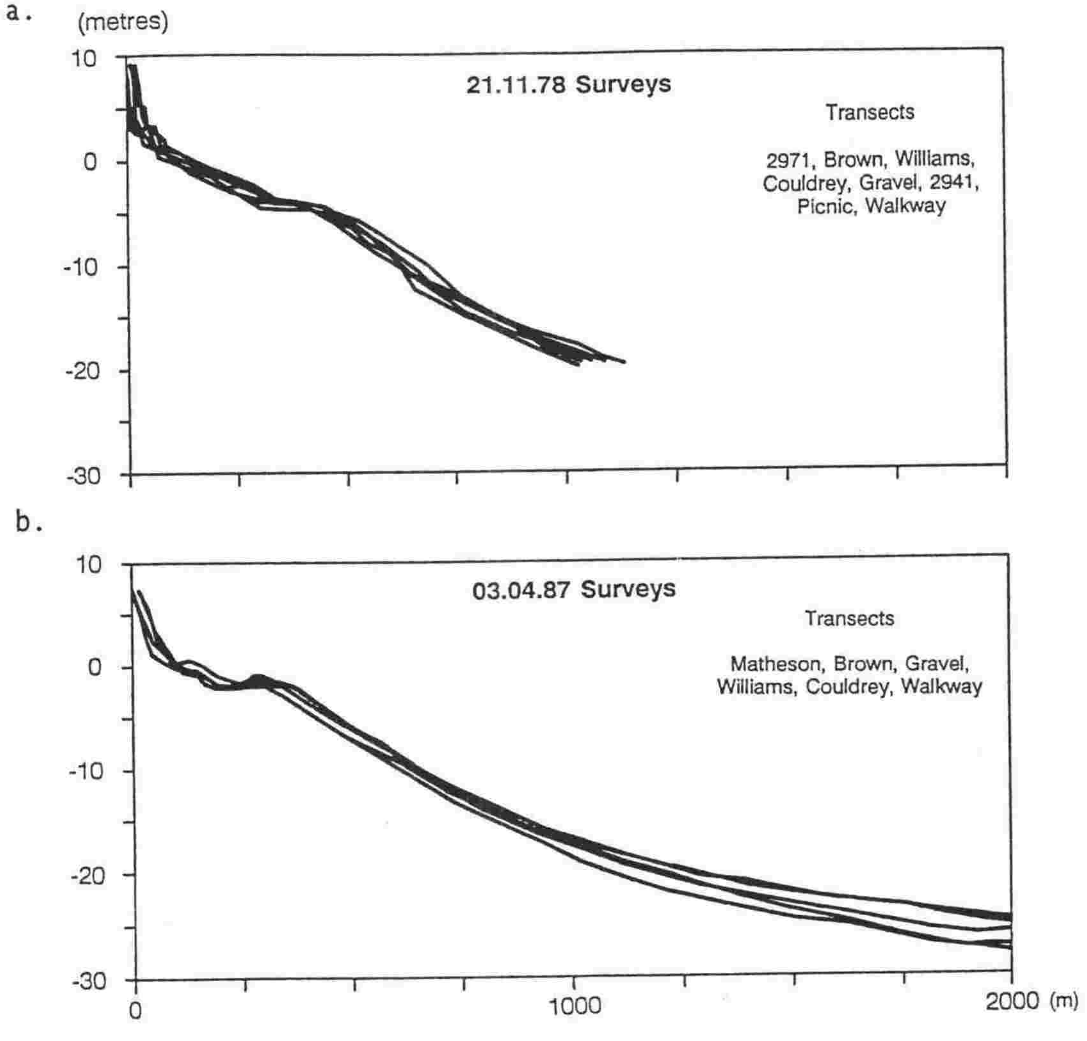



**Figure 5.14** Superimposed plots of (a) 1978 and (b) 1987 shoreface profiles, showing presence of convex bulge 250 to 750 m offshore on 1978 profiles, and characteristic concave geometry of the 1987 shoreface profiles.

Given the quantity of sand inferred to have been eroded from the foreshore and backshore during the 1978 storms, the convex bulge present on the upper shoreface between 1978 and 1984 most likely represents the offshore deposition of this material. The return of the shoreface to a concave profile since 1984 might then result from a redistribution of sand in the beach-nearshore circulatory system, including sand movement back onshore. The waves generated by the persistent easterlies of September 1985 did result in foreshore erosion, but of relatively minor proportions compared with the 1978 event. Certainly the coast has not experienced substantial accretion since the 1978 storms to suggest all the material eroded in 1978 has been transported back onshore.

The variation in offshore bathymetry across Brown transect is typical of the magnitude and direction of change across the six Pakiri Bay transects for the period 1978 to 1987 (Figure 5.15). The excursion distance analysis for the period, even allowing for an error margin of +/- 1 m in the depth determinations, shows evidence of considerable sediment movement on the shoreface to water depths of at least 25 m. These changes reflect the presence (Figure 5.16 a) and gradual disappearance (Figure 5.16 c) of the convex bulge.

In comparison the features of the continental shelf are relatively stable. Echosound surveys were undertaken across the Pakiri Bay transects (Table 5.1) according to the techniques described in Appendix I. The results obtained across Walkway transect (08.04.86 to 08.05.89) are typical of the results obtained across all transects over the survey period. The forementioned morphologic components are evident across the time series of profiles (Figure 5.17 a). The variations that do exist are mostly minor and within the error margin of the echosound technique. The one exception is the form of the hummock on the 1987 survey. Given the agreement of the other profiles this difference is most likely due to a small error in navigation, and hence an area of seabed off the transect being surveyed. The overall configuration of the profiles is also consistent from profile to profile, with minor differences (Figure 5.17 b), that are well within the error margin of the technique.

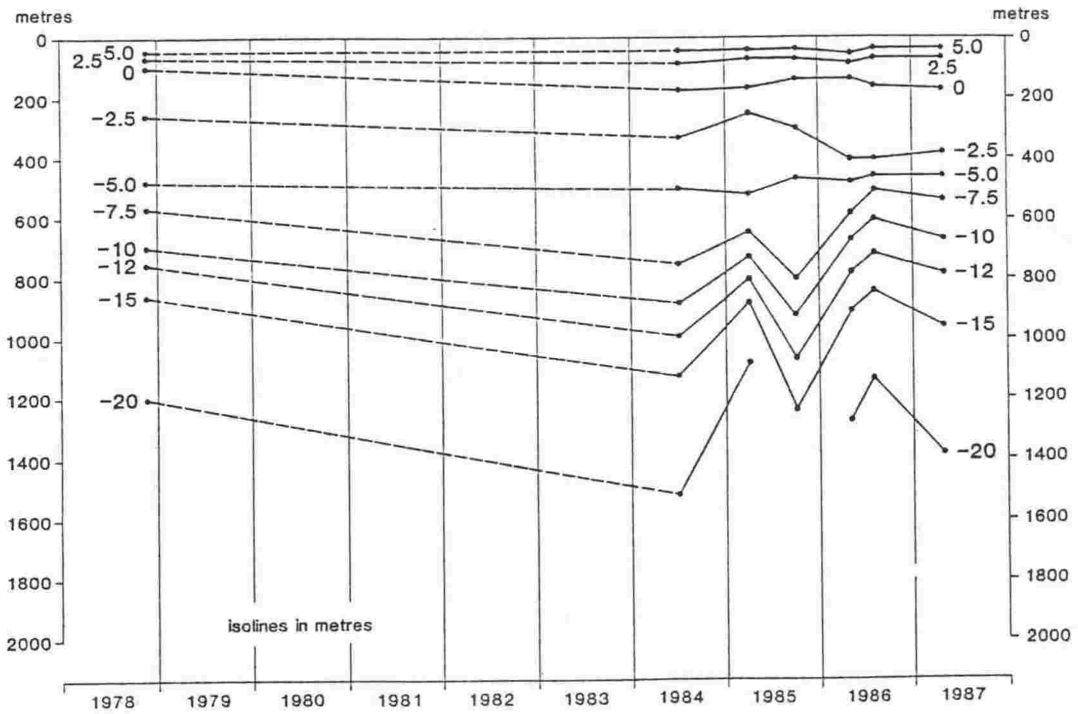



**Figure 5.15** Excursion distance analysis of a 10 year time series of surveys across the foreshore, inshore and shoreface, Brown transect (source of 1978 survey M.North Ltd).

## 5.5 Investigation of Sub-Strata

The subaqueous sediment body has been shown to comprise a sequence of morphologic components that are more or less continuous alongshore. Across the profiles these components are delineated by sometimes abrupt changes in slope. This section investigates the extent to which the morphology of the subtidal sediment body is related to geological or subsurface constraints or, conversely, is a result of past or present processes of sedimentation.

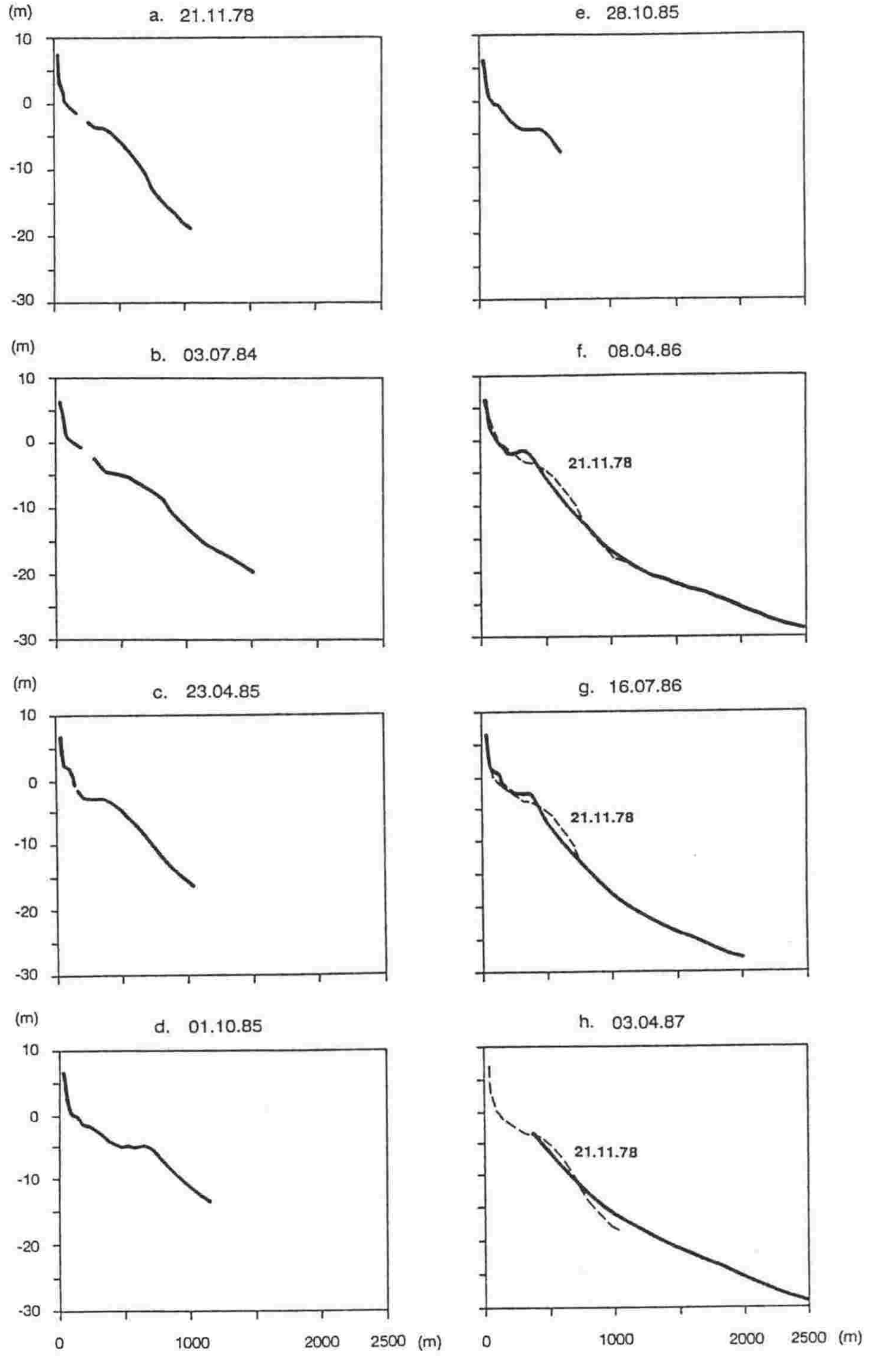
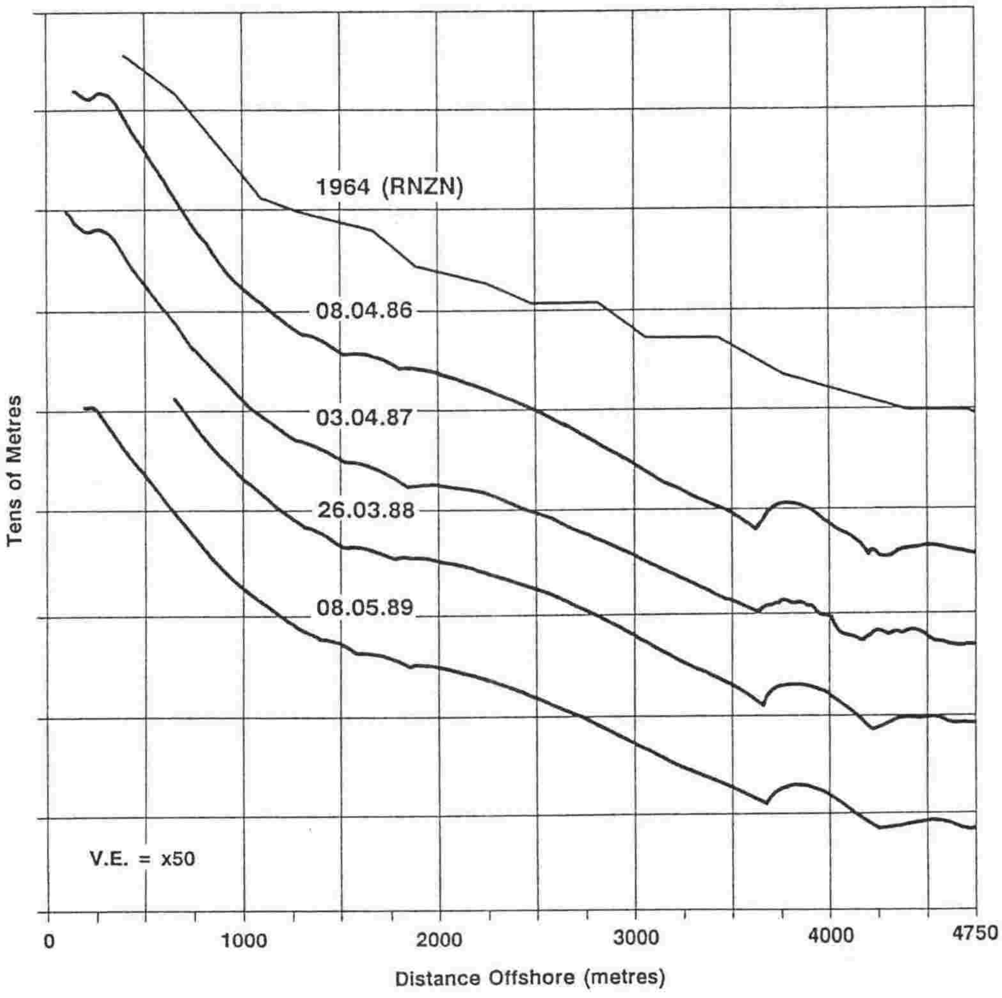


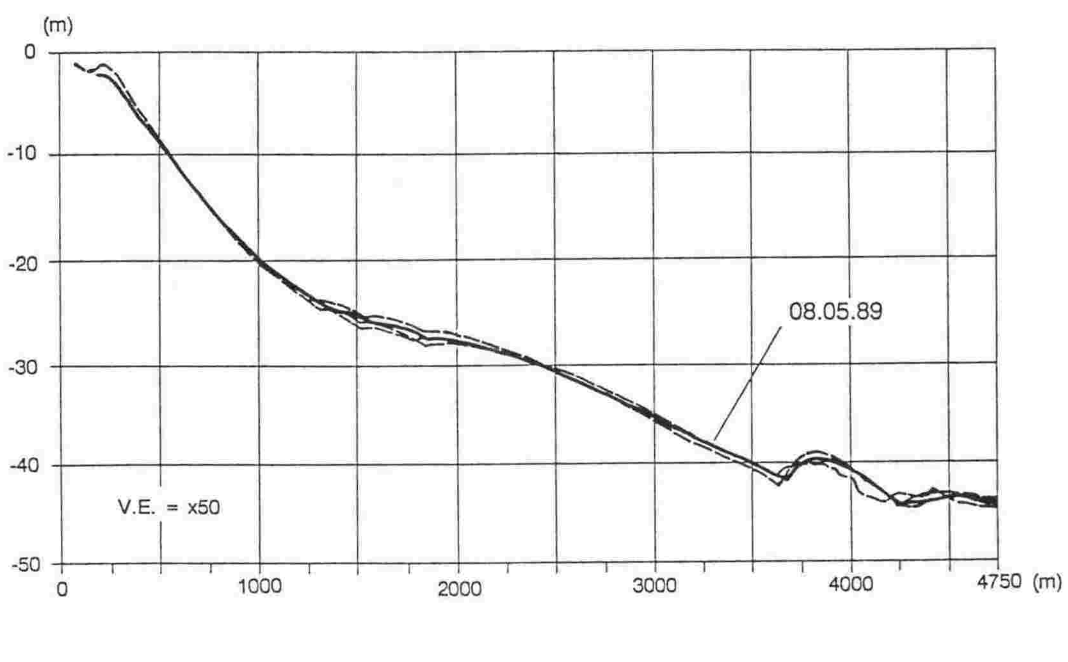

Figure 5.16 Comparison of 1978 (Auckland Regional Water Board) and 1987 inshore and shoreface echosound surveys, Brown transect.

Figure 5.17 (a) Comparison of five echosound profiles, Walkway transect, 1964 to 1989 (1964 profile derived from fair chart, RNZN, 1964), and (b) superimposition of 1986-89 profiles.

a.


1964 (RNZN)
08.04.86
03.04.87
26.03.88
08.05.89
Tens of Metres
V.E. = x50
0
1000
2000
3000
4000
4750
Distance Offshore (metres)

b.


(m)
0
-10
-20
-30
-40
-50
08.05.89
V.E. = x50
0
1000
2000
3000
4000
4750 (m)

Three scenarios are considered. The morphology of the sediment body is determined wholely by constraints imposed by substrata, and the sediments sampled represent a thin veneer over the subsurface indurated material. Conversely the characteristic slope units and their relations to each other, are solely the result of sediment transport. The third option envisages a combination of these processes.

Coastal progradation is prevented and interrupted at the southern and northern ends of Pakiri Beach by the cliffed headlands of Cape Rodney and Te Arai Point. Across the study area, however, between the coast and the middle continental shelf, no rock outcrops have been detected. There is thus no surficial evidence that the underlying basement rocks influence the geometry of the subaqueous sediment body. The actual area of seabed surveyed by echosound is small, however, and bedrock (or other indurated or relatively consolidated material) need not have a surface expression to influence the morphology of the sediment body. To investigate this possibility two sub-bottom sonar surveys were undertaken across alongshore and shore-normal transects on the continental shelf (Figure 5.1)

Ideally such sensing of the sub-surface would be accompanied by coring to identify subsurface reflectors. However, because the long-term development of the inner shelf is not the focus of this investigation, and because of time and financial constraints, coring to verify the reflectors could not be attempted.

Surveys were undertaken across the Pakiri Bay transects using an ORE sub-bottom profiler at a frequency of 3.5 kHz. An additional survey was conducted by the Royal New Zealand Navy (H.M.S. Tui) along the same survey line as the side-scan sonar surveys (Figure 5.1). Initial interpretation involved the identification of major horizons, as well as spurious reflections. The records display characteristic multiple reflections, including single point reflections (producing inverted hyperbolic patterns).

In terms of locating the lower limits of the unconsolidated marine sediments the results are inconclusive, with neither the ORE or Klein instrument providing a signal which could be interpreted as bedrock. However, the location and form of major horizons, and generally, the relationship between subsurface reflectors and the shelf topography are of interest.

The point of inflection between the inner and middle shelves tends to be associated with vertical discontinuities in the substrata. A step in the substrata is most evident beneath the mounds at the base of the convex-out component of the inner shelf, across Gravel, Couldrey and Brown transects (Figure 5.18 a,c,e). The reflector horizons associated with these steps are strong compared with other horizons (Figure 5.19, for example). Across the above transects the points of inflection are closely associated with these substrata variations.

Apart from these discontinuities the substrata show variations in density and orientation across the surveyed profiles. Across the shoreface and inner shelf the substrata are invariably oriented parallel to the seabed. In this respect it seems unlikely that any of these horizons are bedrock contacts - since such continuity of reflectors between transects kilometers apart would be most unlikely.

Seismic penetration of the seabed was relatively shallow (maximum 15 m), and the horizons are generally weakly reflected. While the actual composition of the reflectors has not been established the weakness of the signal suggests they are more likely to be weathered or semi-consolidated surfaces, or layers of shell rich material. One of two companies that mine sand from the alongshore bar at Pakiri reports occasional difficulty in locating a sufficient thickness of clean marine sand. Samples, provided by the mining companies, dredged from the base of borrow pits, are semi-consolidated organic rich materials containing some shell fragments. These are most likely lagoon or back-barrier deposits, and have no contemporary analogue across the exposed shoreface. A single strong

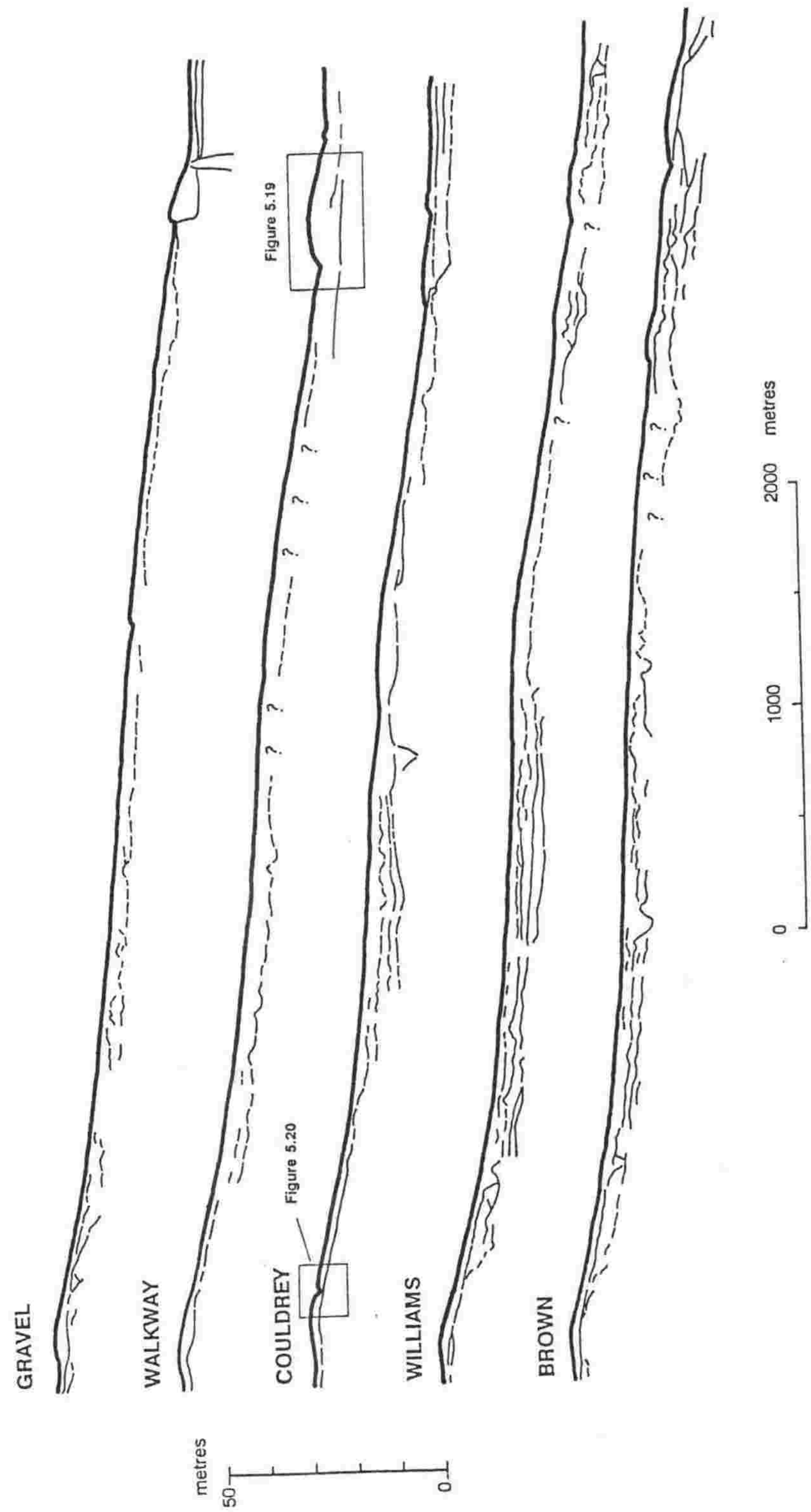



**Figure 5.18** Interpretations of sub-bottom sonar records (08.04.86), Pakiri Bay transects, showing strong (continuous line) and weak (dashed line) reflectors.

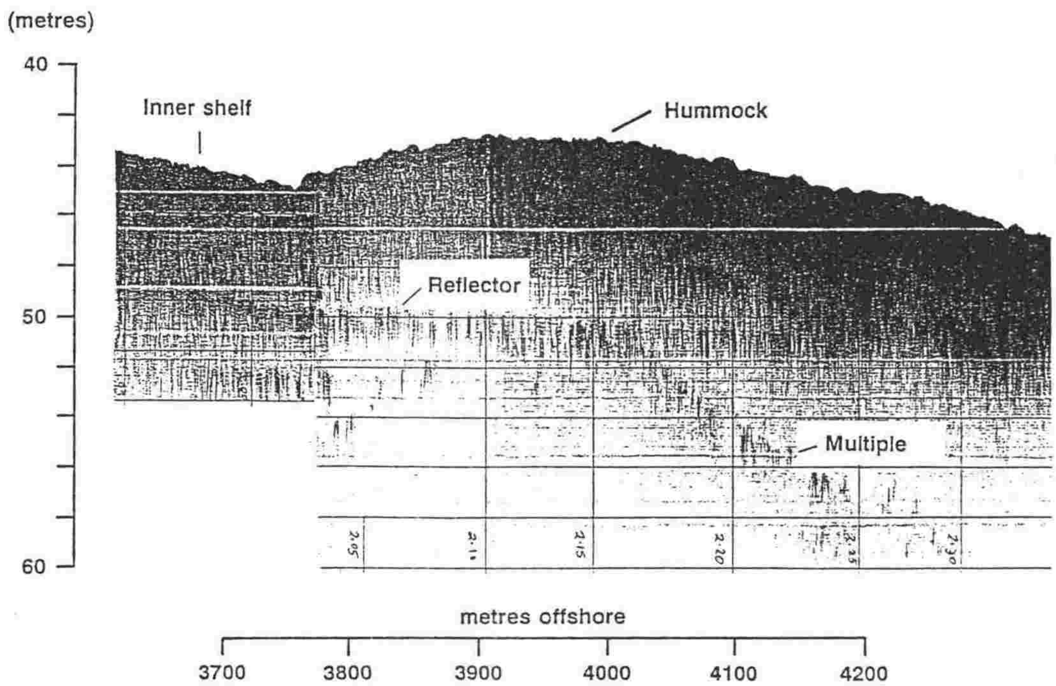



**Figure 5.19** Reproduction of a segment of the ORE sub-bottom sonar record, Walkway transect (08.04.86), showing the presence of a strong reflector beneath the juncture of the inner shelf and mid shelf (located in Figure 5.18).

reflector, beneath the nearshore trough and bar, is common to all transects (Figure 5.20, for example), and is a likely source of the sample provided by the mining companies. This sample may have implications for understanding long-term shoreline fluctuations, since the presence of a shallow peat layer in the nearshore implies the coastline has eroded at least 400 m to its present position.

The density of horizons on the sub-bottom records is not consistent across the transects. The concave shoreface and the relatively flat mid shelf exhibit a greater complexity of substrata compared with the inner shelf and the upper shoreface. The strata of the inner

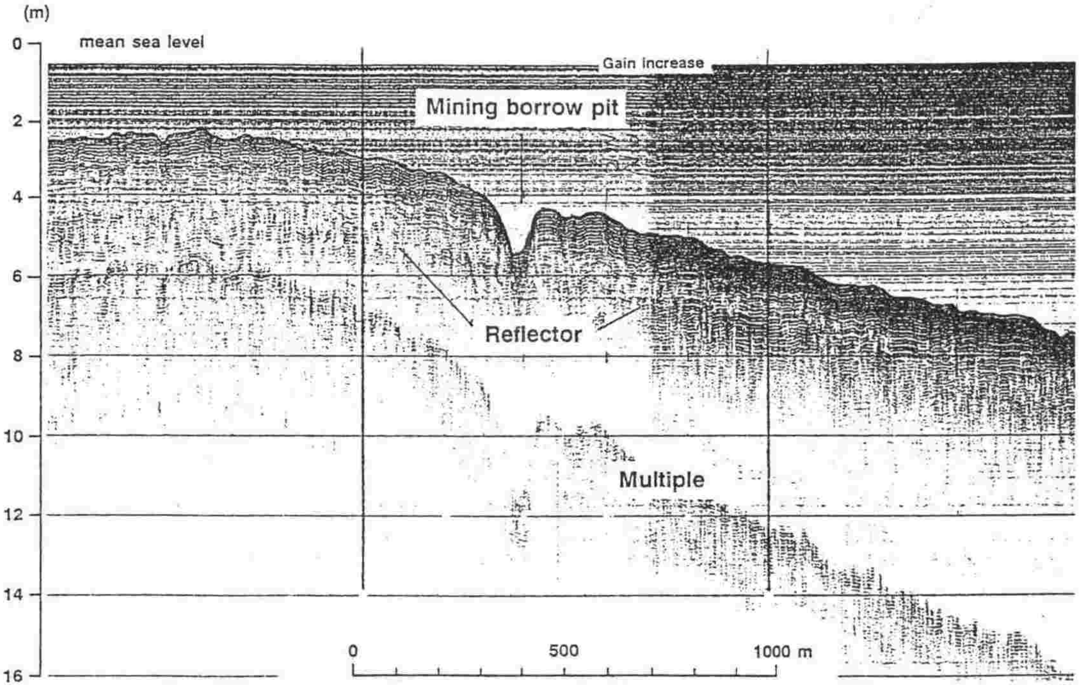



**Figure 5.20** Sub-bottom sonar record, Couldrey transect (08.04.86), showing the presence of a strong reflector below the seaward margin of the alongshore bar (located in Figure 5.18).

shelf occur as relatively uniform and continuous lenses of constant thickness. At the base of the inner shelf the pattern of substrata is more complex. The RNZN survey suggests the presence of an unconformable contact at a level coincident with the change in gradient between the inner shelf and the mid shelf. However there are no exceptional reflectors that might represent a rock outcrop close to the surface.

The results are inconclusive. There appears to be a subsurface step on some of the transects at the inner shelf-mid shelf break, however, its composition and significance is uncertain. Thompson (1975) notes the presence of the abrupt change in slope at the base of the inner shelf, and speculates that it may represent a terrace associated with a low Pleistocene sea level. Such terraces are recorded at a range of sites on the New Zealand continental shelf.

That a terrace should form at this level is not surprizing, given the average sea level over the last 250 ka is about -42 m relative to present (Chappell and Shackleton, 1986). It is possible therefore that the presence of a strong reflector on the sub-bottom records around the landward margin of the mid shelf represents a deposit or eroded surface associated with some former shoreline. Certainly the alongshore continuity of the inner shelf-mid shelf break is consistent with the notion of a sea-level related feature.

## 5.6 Conclusions

Bathymetric surveys in Pakiri Bay show offshore profiles across the sediment body comprise a characteristic sequence of three major slope elements, the concave shoreface, convex inner shelf and planar middle continental shelf. The shoreface extends as a curvilinear concavity approximately 1700 m offshore, between water depths of about 3 and 25-28 m. The seaward margin of this feature is delineated by an abrupt inflexion in the shore-normal profile, at the juncture between the concave shoreface and convex element(s) of the inner shelf. This latter component arcs seaward to water depths of about 42-45 m, 4000-4500 m offshore, at which point there is another abrupt change in gradient at the transition between the inner and mid shelf elements. The transition is complicated by the presence of one or more convexities, interpreted as large-scale bedforms (hummocks). These features lie at the landward limit of the mid shelf or, where more than one is present, may extend some distance onto the inner shelf. The surface of the mid shelf itself is relatively planar (0.0-0.5$^{0}$) compared with the shoreface and inner shelf, where angles of between 0.5 and 2.0$^{0}$ are most common. However, convexities (mounds) similar to those at the base of the inner shelf are present on the mid shelf, superimposed on relatively elevated (1-2 m) areas of the mid shelf surface.

The shoreface and inner shelf slope elements, which comprise most of the width of the Pakiri sediment body, are more or less continuous alongshore. However, departures from the above pattern do occur south of the Pakiri River mouth where the elements become progressively less distinct. Offshore from the cliffed Cape Rodney coast the shoreface component is replaced by rock platforms and reefs, and the shore-normal profiles generally are influenced by the underlying and outcropping bedrock. In contrast the morphology of the shoreface and inner shelf is interpreted as being much less influenced by the underlying bedrock. The sub-bottom records imply that unconsolidated sediments are at least metres thick and continuous across the transects. Further, the absence of any marked alongshore bathymetric variations within Pakiri Bay supports the hypothesis that the cross-sectional geometry of the shoreface and inner shelf is due to sediment transport and deposition, rather than effects of the bedrock embayment.

The large-scale bedforms of the continental shelf (hummocks and mounds) are considered to result from onshore sediment movement of the relatively fine sands of the middle continental shelf. This movement is evidenced by the abrupt sedimentological boundaries between these features and the surrounding relatively coarse sediments, as well as the sudden transition from the fine sediments of the mid shelf to the coarse sediments of the seaward margin of the inner shelf. It is probable that such a distinct textural transition would be likely destroyed by bioturbation were not transport persistent and ongoing.

The hummocks, and the single or multiple convexities of the inner shelf, have an asymmetrical convex profile, skewed towards the coast. This geometry is compatible with onshore rather than offshore sediment transport. That sediment transport occurs over the shoreface and inner shelf is further evidenced by the curvilinear nature and uniform surface of these components of the shore-normal profiles. In general these characteristics are interpreted as consistent with a surface of unconsolidated sediments responding to processes of sediment erosion and deposition. That these processes occur equally along Pakiri Bay is indicated by the alongshore continuity of the morphologic components identified.

The associations between morphological components and sediment types proposed in Chapter Three are confirmed. The transition from mid shelf to inner shelf sediment types occurs along the landward margins of the hummocks. Departures from the trend of offshore bed coarsening across the lower inner shelf (Brown transect, for example, Figure 3.4) are explained by the presence of one or more hummocks. These features are present as discrete accumulations of very fine sediment surrounded by the coarse sediments of the inner shelf. The transition from shoreface to inner shelf sediment types is more subtle, and the relationship between morphologic unit and sediment type weaker. Whereas the finest shoreface sands usually occur 500 to 1000 m offshore, in most instances the base of the shoreface occurs several hundred metres further seaward. These results raise the question as to the relationship between the form of the morphologic components and their sedimentology. In the case of the mid shelf hummocks, assuming these are bedforms resulting from active onshore sediment transport, the two aspects of the geomorphology of the sediment body may be genetically related.

In terms of the potential for sediment transport in Pakiri Bay the historic data indicates that at times substantial quantities of foreshore and inshore sediment may be eroded as a result of storms and deposited on the shoreface. There is thus the potential for at least a proportion of the medium to fine sands of the coastal dunes to be incorporated in the fine, well-sorted sand type of the shoreface. In contrast, profiles surveyed over a three year period have shown the inner shelf, hummock and mid shelf slope components to be stable in this time.

It is proposed that the results of Chapters Three to Five are generally consistent with a scenario that envisages sediment transport on the shoreface and continental shelf in Pakiri Bay, to be primarily or completely in an onshore-offshore direction. Evidence of sedimentation is diverse and from independent sources, and includes the overall configuration of the subaqueous sediment body, the presence of large-scale bedforms associated with areas of textural differentiation, historic records of morphodynamics, the characteristics of the sediments in the study area, the benthic fauna, and the graded bed of the inner continental shelf. The following chapter is one of two that seeks to understand the hydraulic conditions in Pakiri Bay leading to a model of sedimentation and facies development.

# Chapter 6

# THE NATURE AND HYDRAULIC SIGNIFICANCE OF BEDFORMS ON THE SHOREFACE AND CONTINENTAL SHELF, PAKIRI BAY

## 6.0 Introduction

Previous chapters have documented variations in the texture and composition of the bed sediments, the distribution and abundance of the benthic macrofauna and the morphology of the subtidal sediment body. These variations are remarkably regular and invariably occur across the shoreface and continental shelf normal to the coast.

This chapter is concerned with the nature of the interaction between the unconsolidated surface sediments of the sediment body and the hydraulic flows in Pakiri Bay. Wave related currents are thought to be relatively more important than tidal or other long period currents along the east coast of the Northland Peninsula, particularly in the broad embayment of the Outer Hauraki Gulf. However, aside from such generalizations existing understanding affords little basis for interpreting the sedimentological and morphological patterns described in the previous chapters in terms of particular hydraulic processes.

The methodology employed in the present investigation entails field measurement of currents and the analysis of existing current data, and inferring flow characteristics from the form of sedimentary structures (bedforms). For example, Clifton and Dingler (1984) conclude that wave formed sedimentary structures can be diagnostic of depositional environments because they reflect not only the velocity and direction of the oscillatory currents, but also the length of the horizontal component of orbital motion and the presence of velocity asymmetry within the flow. These aspects can be related through standard wave theory to combinations of wave dimension and water depth that have definable natural limits.

The bed features investigated in this chapter have lengths of less than 2 m. The description and classification of bedforms in Pakiri Bay is based on the results of side-scan and remote-controlled photographic surveys of the shoreface and shelf seabed, as well as diver observations to the base of the shoreface. The results are used to derive parameters that describe the geometry of single bedforms, as well as bed configurations. The results of empirical studies by Komar and Miller (1975), Miller and Komar (1980 a,b), Grant and Madsen (1982) and Clifton and Dingler (1984) are then used to relate bedform geometry to the likely formative hydraulic conditions. Hypotheses are developed as to the nature and intensity of water motions affecting the bed of the shoreface and continental shelf, and the potential for sediment transport and facies development.

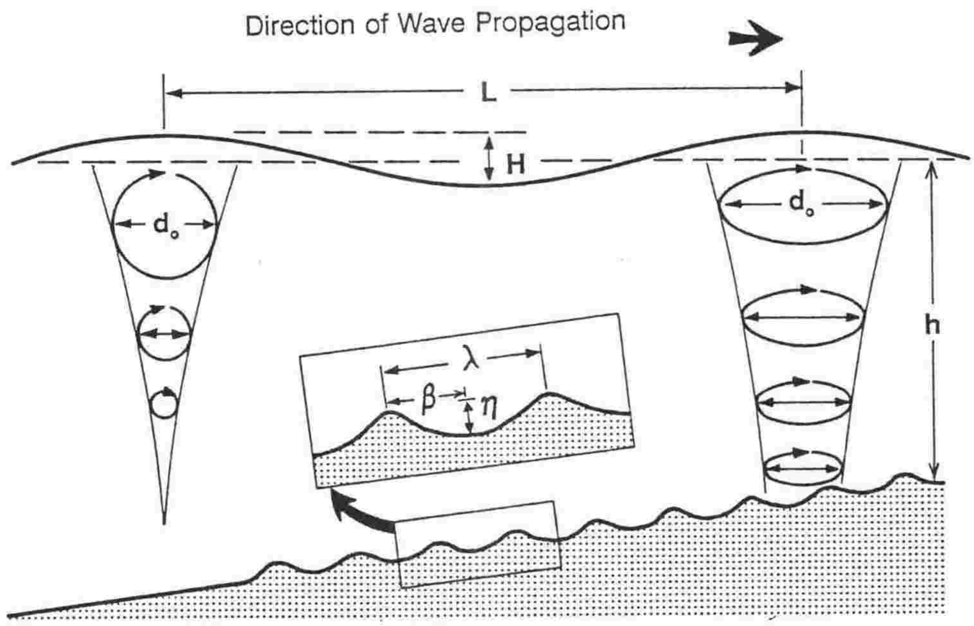
Bedforms are defined as spatially periodic mounds and hollows formed at the sea-fluid interface by the action of fluid forces (Allen, 1970). In wave dominated environments bedforms are thought to reflect the interaction of fluid factors (density and viscosity), flow factors (such as existing unidirectional currents), wave factors (especially their height, periodicity, direction of approach and their variability), bottom configuration factors (such as water depth, local slope and overall slope profile) and sediment factors (including grain diameter, sorting, density and grain shape) (Clifton, 1976).

Confusion has surrounded the classification of bedforms (Allen, 1980; Harris, 1988). However a general distinction is drawn between flow-transverse and flow-parallel forms. The characteristics and physical basis of the many variations are reviewed by Allen (1982) and Clifton and Dingler (1984). Ripples are the predominant transverse bedform in most shallow marine environments, and are widely reported from the shoreface and shelf (for example, Cook and Gorsline, 1972; Davidson-Arnott and Greenwood, 1974; Swift et al., 1979; Cacchione et al., 1984; and Hunter et al., 1988).

The hydraulically important parameters of waves, wave motion and wave formed ripples are portrayed in Figure 6.1 a. Swift et al. (1979) propose the terms ripple, megaripple and sand wave for small, medium and large-scale transverse bedforms. Morang and McMaster (1980) describe ripples ($\lambda$<0.6 m), megaripples ($\lambda$=0.6-6.0 m) and sand waves ($\lambda$>6 m) in terms of their wavelength. In profile, spacing ($\lambda$), height ($\eta$), the average spacing from crest to leading trough ($\beta$) and symmetry ($\beta/\lambda$) characterize ripples. In plan view crest length relative to spacing (horizontal form index), and crest sinuosity are primary characteristics. Crest pattern ranges from straight to sinuous. The ratio of ripple height to wavelength ($\eta/\lambda$) is the ripple steepness, and its inverse, the ripple index (Reineck and Singh, 1973) have been used to describe ripples. Asymmetric ripples may result if one direction of water movement predominates, such that the ripples will have a steep lee side and gentle stoss side. They range in size from 1.5-105.0 cm in length and 0.3- 20.0 cm in height. Symmetrical ripples have a symmetry factor ($\beta/\lambda$) that approaches 0.5, or a ripple symmetry index [$(\lambda-\beta)/\beta$] that approaches 1.0 (Reineck and Singh, 1973). The steeper side of most asymmetric ripples face in the direction of ripple migration, making the symmetry factor <0.5 and the ripple symmetry index greater than 1.0.

Oscillation (wave) ripples and ripples produced by unidirectional currents may be difficult to differentiate (Clifton and Dingler, 1984). Wave ripple marks are generally more regular than current ripple marks (Allen, 1982). In the latter case the upstream or stoss side is comparatively long, gently-sloping, and weakly convex-up (Figure 6.1 b). The downstream or lee side is relatively short and often composite, comprising a weakly convex-up crestal shoulder, a slip face and a gently inclined weakly concave-up bottomset (Allen, 1982). No wave ripple marks are perfectly symmetrical, however, near-symmetrical ripples are generally accepted to result from wave action. Clifton (1981) inferred that ripples that faced or migrated in a landward direction were solely the product of waves.

a.

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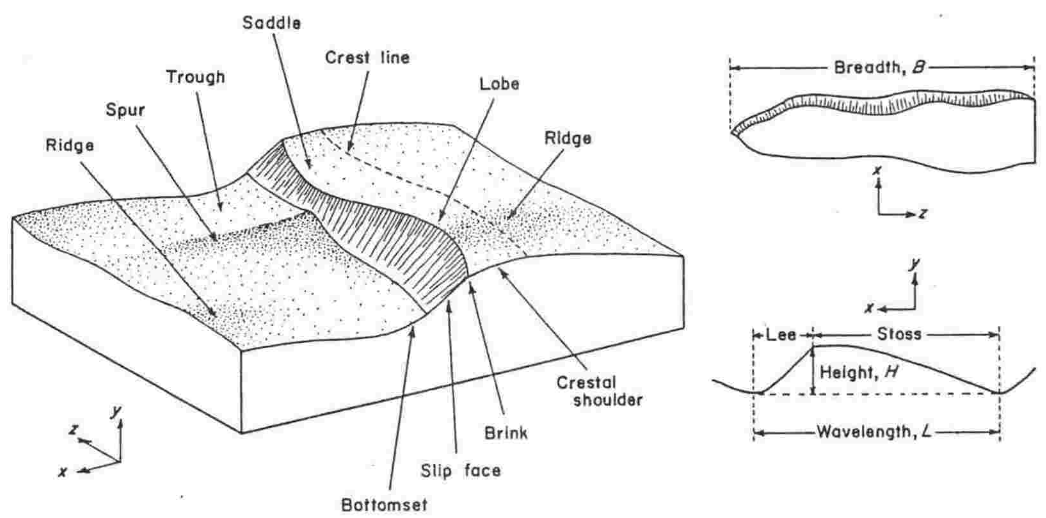



Figure 6.1 (a) Morphodynamically important parameters of waves, wave motion and wave-formed ripples - L = wave length, H = wave height, h = water depth, $d_0$ = orbital diameter, $\lambda$ = ripple spacing, $\eta$ = ripple height, $\beta$ = average distance from ripple crest to leading trough (from Clifton and Dingler, 1984); and (b) schematic representation of the chief morphological features of transverse bedforms (flow right to left) (Allen, 1982).

## 6.1 Hydraulic Interpretation of Bedforms

Clifton and Dingler (1984) outline a procedure that allows aspects of the depositional environment to be reconstructed from wave formed structures. The procedure entails inferring flow parameters from specific characteristics of the wave generated structure, applying wave theory to determine the combinations of water depth and wave size and shape that could produce the inferred flow parameters, and finally, utilizing the natural limits that exist for waves or hindcasting to constrain the range of possible wave characteristics.

Existing laboratory and field studies of bedforms provide the basis for interpreting maximum orbital velocity ($U_m$), orbital diameter ($d_o$), wave period (T) and orbital velocity asymmetry ($\Delta U_m$). It is known that neither line of investigation provides completely satisfactory results, which are subject to some or all of the limitations discussed in Section 6.2. Estimates of orbital velocity are commonly based on the threshold criteria of Komar and Miller (1973, 1975) and Dingler (1979) for grain movement, and Dingler and Inman (1977) for sheet flow (Figure 6.2) for quartz sand in water. In the present investigation the threshold curves of Dingler (1979) are employed, although the effect on $U_m$ of using the more conservative curves of Komar and Miller, for sands in the fine and medium size grades, is minimal.

### 6.1.1 Method

Estimates of orbital diameter are derived from the relationship between ripple spacing (or steepness) and grain size. Figure 6.3 a is a dimensionless plot of $\lambda/D$ (D = grain size in mm) against $d_o/D$ for field studies by Inman (1957), Dingler (1974), Miller and Komar (1980 b) and Clifton and Dingler (1984), and experimental studies by Miller and Komar (1980 a) and others. Figure 6.3 b is an interpretation and classification of ripples as orbital, anorbital and suborbital. Orbital ripples are those whose ripple spacing is

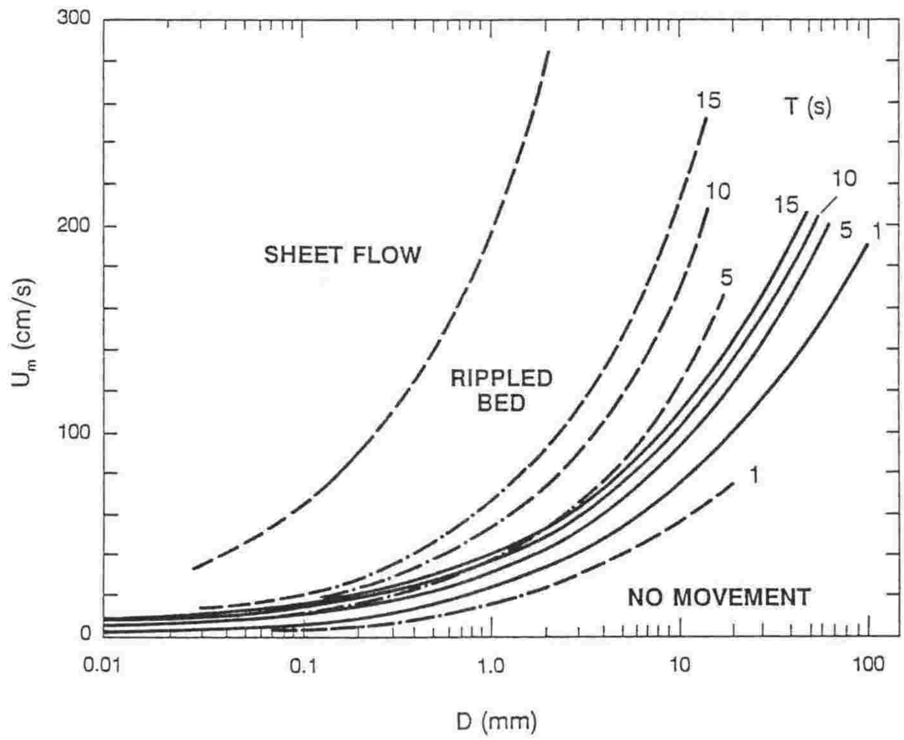



**Figure 6.2** Velocity thresholds for grain movement and sheet flow of quartz sand in water (from Clifton and Dingler, 1984) - threshold curves of Komar and Miller (1975) (solid lines) and Dingler (1979) (dashed lines connected by dots - dashed lines where curve extrapolated) for grain movement. Threshold curve for sheetflow (Dingler and Inman (1977) is solid in the range of experimental data, and dashed where extrapolated.

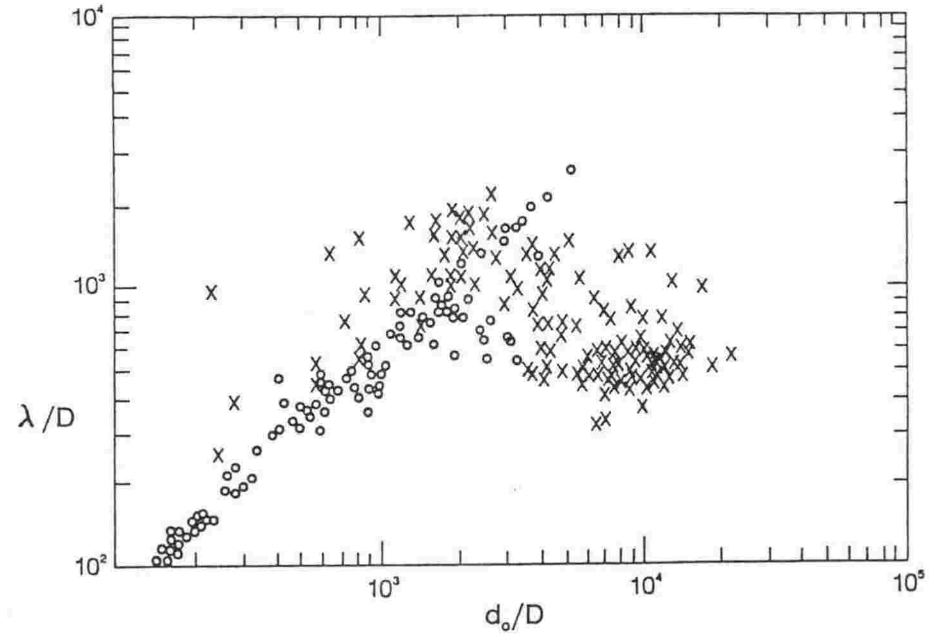
proportional to orbital diameter in the approximate relationship

$$\lambda = 0.65d_0 \quad (1)$$

as determined by (Miller and Komar, 1980 a).

Such ripples can form under conditions where the $d_0/D$ ratio lies in the range of 100-300, and their spacing to grain size ratio ($\lambda/D$) ranges from less than 100 to more than 2000. Ripple spacing remains proportional to orbital diameter until the $d_0/D$ ratio reaches the

a.

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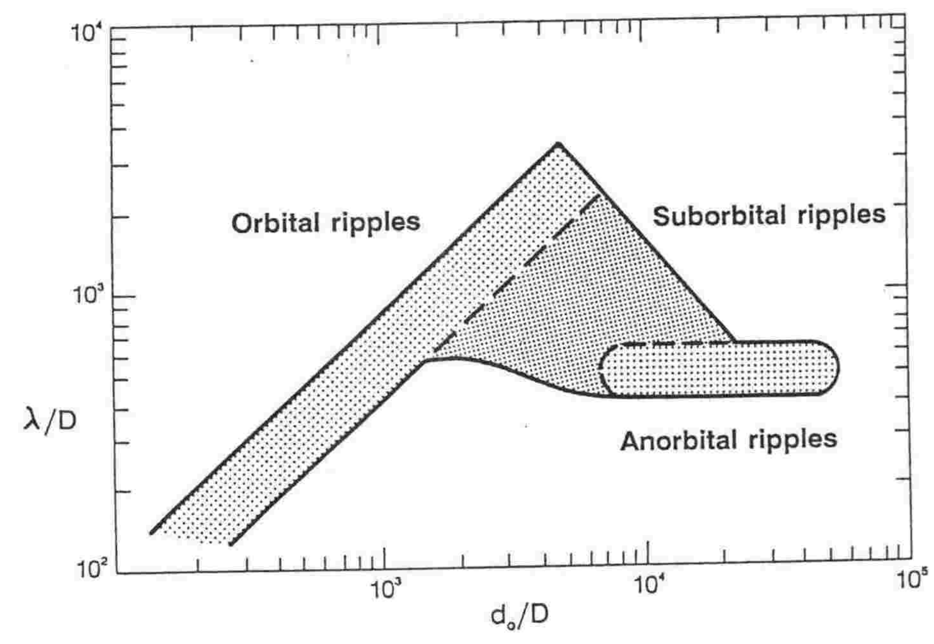



Figure 6.3 (a) Plot of ratio of ripple spacing to grain size against ratio of orbital diameter to grain size (field observations - x, experimental - o), from Clifton and Dingler (1984); and (b) classification of ripples based on the distribution shown in (a).

range 1000-3000 (Clifton and Dingler, 1984). Under these conditions the ripple spacing decreases as orbital diameter increases (suborbital ripples). At $d_o/D$ values in excess of 5000, ripple spacing stabilizes at a value that is independent of orbital diameter (anorbital ripples). These ripples are most commonly observed in fine sand where they have a spacing of 5-10 cm, and typically a $\lambda/D$ ratio that lies in the range of 400-600. The relationship between $\lambda$ and $d_o$ is valid only for symmetrical ripples.

These relationships are used to derive $U_m$ and $d_o$ from ripple wavelength, grain size and wave period. Airy, Stokes, cnoidal or solitary wave theory can then be used to relate these flow parameters to basic wave parameters. Each wave theory is most applicable under a specific set of conditions of wave height, wave period and water depth. Using the criterion employed by Komar (1976) for the range of conditions thought to occur in Pakiri Bay (wave period (T) equals 5-15 s, wave height (H) equals 1-10 m, in water depths (h) of 20-50 m) Airy is the most appropriate theory. Airy theory is somewhat simplistic, in that it treats waves as sinusoidal forms. However, it has the advantage of being relatively simple to use, and robust under a range of conditions.

The maximum threshold velocity and orbital diameters derived from ripples are a result of different combinations of wave size, shape and water depth. In Airy wave theory the orbital diameter ($d_o$) at the sea floor is

$$d_o = \frac{H}{\sinh(kh)} \tag{2}$$

where H equals wave height, k (the wave number) equals $2\pi/L$ and h equals water depth. The maximum orbital velocity at the sea floor ($U_m$) under the crest of the wave is

$$U_m = \frac{\pi d_o}{T} = \frac{\pi H}{\sinh(kh)} \tag{3}$$

These equations can be restated in terms of wave height, where

$$H = d_o \sinh(kh) = \frac{U_m T \sinh(kh)}{\pi} \qquad (4)$$

and solved for a series of selected water depths under waves of different periods using the values $d_o$ and $U_m$ derived from the bedforms.

Three configurations characteristic of the Pakiri Bay seabed (described in the following section) are used to infer flow parameters according to the method of Clifton and Dingler (1984). These comprise the plane bed of the shoreface, the megarippled bed of the inner shelf and the mostly featureless (but partially rippled) bed of the middle continental shelf. The ripple geometries chosen are typical of the bedforms observed - although the ripple heights ($\eta$) are estimates only (Table 6.1). Large ripples and megaripples occur over the width of the inner shelf, and the equivalent range of (mean) grain sizes varies between 1.5 and 0.0 $\phi$ (0.35-1.00 mm). A mid range size value is used, although because of the exponential shape of the threshold curves, the selection of any size value within the fine or medium sand grades has relatively little effect on the derived orbital threshold velocities.

Selecting an appropriate grain size for the mid shelf ripples is more problematic. The side-scan records indicate these ripples are associated with isolated patches of relatively coarse sediment. The grain size data from the mid shelf indicates mean grain sizes range between 1.5 and 2.5 $\phi$, although most samples have means over 2.0 $\phi$. A compromise value of 2.0 $\phi$ was therefore employed.

The final step in the Clifton and Dingler (1984) method entails computing wave height (H) for various combinations of wave period (T), wave length (L) and threshold velocity (Um) using equation (4). Wiegel (1954) has solved the expression (sinh ($2\pi h/L$)) for a range of $h/L_o$ values (U.S. Army Coastal Engineering Research Centre, 1973).

Table 6.1 Ripple Characteristics and Derived Flow Conditions For Representative Continental Shelf Ripples

| Observed Ripple Characteristics | | | | Derived Flow Parameters | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | $U_m$ (cm/s) | | | | |
| $\lambda$ (m) | $\eta$ (m) | D (mm) | h (m) | $d_0$ | T=5s | T=10s | T=15s | $\lambda$/D | $_0$/D |
| a. Inner Shelf Megaripples | | | | | | | | | |
| 1.2 | 0.20 | 0.50 | 25-40 | 1.85 | 22 | 30 | 42 | 2400 | 3700 |
| b. Mid Shelf Megaripples | | | | | | | | | |
| 0.9 | 0.15 | 0.25 | 40-50 | 1.31 | 18 | 23 | 30 | 3400 | 5240 |

## 6.2 Problems Associated with the Interpretation of Bedforms

Swift and Freeland (1978) caution that side-scan sonar records must be interpreted carefully. On the inner Atlantic Shelf they found that the wave rippled, coarse, pebbly sand of the trough is readily apparent, because such material strongly reflects acoustic energy, quite apart from the sensitivity of the instrument. Long, gentle up-current slopes, composed of finer, more weakly reflective sand, are much less apparent. It is therefore important to obtain independent evidence of the seabed characteristics. In the present investigation bedform patterns are described from both seabed photography and side-scan sonar recordings. While these techniques have provided a reasonable assessment of ripple wavelength ($\lambda$), and the photographic data the distance from ripple crest to trough ($\beta$), ripple height ($\eta$) is difficult to estimate from either the sonar or photographic data. Diver observations at water depths of 30-32 m along Brown Transect at the time of the current meter deployment (see Chapter Seven) indicated that the megaripples present attained wavelengths of 1.0 to 1.2 m and heights of 0.15-0.20 m.

A more fundamental problem relates to the extent single surveys are representative of the long term bed configuration, and whether the bedforms observed are in dynamic equilibrium, or are evolving in response to a steady or changing hydraulic regime. At any time a depth cross section of the seabed will contain bedforms that are both in and out of phase with the wave characteristics, and exhibit a configuration that may be transitional between bedform states. Individual bedforms are not necessarily in phase with the current regime in that they may have been in the process of forming when energy levels dropped, or deteriorating with the onset of different flow conditions. An existing, well developed bed configuration may undergo modification from oscillatory currents associated with waves arriving from a different direction. The antecedent configuration may be completely, or only partially modified, depending upon the duration and magnitude of the event. Kos'Yan (1988) comments on the use of passive ripple marks to reconstruct flow conditions during severe storms, and notes that the characteristics of the bedforms will most likely represent conditions during damping of the agitation (in the case of wave formed ripples). He concludes that passive ripples will never indicate the storm strength in its maximal development, and it is therefore impossible to completely reconstruct former conditions of wave generation. This may represent a serious limitation in situations where mass transport or return flows related to shoaling storm waves are significant forces on the shoreface and/or continental shelf. The bedforms observed at any time may reflect much lower energy flows at some later stage of bed disturbance.

Some of the assumptions on which the bedform models are based have little basis (Clifton and Dingler, 1984). The sediment is assumed to be well sorted, equidimensional, quartz grains of density 2.65 g/cm$^3$. Wave winnowed sand commonly is well sorted, but it is not uniform in texture and composition. Most of the expressed relationships between wave formed structures, flow parameters and waves assume an absence of superimposed unidirectional currents. This is a simplification of reality, since in natural environments combined oscillatory and unidirectional flows, such as tidal, rip or alongshore currents, are common. The studies that have investigated combined flow ripples (Harms, 1969; Bliven et al., 1977; for example) as yet provide an insufficient basis for application to real environments. Clifton and Dingler (1984, p.195) warn that the results are approximations, and that the 'indicated values should be considered as reasonable estimates only'.

## 6.3 Survey Techniques

The sampling strategy involved both shore-normal (point) and alongshore (continuous) observations of the Pakiri Bay seabed, entailing seabed photography and side-scan sonar respectively. Bed photographs were obtained across Gravel, Walkway, Couldrey, Williams and Brown transects. This approach is consistent with the methodology adopted throughout the present study, and appropriate given the factors that are known to effect bedform development. For example, water depth and sediment type are important factors in ripple formation, that are known to be more or less continuous alongshore, but vary regularly offshore. Seabed photography was undertaken across all Pakiri Bay transects, with the exception of Matheson, to water depths of about 45 m (Figure 6.4). Each transect was photographed on one occasion only, except Brown, which was photographed twice. Photographic stations were selected to coincide with the stations employed for the sediment sampling program, although in most cases the surveys could not be commenced until the second or third station offshore. Excluding approximately 30 experimental images, 157x35 mm colour transparencies were obtained.

The side-scan sonar technique is described in the previous chapter. Approximately 3.3 km$^2$ of side-scan record is available (Figure 6.4). Compared with the photographic records these data provide synoptic views of the bedform configurations present. The records also show the alongshore continuity of particular configurations, and the extent to which the extrapolation of results between transects is justified.

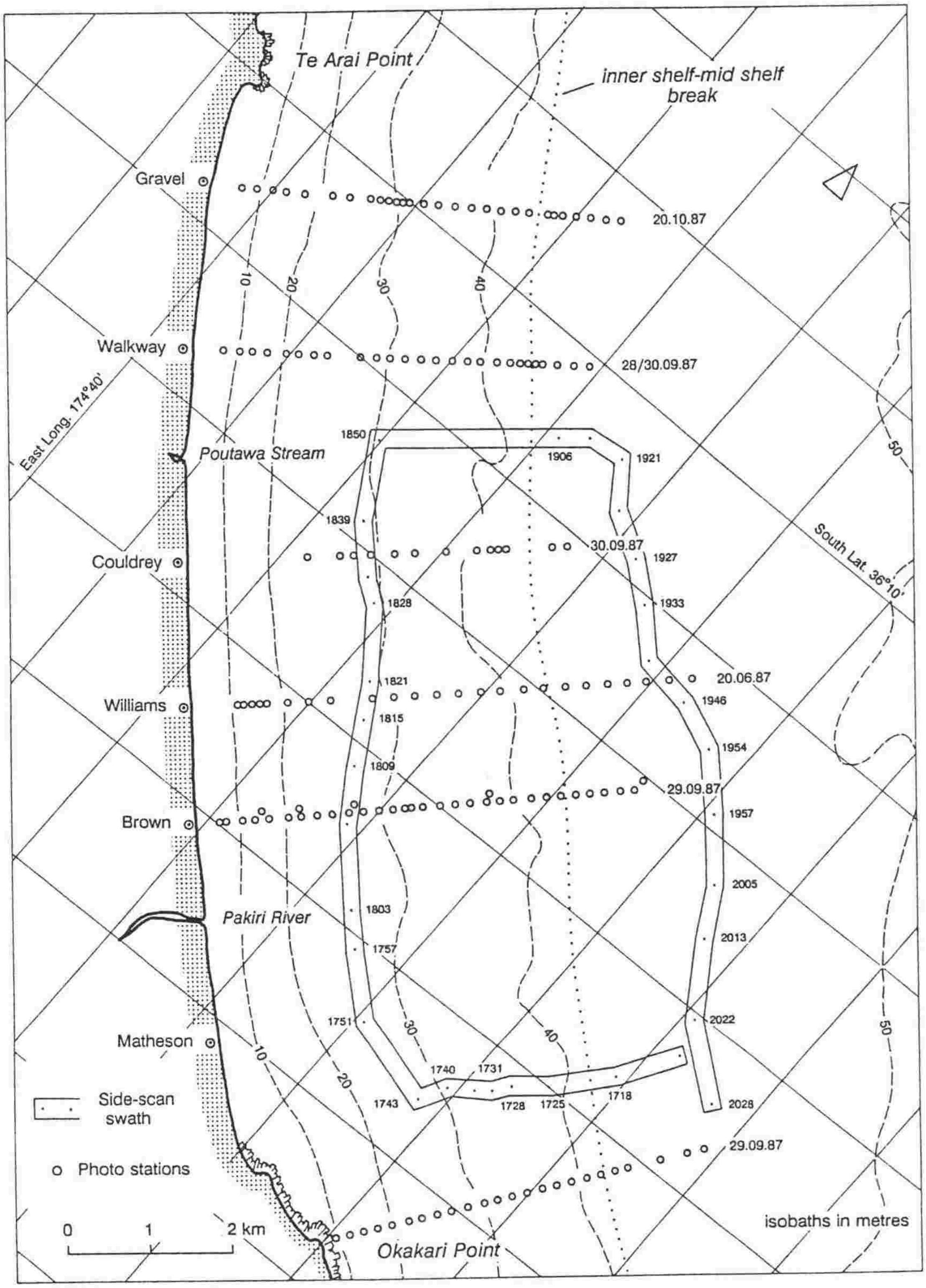



**Figure 6.4** Location of transect photo stations and side-scan sonar survey, Pakiri Bay.

### 6.3.1 Remote Controlled Photographic System

The photographic system (Figure 6.5) contains a housed 35 mm (still) camera attached to a structure that allows vertical images of the seabed. The variables involved in obtaining correctly exposed images of the sea floor using the above system are given in Appendix L for the normal and wide angle lenses employed. Each colour transparency was examined for evidence of bedforms, sedimentological variations and the presence of live benthos. The orientation and wavelength of the linear ripples was determined using the 10x10 $cm^2$ grid and compass. The amplitude of the ripples was estimated by the depth of the grid line shadow and whether the grid was touching the crests of the ripples. The proportion of sand and shell was estimated following examination of the colour and texture of the sediments, and the mud content by the degree of disturbance of the bed by the legs of the tetrapod. The resolution of the 35 mm camera lens allowed identification of the macrobenthic epifauna, such as sand dollars, hermit crabs and large molluscs.

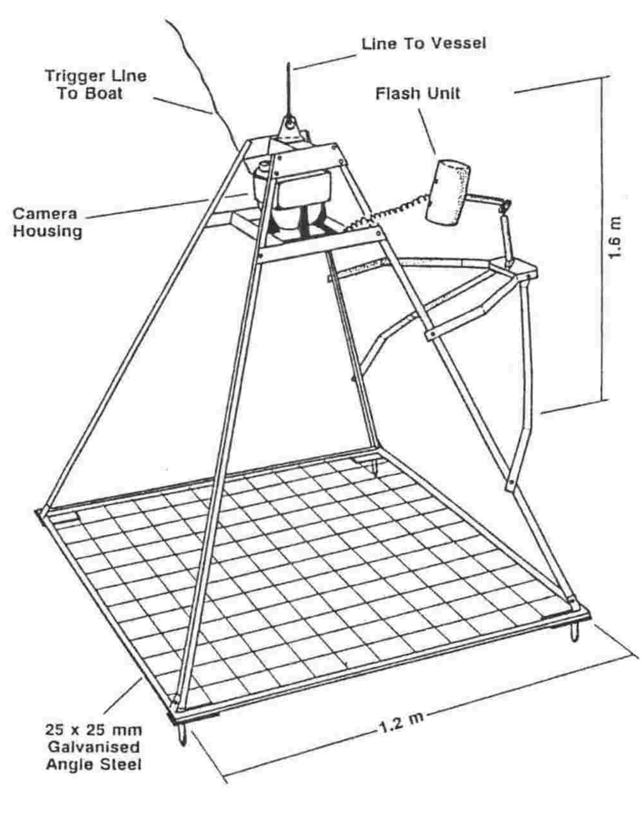



Figure 6.5 Remotely triggered underwater photographic system

## 6.4 Results

### 6.4.1 Results of Photographic and Side-scan Bedform Surveys

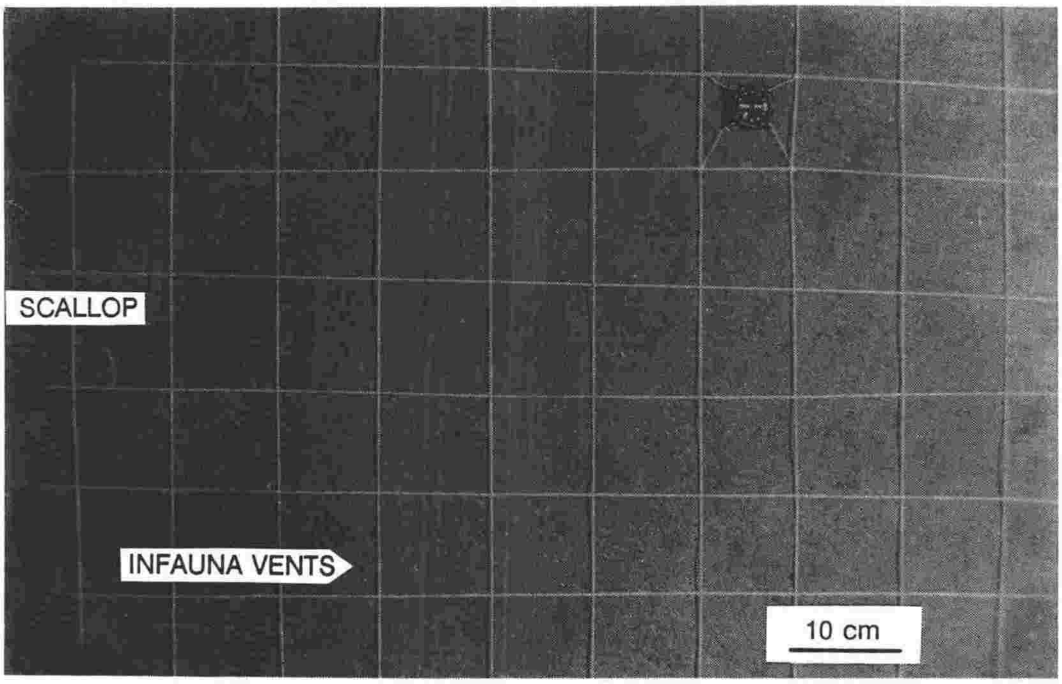
Three (major) bed configurations are recognized in Pakiri Bay. The interpretation of the bed configuration at each photographic station, including estimates of the wavelength and amplitude of ripples, is listed in Appendix M.

a. Middle continental shelf (bedform types N and Ri)

The photographic and side-scan data show the surface of the mid continental shelf to be mostly featureless (type N). Few images exhibit evidence of bedforms. The minor topographic variations detected in many images are probably the result of bioturbation. The vents of infauna are abundant in the middle continental shelf images, although direct observations of any benthos is rare. Of the epifauna captured live from the mid shelf only **Luidia varia** is commonly observed in the photographic images. The eroded imbricated tubes of polychaetes are sometimes seen to extend about 1 cm from the bed. These were recovered from mid shelf sediment samples (but not the benthos dredge samples due to the large mesh size) in great numbers.

The sediments of the mid shelf appear textually and mineralogically uniform in the photographs, except where the blue-grey hue of the bed is peppered by the vents of the infauna (Figures 6.6 a,b). Large shell fragments are rare, although the 55 mm camera lens shows the bed to include low to moderate (relative to the lower inner shelf carbonates) quantities of fine shell fragments. The sediments also contain a high mud content, evident in many images where the feet of the camera structure, or the compass, have disturbed the bed. In general these observations are consistent with the results of the sediment surveys of the mid shelf, which indicate the bed of the mid shelf comprises very fine, well sorted, muddy sands, containing up to 10 and 20 percent mud and carbonates respectively.

a.




b.

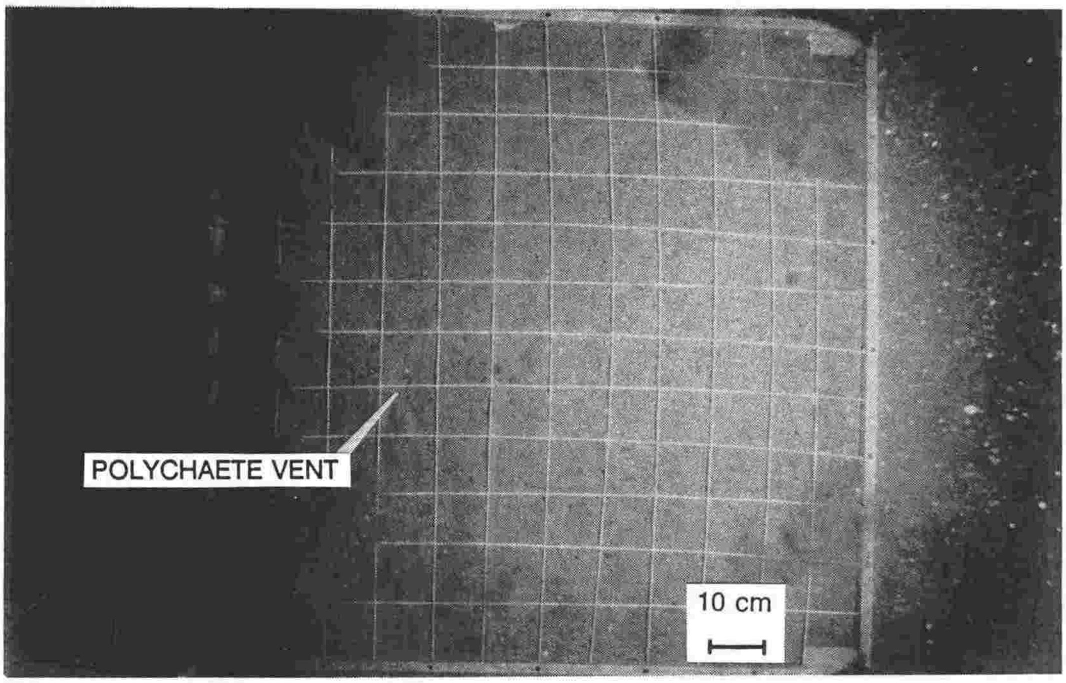



**Figure 6.6** Normal (a) and wide-angle (b) lens images of the middle continental shelf seabed (type N configuration), Brown transect (image 59, 49 m) and Williams transect (image 80, 48 m) respectively (grid spacing 10 cm).

The mid shelf is not however a completely homogeneous surface of the mid shelf sediment type. Textural segregation of the bed is associated with the large scale bedforms (mounds) described in the previous chapter. The mounds of fine sediment are separated by narrow bands of relatively coarse sediment. The side-scan data shows that ripples (type Ri) are occasionally present in the latter, especially where the coarser sediments occupy intervening depressions (Figure 6.7, for example). Such ripples are mostly indistinct and restricted to only a few percent of the total area of mid shelf surveyed.

The average wavelength of ripples observed on the side-scan record on the mid shelf survey leg is 0.84 m (range 0.75-0.88 m), somewhat smaller than those on the inner shelf. The crests of all ripples, regardless of their location on the shelf, are orientated approximately parallel to the Pakiri coast. In terms of their amplitude these ripples are probably near the limit of resolution of the sonar (about 10 cm). Only one (possible) example of a mid shelf ripple was recorded during the photographic surveys. This example occurs in 46 m of water 4255 m offshore across Walkway transect, close to the base of the inner shelf (Appendix M, image 124). Both the trough and crest appear rounded, the former being distinguished by the anomalous (for the mid shelf) presence of shell gravel, and the shadow cast by the grid. Some of the mid shelf images, especially close to the base of the inner shelf, suggest an undulating, variable topography comparable to, but of greater relief than, the shoreface (type Mit) configuration. This configuration may represent the degraded remnants of former ripples. Most of the mid shelf seabed surveyed however, exhibits no bedforms, and is a comparatively featureless surface.

b. Inner continental shelf (bedform types Ri and Lat)

The bed configuration of the inner shelf forms a marked contrast with the surface of the middle continental shelf. Ripples and megaripples characterize broad areas of the surface of the inner continental shelf. In the photographic images they are indicated by

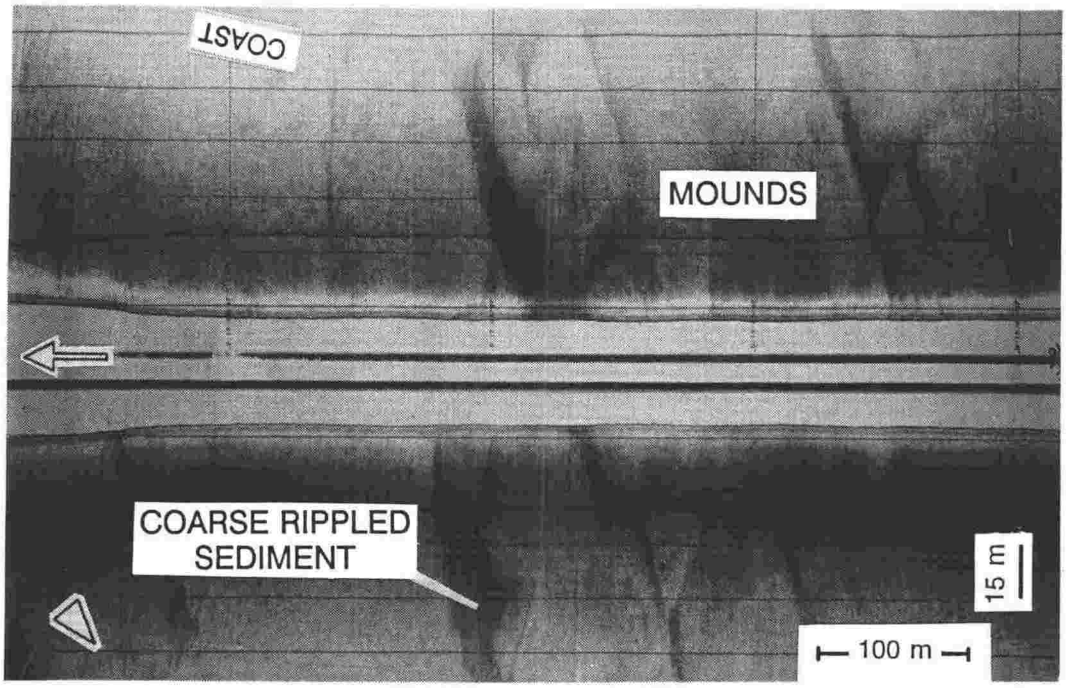



**Figure 6.7** Side-scan sonar record of rippled bands of relatively coarse sediment on the middle shelf (station 1940).

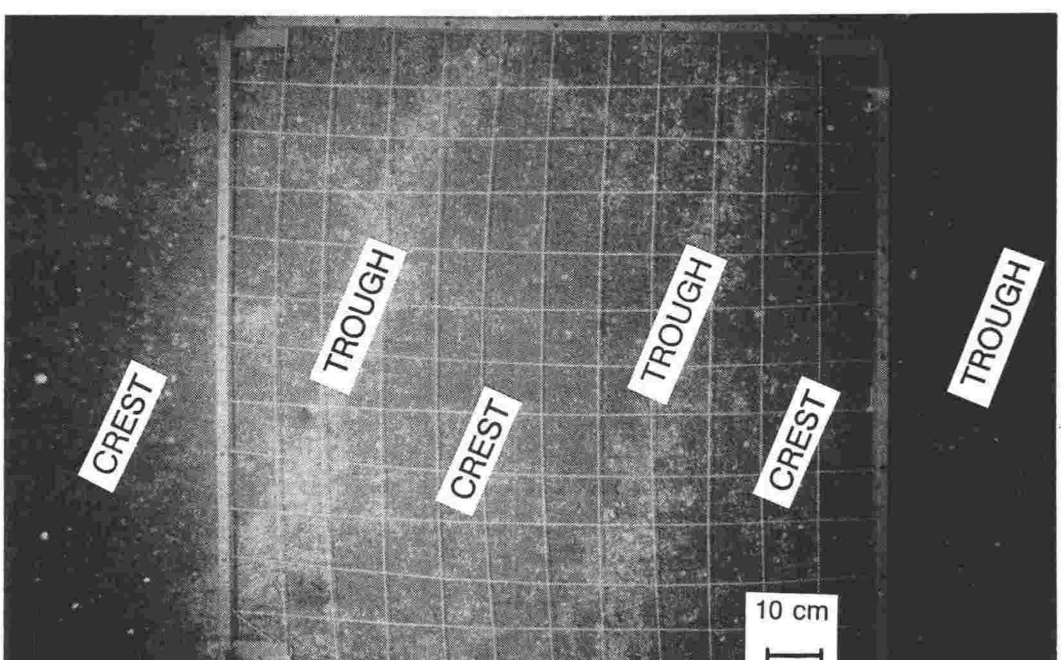



**Figure 6.8** Wide-angle lens view of rippled bed (configuration Ri), inner shelf, Williams transect (image 70, 34 m).

the accumulation of shell and coarse sediments in the troughs and the shadow cast by the grid lines (for example, Figure 6.8). The wavelengths of individual ripples average 1.04 m (with a range of 0.83 to 1.36 m and sample standard deviation of 0.13 m). They appear approximately symmetrical, with rounded troughs and crests, with low steepness values of 0.15 to 0.40.

Ripples are not recorded from either of the shore-normal side-scan survey lines (1710-1743, 1850-1906 hours, Figure 6.4), but this is almost certainly due to the simultaneous alignment of the ripple crests and sonar pulses.

The positioning of a compass on the camera structure grid allowed the orientation of the larger ripples ($\lambda > 0.50$ m) to be estimated. Invariably these are orientated within $35^0$ of parallel to the strike of the adjacent coastline, and most are within $25^0$ (Figure 6.9). Ripples photographed along the same transect at the same time tend to have the same approximate orientation, whereas differences occur between transects. However, the average orientation is close to parallel to the Pakiri coast. The side-scan data showed the seabed to be intensely rippled, with moderate to high linearity. Ripple crests show a high degree of linearity and parallelism, with horizontal form index values commonly in excess of 50 (Figure 6.10 a,b for example).

The side-scan records show that the rippled bed configuration near the landward margin of the inner shelf, in water depths of about 30 m, is not uniform alongshore. The ripples are superimposed on an alongshore sequence of large scale, low amplitude, convexities (Figures 6.10 b and 6.11 a,b). Associated with this rhythmic topography are areas of relatively coarse and fine sediments. Ripple development is absent or indiscernible on these finer sediments. Separation of coarse and fine sediment areas is abrupt, the transition occurring across lines orientated approximately normal to the coast. The relative relief of these convexities is less than 1 m, and their alongshore periodicities range from 100 to 400 m.

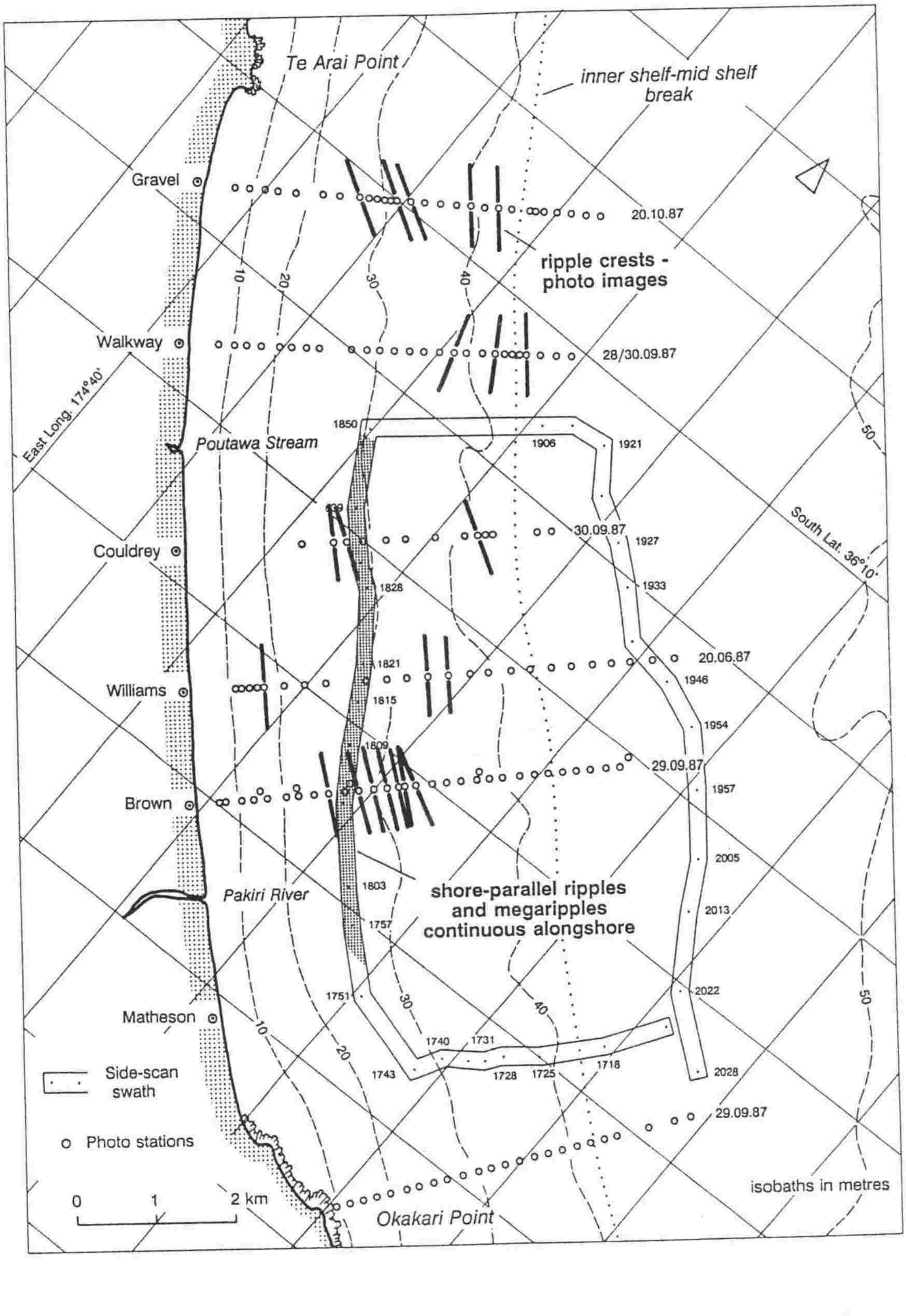
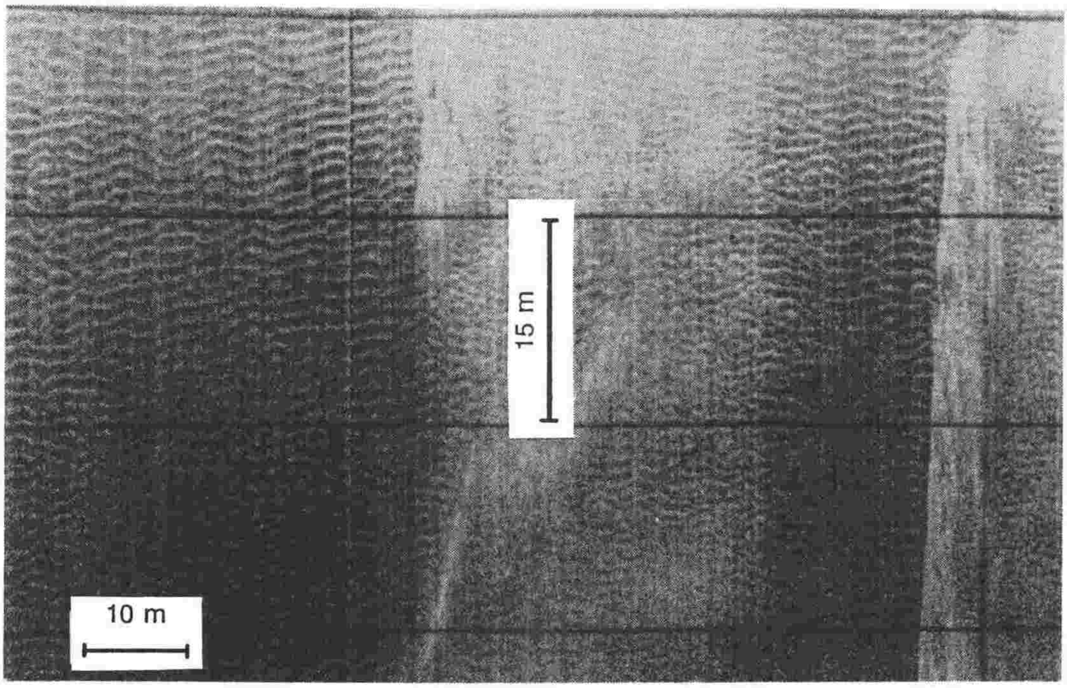



Figure 6.9 Location and orientation of ripples (λ>0.50 m) observed during photographic survey (dates of photography indicated).

a.




b.

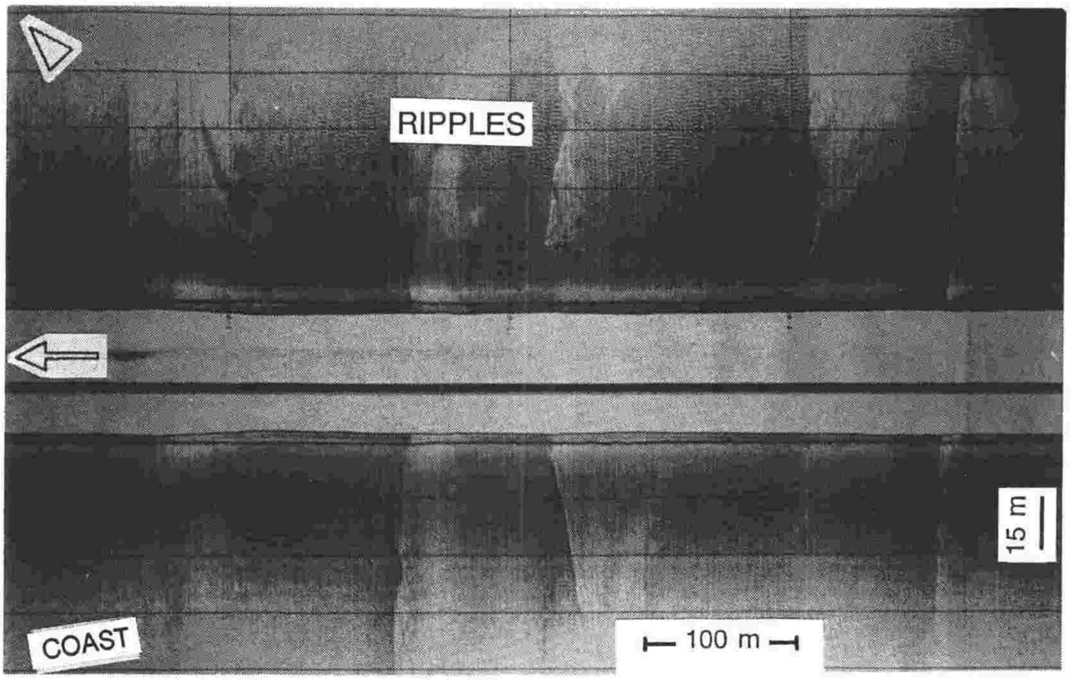
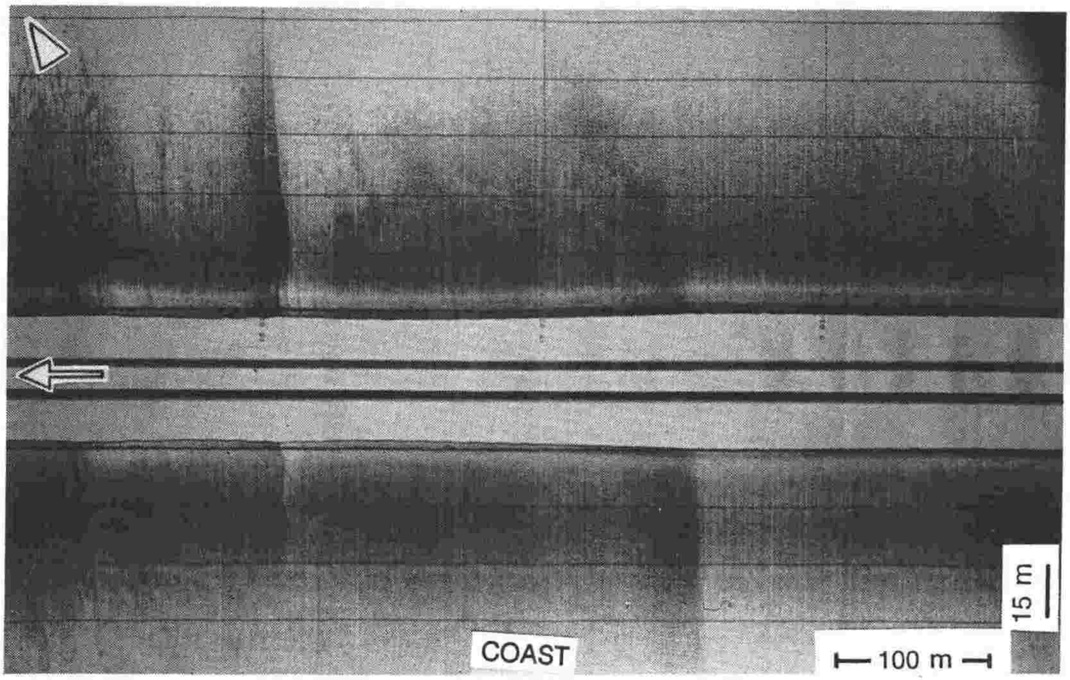



**Figure 6.10** Sections of side-scan sonar record showing (a) large ripples and megaripples and (b) alongshore pattern of rippled (coarse) and unrippled (fine) sediments (Station 1821, 30 m water depth, Figure 6.4).

a.




b.

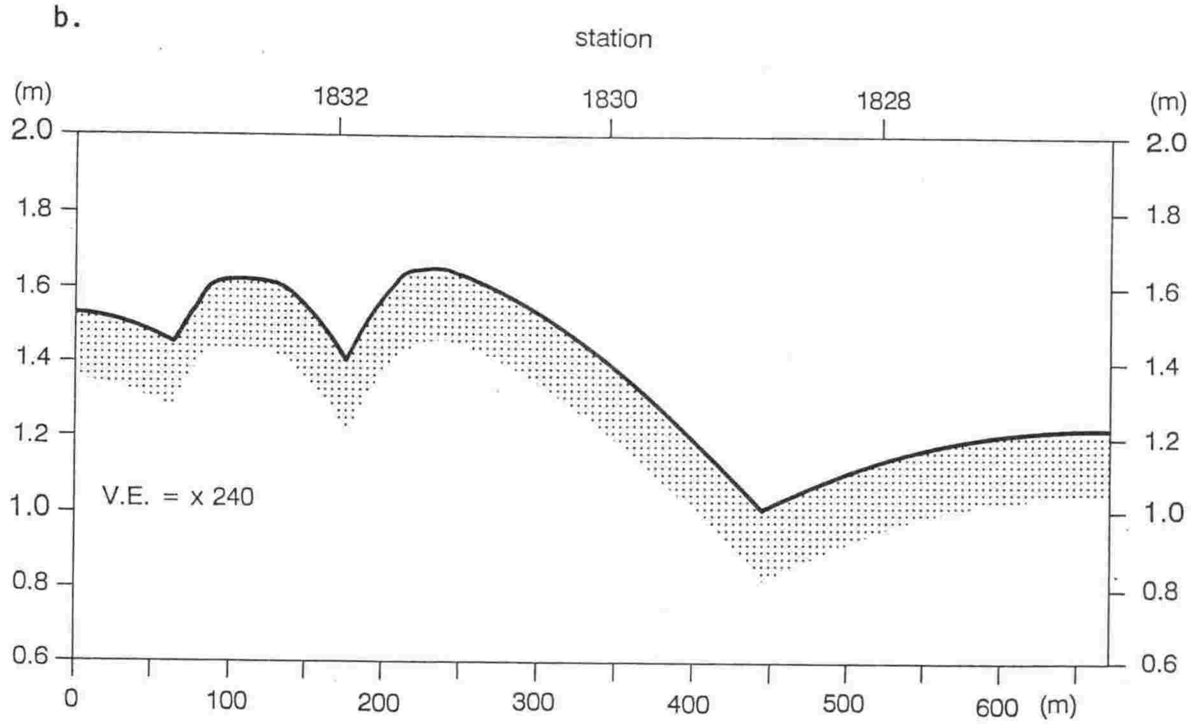



**Figure 6.11** Alongshore side-scan sonar record (a) (station 1828, Figure 6.4) and seabed profile (b) showing pattern of alongshore convexities and associated fine and coarse sediments.

The linear, approximately symmetrical ripples of the lower inner shelf are interspersed with areas of more complex topography (type Lat). These bedforms are not cross ripples. The lattice pattern arises from the textural differentiation of the bed sediments. The troughs are comprised of poorly sorted shell material and other sediments that separate low, curvilinear humps, which appear to comprise relatively well sorted, largely shell-free, sands. Their shape is approximately elliptical, with typical maximum dimensions of 30 x 50 cm, and an estimated relief of less than 10 cm.

This bed type tends to occur nearer the base of the inner shelf (to water depths of about 43 m across Walkway transect for example). In terms of the known sedimentology of the bed at these locations they are spatially correlated with very coarse (biogenic and terrigenous) sands and fine gravels. Shell material is abundant in the images of this type of bed configuration (Figure 6.12, for example), occupying the depressions between the areas of finer sediments.

c. Shoreface (bedform type Mit)

Ripples of the dimensions observed on the inner shelf are not recorded landward of the 25 m isobath. The seabed of the shoreface, to about the 10 m isobath, is characterized by an irregular, undulating topography of hummocks and depressions (Mit). The depressions are evidenced by relatively high concentrations of shell fragments and the shadow of the grid (Figure 6.13). The relief of the seabed does not exceed the height of the grid (12 cm) and is probably much less. The moderately uniform textural appearance of the bed is in keeping with the very well-sorted, fine sands of the shoreface sediment type. The carbonates comprise a comparatively small, and highly fragmented, fraction of the bed sediments compared with the coarse shell gravels evident over the lower inner shelf surface.

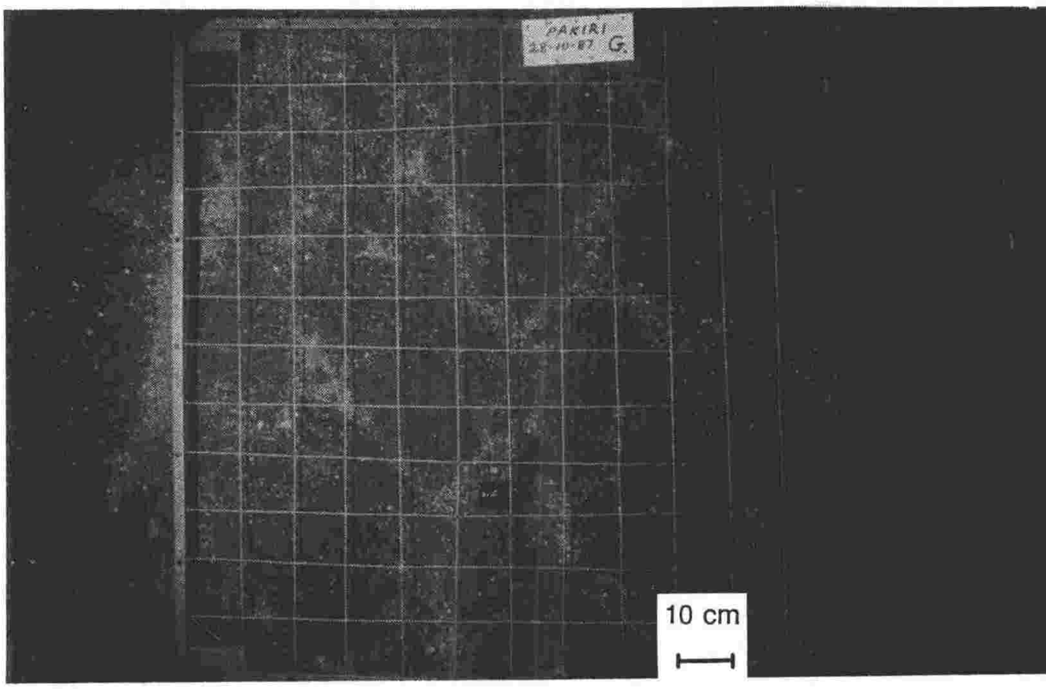



**Figure 6.12** Wide angle view of lattice-type (Lat) lower inner shelf bed configuration, Gravel transect, 38 m (image 146).

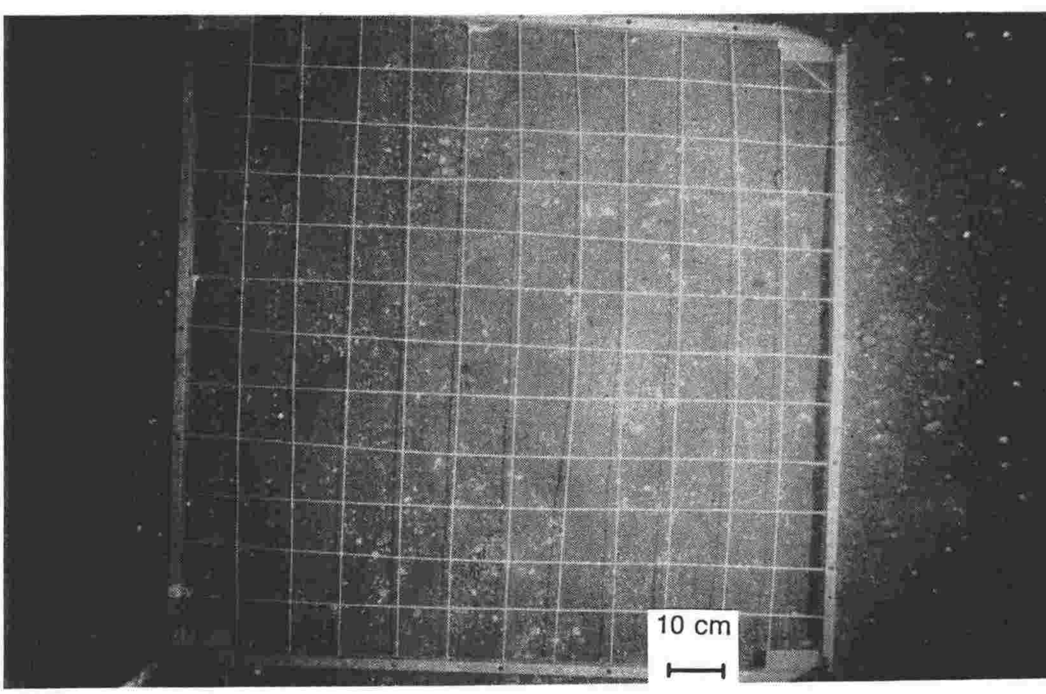



**Figure 6.13** Example of minor irregular topography (Mit), shoreface bed configuration, Williams transect, 18 m (image 64).

In addition to the bed configurations of the shoreface and continental shelf, some observations of the seabed near the coast were made while diving. Small asymmetric, discontinuous, ripples with wavelengths of 10-15 cm and heights of 5-8 cm, were commonly observed between the alongshore bar and the 10 m isobath. About 400 m offshore, in water depths of 8-10 m, these bedforms grade into the more irregular surface of the Mit configuration of the shoreface.

## 6.5 Discussion

The three main bed configurations recognized form a sequence of shore-parallel juxtaposed zones, that are continuous alongshore within Pakiri Bay (Figure 6.14). Although there is some overlap (ripples on the mid shelf for example) the areal extent of these configurations correlates quite well with the sedimentological and morphologic components of the sediment body described in the preceding chapters. The bed configurations of the shoreface (type Mit), inner shelf (Ri and Lat) and middle continental shelf (N with sparse Ri) accord with shoreface, inner shelf and mid shelf sediment types respectively.

Ripples are observed across the width of the continental shelf in the study area, but they are scarce on the middle continental shelf. Their geometry is consistent with the 'rolling grain' and 'anorbital' ripples of Allen (1982) and Clifton (1976) respectively. These ripples form as a result of oscillatory water motions caused by shoaling progressive gravity waves. Ripples of the form associated with unidirectional currents, or combined wave and current flows, were not observed in Pakiri Bay.

The occurrence of ripples is closely related to the distribution of relatively coarse sediments, a pattern noted elsewhere (Channon and Hamilton, 1976; Hunter et al., 1988). There is, however, no relationship between ripple wavelength and the mean grain size of the bed, as observed experimentally (Bagnold, 1946; Carstens et al., 1969). Where the mean grain size of sediments exceeds about 1.5 $\phi$

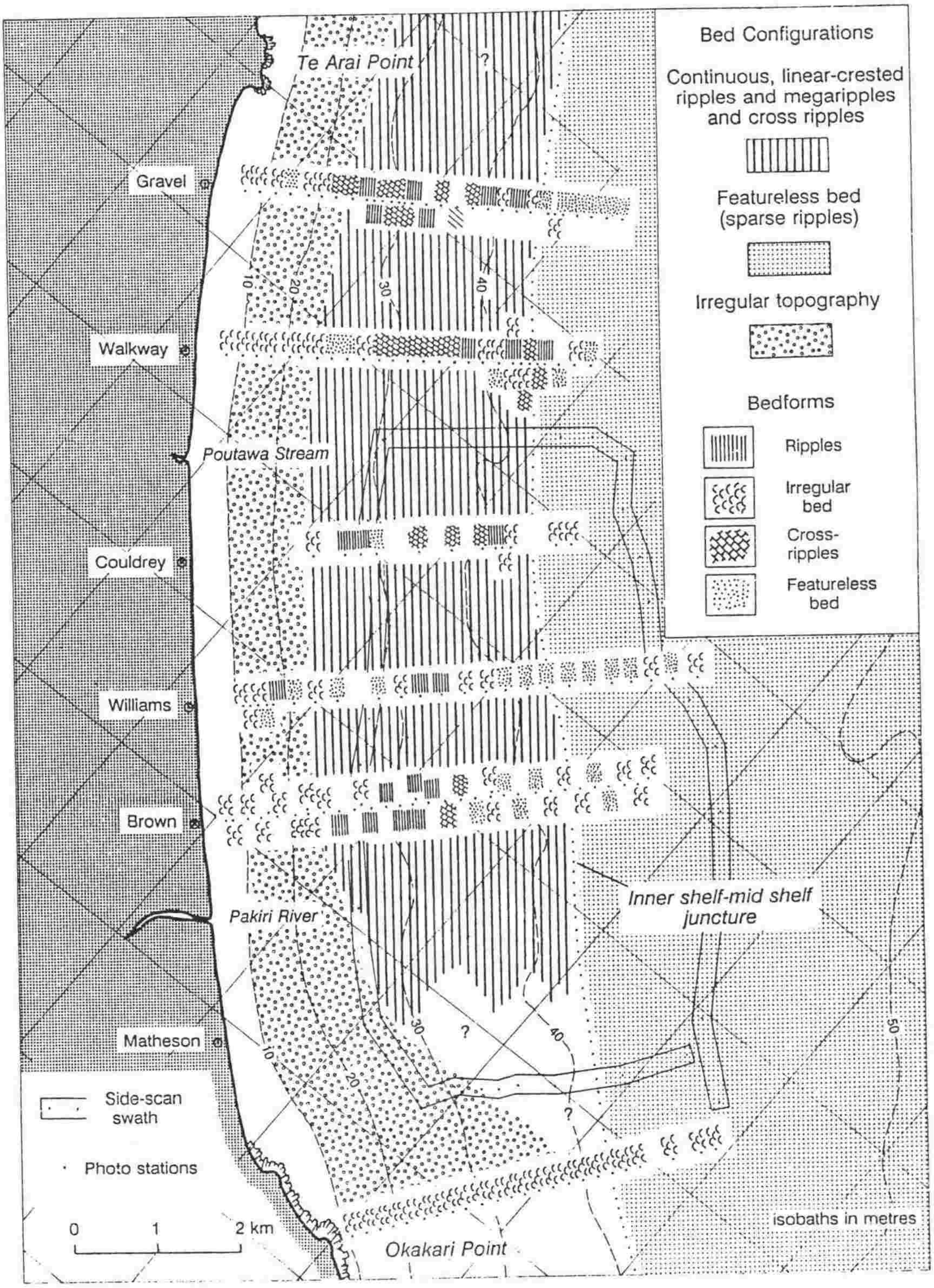



**Figure 6.14** Interpretation of photographic and side-scan bedform data, showing alongshore continuity of the three major bed configurations identified.

ripples are absent. Or conversely, ripples are observed over the inner shelf where mean grain size ranges between about 0 and 1.5 $\phi$. However, ripples are also present on the mid shelf, in water depths exceeding 45 m. According to the side-scan records these are formed in relatively coarse sediments, compared with most of the surface of the mid shelf. However, almost all the samples obtained from the mid shelf are finer than 2.0 $\phi$, the exceptions being several samples from Williams transect of 1.5 to 2.0 $\phi$ mean grain size. Although it is possible that the coarser bands of sediment on the mid shelf have not been sampled, it is likely the mid shelf ripples are formed in somewhat finer sands.

Ripples are not observed across Okakari transect, despite the bedform surveys extending well beyond the water depths at which ripples and megaripples were noted on the other transects. There is no apparent difference in the relative exposure of this part of the shoreface and shelf to shoaling waves, although it is the only transect bordering the steep rocky coast. The absence of ripples may reflect the relative fineness of the Okakari sediments (see Figure 3.18). With the exception of one coastal and one inner shelf sample all have mean grain sizes higher than 2.0 phi. Ripple development may be contingent upon the preferential erosion and transport of the finer sand fraction of a sediment that contains a range of grain sizes. The sediments of Okakari transect may be too well sorted for this process to occur. Or, where the sediments are fine, well sorted sands, disturbance of the bed may not result in the formation of discrete bedforms. The side-scan sonar images of the seabed of the inner shelf (for example, Figure 6.10) show what appears to be a sheet of fine sediments overlying a rippled coarse bed. The application of sediment transport models has shown that under moderate to high waves sheetflow of sediments may occur on both the shoreface and middle continental shelf in Pakiri Bay.

On both the inner shelf and mid shelf ripples occur in elongated depressions of relatively coarse sediments. These depressions lie between elevated areas of finer sediments, the mounds of the mid shelf, and a previously undescribed topography near the landward margin of the inner shelf. There is a spatial relationship between these features and the convexities evident near the top of the inner shelf on the shore-normal echosound records (Figure 5.5, for example). Both are present on the relatively flat surface at the transition between shoreface and inner shelf, and it is possible they represent the same landform.

In the case of both the mid shelf mounds and the alongshore convexities the intervening depressions comprise narrow ribbons or bands of relatively coarse rippled sediment. Similar features are well known from shallow marine environments subjected to strong tidal currents (Kenyon, 1970; Stride et al., 1982) as well as from wave affected, open coast, shallow marine environments (Table 6.2). Most explanations of their formation are somewhat speculative, and require the generation of a current across the inner shelf with sufficient competence to entrain and transport the fine sands. The coarse sediments remain behind as a lag deposit. Cacchione et al. (1984) describe elongate, shore-normal rippled scour depressions of low relief on the inner shelf off Central California. The proposed mechanism is storm generated bottom currents associated with coastal down-welling during the winter, which scour the surficial fine sediment and expose the coarser sand substrate in the depression.

Hunter et al. (1982) describe ribbons and irregular, elongate and lobate patches of coarse sand and fine gravel on the inner shelf of the Northeastern Bering Sea. These areas have convex-up profiles, and are characterized by symmetrical ripples, spaced 0.5 to 2.0 m apart, that '...could only have been generated by storm waves' (Hunter et al., 1982, p.49). In addition, the ribbons themselves are interpreted as most likely the result of wave action. The most likely hypothesis envisages the continued development of a textural variation, produced by some other process, such that relatively transportable grains are eroded and transported in the direction of net water movement. This mechanism might result from either wave-induced net water motion in the direction of wave propagation or from the time-velocity asymmetry of wave orbital motion (whereby short but strong pulses occur in the direction of wave propagation

Table 6.2 Reported Occurrences on the Inner Shelf of Coarse-Bedded, Shore Normal Orientated Rippled Depressions

| Bed Features/Reference | Location | Water Depth |
|---|---|---|
| 1. McIntyre and Pilkey (1969) | | |
| Cross-shelf, elongate, depressed channels of coarse, calcareous sands cut across finer, less calcareous sands.<br>Widths: about 20 m.<br>Spacing: 60-100 m.<br>Ripples: normal to channel sides.<br>H: 5-9 cm; h: 30-50 cm. | Onslow Bay N. Carolina | 0-20 m |
| 2. Reimnitz et al. (1976) | | |
| Cross-shelf, rippled bands seaward of rocky headlands and depressed about 0.5 m relative to surrounding sea floor.<br>Widths: 50-100 m.<br>Spacing: irregular.<br>Ripples: normal to channel sides.<br>h: 1.5 m. | Rio Balsas, Mexico | 0-30 m |
| 3. Swift and Freeland (1978) | | |
| Shore-normal, elongate bands of coarse sand or shelly gravel depressed about m below adjacent sea floor in shallow water (0-20 m). Bands become shore-parallel in deeper water.<br>Widths: 10-several 100 m.<br>Spacing: 10-100 m.<br>Ripples: normal to channel sides.<br>h: 1.0 m (approx.). | Middle Atlantic Bight | 5-30 m |
| 4. Morang and McMaster (1980) | | |
| Shore-normal, elongate strips or bands in nearshore sands, generally depressed below surrounding sea floor.<br>Widths: 50 m.<br>Spacing: irregular.<br>Ripples: normal to channel sides.<br>h: 0.7-1.5 m. | Southern Rhode Island | 0-10 m |

Table 6.2 (continued)

| Bed Features/Reference | Location | Water Depth |
|---|---|---|
| 5. Hunter et al. (1982) | | |
| Ribbons or elongate textural patches of pebbly, coarse sand and gravel amidst finer sand that rests above the ribbons. Orientation is oblique to shore, with higher angles closer to shoreline.<br>Widths: 10-500 m.<br>Spacing: irregular; average is 450 m.<br>Ripples: normal to channel sides.<br>h: 0.5-2.0 m. | Northern Bering Sea | 4-15 m |
| 6. Molnia et al. (1983) | | |
| Linear, elongate scour channels incised as deep as 5 m into medium to coarse sand and occurring in parallel groups or sets.<br>Widths: 5-250 m.<br>Spacing: irregular; orientation varies from shore-normal to shore-parallel.<br>Ripples: present, but no wavelength estimates given. | Bristol Bay Alaska | 30-80 m |
| 7. Cacchione et al. (1984) | | |
| Cross-shelf, elongate depressions of coarse sand cut across finer sand surface.<br>Widths: 5-500 m.<br>Spacing: irregular.<br>Ripples: normal or oblique to channel sides.<br>H: 7-36 cm; h: 1.0-1.7 m. | Central California | 30-70 m |
| 8. This Study | | |
| a. Inner shelf, shore-normal, elongate depressions of medium to coarse sand between accumulations of fine sand.<br>Widths: 50-150 m.<br>Spacing: 50-200 m.<br>Ripples: normal to channel sides.<br>H: 5-15 cm; h: 0.40-1.25 m. | Hauraki Gulf New Zealand | 25-30 m |
| b. Middle continental shelf, bands of relatively coarse sand, between mounds of very fine, muddy sand. Long axis of patches orientated at high angles to coast.<br>Widths: 10-50 m.<br>Spacing: 200-300 m.<br>Ripples: normal to depressions | " | 40-50 m |

and longer but weaker pulses in the opposite direction). Hunter et al. (1982) consider that Langmuir circulations, induced by waves or by wave-current interaction (Faller and Caponi, 1978) might also be capable of forming linear textural segregations.

The rippled coarse sediments in Pakiri Bay are also those that are least well sorted. In all images the crests and troughs of the ripples are comprised of fine and coarser sediments respectively. Large fragments of shell are particularly typical of the latter. The ripples are therefore direct evidence of processes of sediment sorting and the grain size differentiation of bed sediments. Given that ripples are unlikely to be preserved, if only because of bioturbation, their presence is evidence of contemporary sediment transport and sorting on the continental shelf in Pakiri Bay.

The following section employs existing models of the interaction between an unconsolidated bed and water flows, according to the method outlined in Section 6.2, to investigate the origin of the Pakiri Bay bedforms, and in particular the hypothesis that the ripples and other bedforms are primarily formed by shoaling waves.

## 6.6 Application of Existing Hydraulic Models

### 6.6.1 Results

Table 6.3 presents the results of the calculations of H over the range of water depths (20-40 m) at which megaripples have been observed on the inner continental shelf. Three wave periods (T = 5, 10, 15 s) and associated threshold velocities (from Figure 6.2) are employed. These comprise the range of wave periods likely to be experienced in Pakiri Bay. With the exception of the 20, 25, 30 and 35 m depth intervals for T = 5 s, the wave heights are consistent with locally-observed waves (Chapter Seven). Progressive gravity waves of 10 to 15 s period clearly have the potential to generate orbital velocities sufficient to initiate sediment movement on the inner shelf for the grain sizes used. The smaller grain sizes of

Table 6.3 Computation of Wave Heights (H) Required to Generate $U_m$ (Derived from Inner Shelf Megaripples) at Various Combinations of Depth (h) and Wave Period (T), Using Airy Wave Theory

| $h^1$ (m) | $h/L_o{}^2$ | $\sinh(2\pi h/L)^3$ | $H^4$ (m) | $H^5$ (m) |
|---|---|---|---|---|
| $T = 5$ s, $U_m = 0.22$ ms$^{-1}$, $L_o = 39$ m, $d_o = 1.85$ | | | | |
| 20 | 0.513 | 12.66 | 4.4 | 23.4 |
| 25 | 0.641 | 27.95 | 9.8 | 51.7 |
| 30 | 0.769 | 59.31 | 20.8 | 109.7 |
| 35 | 0.897 | 134.20 | 47.0 | 248.3 |
| $T = 10$ s, $U_m = 0.30$ ms$^{-1}$, Lo = 156 m, $d_o = 1.85$ | | | | |
| 20 | 0.128 | 1.23 | 1.2 | 1.8 |
| 25 | 0.160 | 1.52 | 1.4 | 2.8 |
| 30 | 0.192 | 1.84 | 1.8 | 3.4 |
| 35 | 0.224 | 2.23 | 2.1 | 4.1 |
| 40 | 0.256 | 2.69 | 2.6 | 5.0 |
| $T = 15$ s, $U_m = 0.42$ ms$^{-1}$, Lo = 351 m, $d_o = 1.85$ | | | | |
| 20 | 0.057 | 0.68 | 1.4 | 1.3 |
| 25 | 0.071 | 0.79 | 1.6 | 1.5 |
| 30 | 0.085 | 0.89 | 1.8 | 1.6 |
| 35 | 0.099 | 0.99 | 2.0 | 1.8 |
| 40 | 0.114 | 1.12 | 2.2 | .1 |

Notes:-
1. Depth range of megaripples on inner continental shelf.
2. Calculated ($L_o = 1.56\ T^2$ m).
3. From Wave Data Tables (C-1), U.S. Army Coastal Engineering Research Centre, 1973).
4. Calculated from equation (4) using $U_m$.
5. Calculated from equation (4) using $d_o$.

the sediment has the effect of reducing the wave height necessary to initiate sediment movement on the mid shelf, despite the greater water depths (Table 6.4). Waves of between 1.5 and 3.0 m height, and period 10 to 15 s, will generate the derived maximum orbital velocities on the middle continental shelf.

Table 6.4 Computation of Wave Heights (H) Required to Generate $U_m$ (Derived from Mid Continental Shelf Megaripples) at Various Combinations of Depth (h) and Wave Period (T), Using Airy Wave Theory

| $h^1$ (m) | $h/L_o^2$ | sinh $(2\pi\theta/L)^3$ | $H^4$ (m) | $H^5$ (m) |
|---|---|---|---|---|
| T =10 s, $U_m$ = 0.23 $ms^{-1}$, Lo = 156 m, $d_o$ = 1.31 | | | | |
| 40 | 0.256 | 2.69 | 2.0 | 3.5 |
| 45 | 0.288 | 3.25 | 2.4 | 4.2 |
| 50 | 0.320 | 3.92 | 2.9 | 5.1 |
| T = 15 s, $U_m$ = 0.30 $ms^{-1}$, Lo = 351 m, $d_o$ = 1.31 | | | | |
| 40 | 0.114 | 1.12 | 1.6 | 1.5 |
| 45 | 0.128 | 1.23 | 1.8 | 1.6 |
| 50 | 0.142 | 1.35 | 1.9 | 1.8 |

Notes:- 1. Depth range of megaripples on middle continental shelf.
2. Calculated ($L_o = 1.56\ T^2$ m).
3. From Wave Data Tables (C-1), U.S. Army Coastal Engineering Research Centre, 1973).
4. Calculated from equation (4) using $U_m$.
5. Calculated from equation (4) using $d_o$.

The use of orbital diameter ($d_o$) in equation (4) gives similarly reasonable results for 10 and 15 s period waves in both inner shelf and mid shelf environments (Table 6.3 and 6.4). Although it is interesting that the predicted wave heights using both flow parameters shows much closer agreement for T=15 s waves. It may be that the Airy wave theory is less appropriate for the combination of higher wave heights and lower periods necessary to generate $U_m$.

Regular, periodic bedforms are not present on the shoreface between water depths of 10 and 25 m. Seaward of this zone the coarser sediments of the inner shelf are extensively rippled, while small-scale, linear-crested, discontinuous, asymmetric ripples are typical of the bed seaward of the alongshore bar to about the 10 m isobath. The lack of bedforms on the shoreface may result from one of several reasons. Threshold velocities across the shoreface may not be attained during typical calm swell wave conditions. Ripples that are subsequently formed under intermediate or storm-wave velocities are subsequently degraded with the progressive onset of less energetic conditions, by bioturbation, or as a result of the influence of unidirectional currents. However, conditions on the shoreface may never be suitable for the formation of the small, anorbital ripples described from the upper shoreface. During non-storm conditions thresholds are not attained, while high orbital velocities, and velocity symmetries, under storm waves result in sheetflow conditions prevailing. The absence of ripples is probably also related to some non-flow parameter, such as the grain-size of the sediments.

Threshold velocities are surpassed seaward of the shoreface for quite small waves of 10-15 s period. In shallower water (10-25 m), and finer sediment (1.5-2.0 $\phi$, 0.25-0.35 mm), threshold velocities should be attained more often and under smaller waves. Dingler and Inman (1977) calculated that sheet flow occurs in fine sand under a relationship whereby $\rho U_m^2/(\rho_s - \rho)gD = 240$, where $\rho$ is the fluid density, $\rho_s$ equals is sediment density and g is the gravitational constant. For quartz sand in water, therefore

$$U_m = 19.9(gD)^{1/2} \tag{5}$$

which, in units of centimeters and seconds equals 623 $D^{1/2}$ $cms^{-1}$. The threshold curve for sheetflow derived from this relationship is included in Figure 6.2. However, Clifton and Dingler (1984) warn that this curve was observed only in a narrow range of grain sizes (0.128-0.158 mm, 2.5-3.0 $\phi$) and that extrapolation beyond this range must be done with caution.

Figure 6.15 portrays the combinations of wave height and water depth that will generate sheetflow of 0.25 mm (2.0 $\phi$) quartz sand ($U_m$ = 100 $cms^{-1}$) under waves of different period. The curves are derived from equation (4), at the limit of experimental evidence reported by Dingler and Inman (1977). Waves of from 2 to 5 m height (H) and periods of greater than 8 s, may produce sheetflow over the Pakiri shoreface. Because the sediments are even finer on the middle

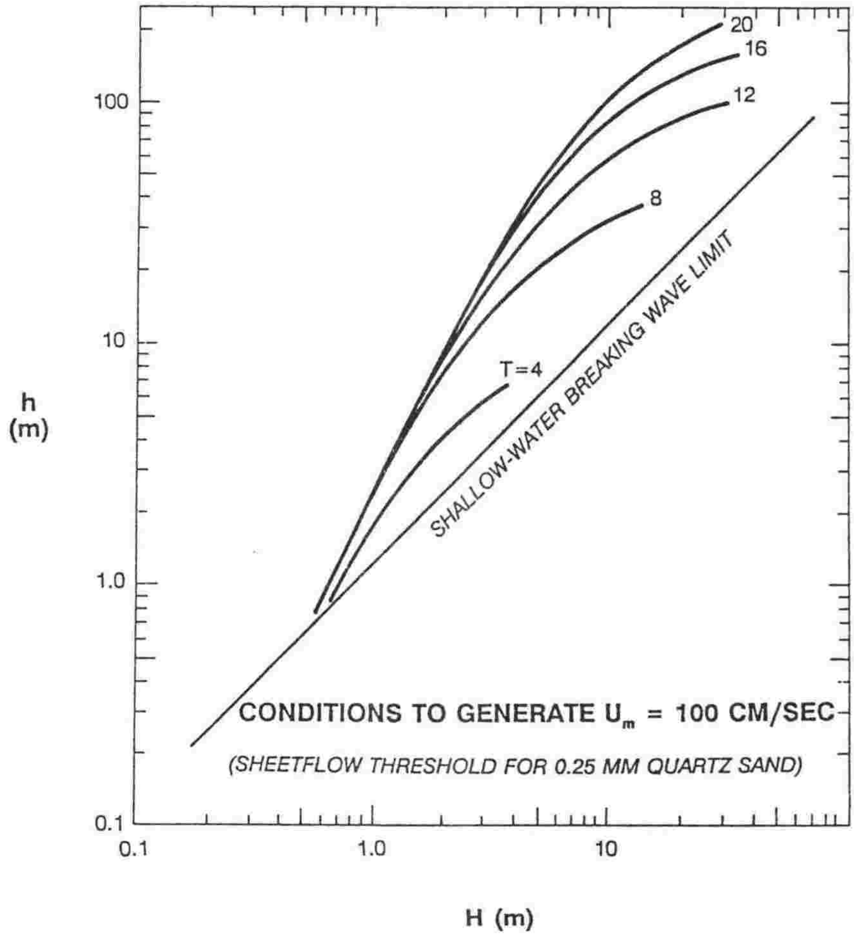



**Figure 6.15** Combinations of wave height and water depth that will generate sheetflow of 0.250 mm quartz sand ($U_m$ = 100 cm $s^{-1}$) under waves of different period (curves for waves terminated at maximum stable wave height).

continental shelf ($M_Z$=2.0 to 2.5 $\phi$) approximately the same wave conditions will also produce sheetflow over this surface. Under quite a range of wave conditions therefore, ripples are unlikely to occur over broad areas of the study area, corresponding to the areas of fine and very fine sands of the shoreface and middle continental shelf, respectively.

Cacchione et al. (1984) use a similar approach to that of Clifton and Dingler (1984) to explain the origin of ripples in scour depressions on the inner continental shelf off Central California. The origin of megaripples and small oscillatory ripples are inferred from the geometry of the bedforms using linear wave theory and the method of Grant and Madsen (1982). They concluded that ripples of wavelength 1.0 to 1.7 m, comprised of coarse sand ($M_Z$=0.75 $\phi$, 0.59 mm), in water depths of 35-60 m, were formed by large amplitude, long-period surface waves generated by winter storms. The results of the analysis of Pakiri Bay bedforms support a similar hypothesis for the Pakiri inner shelf and mid-shelf ripples. Although in the Pakiri case the lesser water depths mean comparatively smaller waves are effective in producing ripples at shallower depths on the continental shelf.

## 6.7 Conclusions

Three bedform configurations are recognized in Pakiri Bay. Each corresponds to one of the three major morphological components described in Chapter Five (the shoreface, inner shelf and mid shelf). Each configuration is therefore continuous alongshore and accords with one of three major sediment types described in Chapter Three (see Figure 3.13). The distribution of the irregular (non-rippled) bed (type Mit) corresponds to the fine, very well sorted sands of the shoreface, the rippled bed (Ri) with the medium to very coarse sands of the convex inner shelf, and the (mostly) plane bed (N) with the very fine, muddy sands of the middle continental shelf.

Near symmetrical ripples are the only regular bedforms identified on the shoreface and continental shelf. Ripples are typical of the surface of the inner shelf and limited bands of relatively coarse sediments on the middle continental shelf. Their form is consistent with the 'rolling grain' ripples, and an origin related to shoaling waves. Their geometry, and orientation relative to the coast, also indicates an origin related to oscillatory water motions produced by shoaling waves.

The implication of this interpretation is that shoaling gravity waves, either alone, or in conjunction with other currents are able to detach grains from the bed and initiate ripple formation across the width of the study area, to water depths of at least 49 m on the middle continental shelf. The sedimentological characteristics of the ripples themselves indicates water flows must be sufficiently intense to result in the textural differentiation of the crests, comprised of relatively fine sediments, and the troughs, comprised of relatively coarse sediments. This conclusion is consistent with the calculated water depths at which thresholds of sediment transport should be surpassed under shoaling progressive waves.

The absence of ripples on the shoreface and middle continental shelf is predicted by existing empirical relationships. Moderate waves, of between 2 and 5 m amplitude, are able to induce sediment transport as sheetflow in these environments. Ripples are present, but these are confined to areas of relatively coarse sediments, for the most part occupying depressions between the mounds described in the previous chapter. Whether these ripples form solely as a result of oscillatory currents, or are partly or entirely related to some other hydraulic process, is uncertain. It is reasonable to conclude however, that the differential response of the rippled and plane bed is at least partly due to variations in the grain size characteristics of the bed. Ripples will not form in either the very well-sorted, fine sands of the shoreface or the well sorted, very fine sands of the middle continental shelf. When sediment thresholds are surpassed transport must occur as sheetflow. That transport does occur is indicated by the presence of ripples on the mid shelf associated with areas of somewhat coarser sediment.

That sediment transport occurs relatively infrequently on the mid shelf is suggested by the relatively high (10 to 20 percent) proportion of mud in the mid shelf sediments. If disturbance of the bed were constant silt and clay particles would not settle. Conversely, disturbance must occur reasonably frequently to maintain the form of the rippled segments of bed in an environment in which bioturbation by the infauna (especially polychaetes) is probably intense.

The widespread occurrence of ripples on the inner shelf invites consideration of the extent to which these features may represent longterm sediment transport. If wave formed ripples are migratory the direction of movement is most probably onshore. Such a scenario in the Pakiri case may provide a mechanism that accounts for both the graded bed and the cross sectional convex geometry of the inner shelf. It may be particulary significant that the crests and troughs of the ripples are comprised of fine and coarse sediment respectively. If onshore movement occurs it may entail only the finer, crest sediments, which are themselves the finer fraction of the bed at any location across the inner shelf. If wave related currents are geomorphically significant, as predicted, the intensity of the interaction at the fluid-sediment interface will decrease with increasing water depth. The competence of the oscillatory currents to entrain particles will decrease across the inner shelf, a process which might explain the observed textural gradation.

Sheetflow is predicted to occur on the middle continental shelf under shoaling gravity waves alone. That sediment transport does occur on the mid shelf over large areas is suggested by the abrupt sedimentological transition between the mid shelf and inner shelf, the presence of large scale bedforms (mounds and hummocks) and the evidence of textural differentiation associated with these features.

Sheetflow is also predicted to occur on the shoreface, landward of the 25 m isobath. Such a process would provide a mechanism to return coastal sediments eroded from the inshore, upper shoreface and coast landward.

In the absence of measurements of unidirectional currents in Pakiri Bay, there remains the possibility also that the bed configurations do not reflect the most important hydraulic flows in terms of sediment transport. The following chapter considers the potential for currents to initiate sediment transport across the subtidal sediment body, and develops a model of sedimentation and facies development in Pakiri Bay.

# Chapter 7

# HYDRAULIC CONDITIONS AND A MODEL OF SEDIMENTATION AND FACIES DEVELOPMENT IN PAKIRI BAY

## 7.0 Introduction

The bedforms described in the previous chapter are indicative of near bed currents induced by progressive gravity waves. Calculated maximum orbital velocities under such waves exceed thresholds in Pakiri Bay on the continental shelf for medium to very coarse sand grades, at least as far seaward as the 48-50 m isobaths. Bedform types that are known to result from tidal or other long period currents alone are not evident. These results accord with the existing regional interpretation of east coast shelf sedimentation (for example, Carter, 1975; Harris et al., 1983). Tidal and other long period currents are generally considered too weak to transport shelf sands and gravels, except where flows are channeled.

However, there remains the possibility that the bed configurations observed, especially the plane beds of the shoreface and mid shelf, are at least partly influenced by tidal and/or unidirectional currents. Ripple marks formed by a combination of such currents and oscillatory water motions may be difficult to distinguish from wave formed ripples alone (Allen, 1982). Further, little is known of either the magnitude or direction of near bed flows in Pakiri Bay during storm conditions. Return flows during periods of high wave activity have been shown to influence the morphology and sedimentology of the shoreface and adjacent inner continental shelf (Niedoroda et al., 1984), and are considered to be an important process along the eastern New South Wales shelf (Field and Roy, 1984; Gordon and Hoffman, 1985). The dynamism of exposed sandy coasts is such that bed configurations resulting from infrequent intermediate or high magnitude flows are unlikely to be preserved.

This chapter investigates the potential for wave induced and other currents to transport sediment on the shoreface and continental shelf in Pakiri Bay. The methodology involves direct field measurement of hydraulic flows and application of existing sediment threshold and transport models. The results are used to construct a model of sediment transport and facies development in Pakiri Bay. Such a model must account for the contrasting geomorphology of the shoreface, inner shelf and mid shelf, whereby alongshore variations in the characteristics of each have been shown to be relatively minor compared with shore normal variations.

## 7.1 Tidal and Long Period (non Storm) Currents in Pakiri Bay

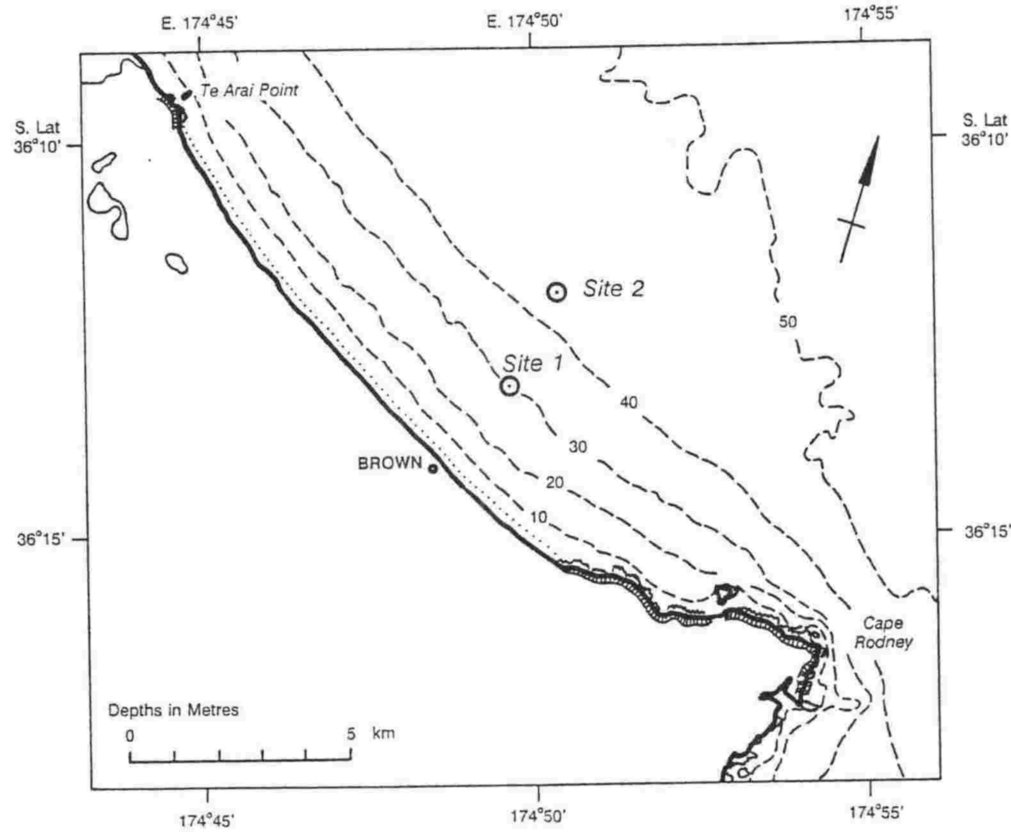
Little is known of the hydraulic regime in Pakiri Bay (see section 1.2). Prior to the present study the only current meter records were obtained close to Goat Island on the steep inner shelf bordering the rocky Cape Rodney coast. These are of unknown relevance to the relatively gently sloping and embayed seabed of Pakiri Bay. This section describes the results of Eulerian type field measurements of currents in Pakiri Bay. The technique entails the deployment of an Aanderaa RCM-4 current meter and a pressure type water level recorder.

### 7.1.1 Aanderaa Current Meter Deployment

A full discussion of the deployment and method of analysis of the records is provided in Appendix N. The instruments were originally placed in 30 m water depth, 2500 m offshore along Brown transect (Figure 7.1 a,b). An additional record was (unintentionally) obtained from the base of the inner shelf, in water depths of approximately 45 m, when a trawler snagged the instruments and dragged the whole configuration into water depths of about 45 m (site 2, Figure 7.1 a,b).

Maximum speeds of 19.40 and 14.90 cm $s^{-1}$ were recorded at sites one

a.




b.

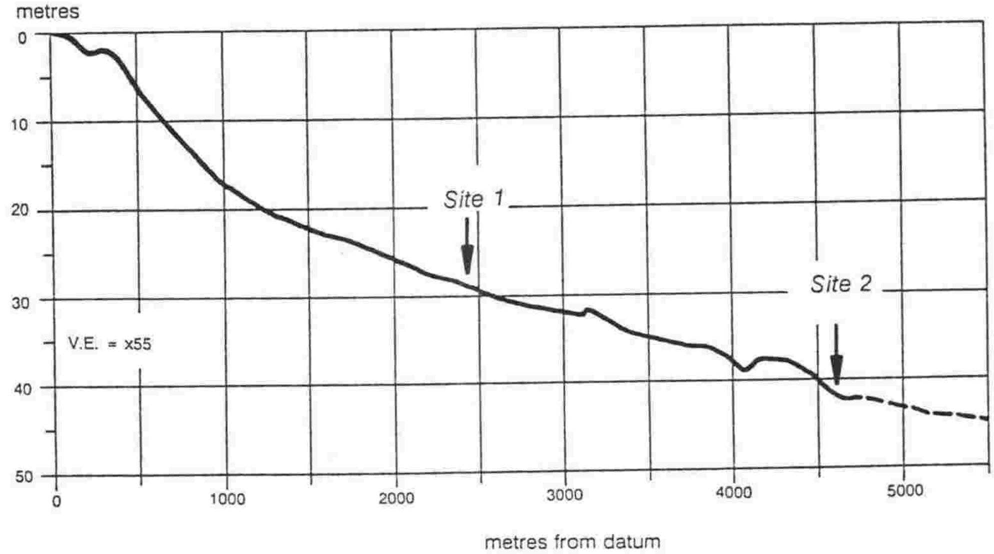



**Figure 7.1** (a) Location of intended (site 1) and unintended (site 2) current meter deployments, Pakiri Bay, and (b) equivalent location of deployments on Brown offshore profile.

and two respectively (Table 7.1). However, these speeds tend to be exceptional. At site 1 speeds greater than 15 $cms^{-1}$ are exceeded only 0.02 percent of the time (Figure 7.2). Highest speeds are associated with the alongshore current component (Nspeed, Table 7.1), although the values are of the same order of magnitude as the shore normal (Espeed) component.

**Table 7.1 Aanderaa Current Meter Summary Statistics of the Edited Raw Data Set**

| | Site | Speed ($cms^{-1}$) | Nspeed ($cms^{-1}$) | Espeed ($cms^{-1}$) |
|---|---|---|---|---|
| Median | 1 | 4.00 | -1.40 | 0.40 |
| | 2 | 4.00 | -3.40 | -0.20 |
| Mean | 1 | 4.85 | -0.73 | 0.48 |
| St.Dev. | | 2.32 | 4.76 | 2.36 |
| Mean | 2 | 5.33 | -3.36 | -0.28 |
| St.Dev. | | 3.14 | 4.94 | 1.60 |
| Minimum | 1 | -1.50 | -17.60 | -14.20 |
| | 2 | 1.80 | -14.50 | -6.00 |
| Maximum | 1 | 19.40 | 14.20 | 10.70 |
| | 2 | 14.90 | 5.60 | 4.30 |

Notes: 1. Nspeed - alongshore velocity component.
2. Espeed - offshore/onshore velocity component.
3. Observations: Site 1 - 4700, Site 2 - 756.

Plots of the time series of the onshore/offshore and alongshore velocity components (Figures 7.3 a,b) display a sinusoidal rhythmicity with a periodicity of approximately 12 hours. This pattern of reversing (bidirectional) flows is very similar to the semi diurnal tidal wave measured simultaneously by the water level recorder (Figure 7.3 c). There is precise correlation between the recorded fluctuations in duration and speed and the variations in sea level due to the bidirectional propagation of the semi diurnal tidal wave (Figure 7.3 c).

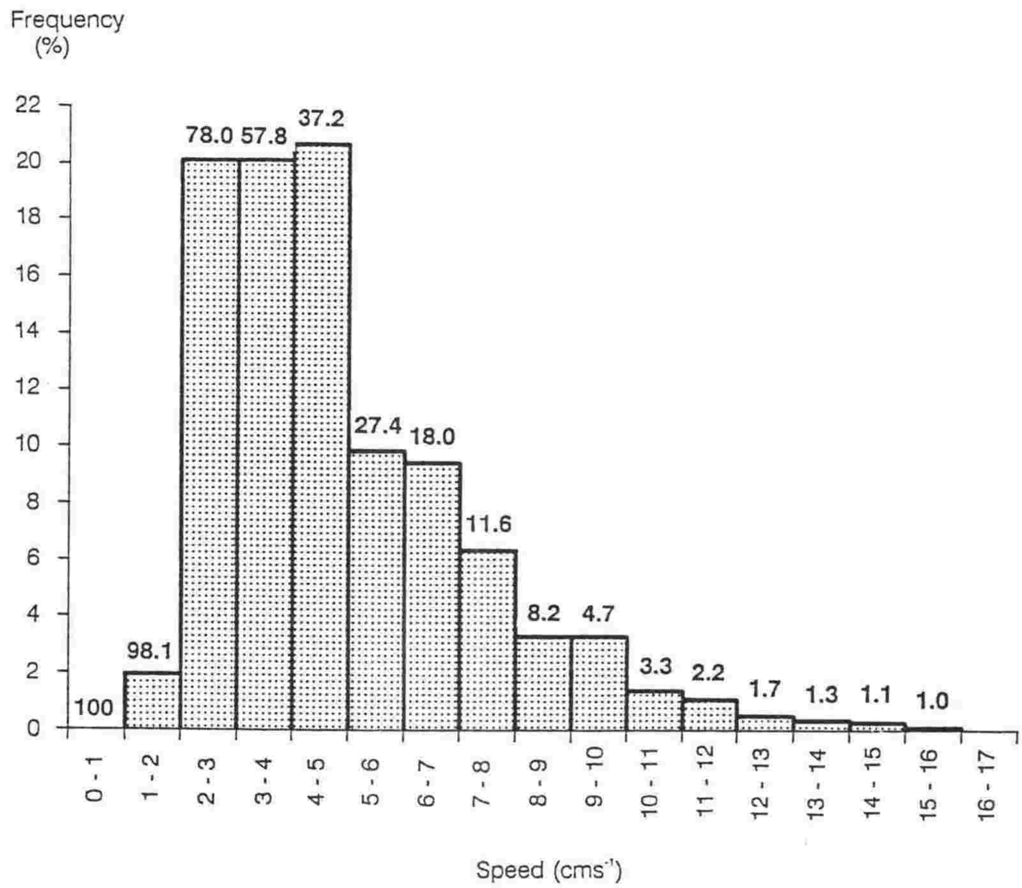



**Figure 7.2** Aanderaa current meter deployment (site 1) - speed frequency distribution and the percentage of time each class is exceeded 25 March - 27 April, 1986

The frequency of occurrence of alongshore versus onshore-offshore current components is markedly different (Figure 7.4). Current vectors normal, or at a high angle to the coast, account for only a minor portion of the total record. The tidal wave floods to the south somewhat more strongly than it ebbs to the north. This asymmetry is more pronounced at site two. Relative to the strike of the coast the flood tide has a 10 to 15$^0$ onshore component and the ebb tidal flow a similar offshore component.

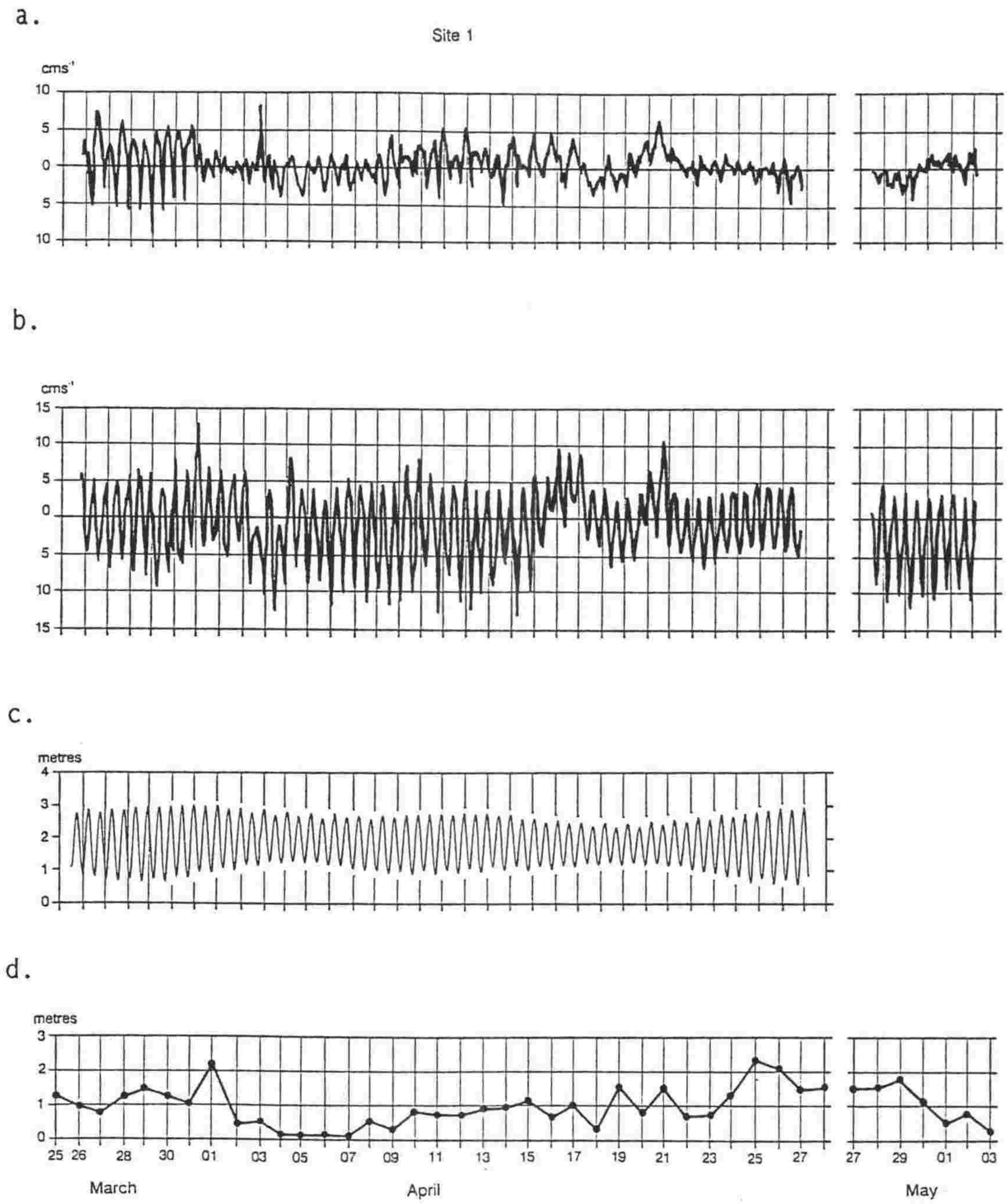



**Figure 7.3** Time series (25/3-3/5/86) of the (a) onshore/offshore velocity components (050-230°) and (b) alongshore (320-140°) velocity component of the Aanderaa current meter record (source: Bell, 1986); (c) simultaneous water level recording with maximum predicted daily tidal range (source: Evans, 1987), and (d) 'wave surge', observed at the Leigh Marine Laboratory (source: Evans, 1988).

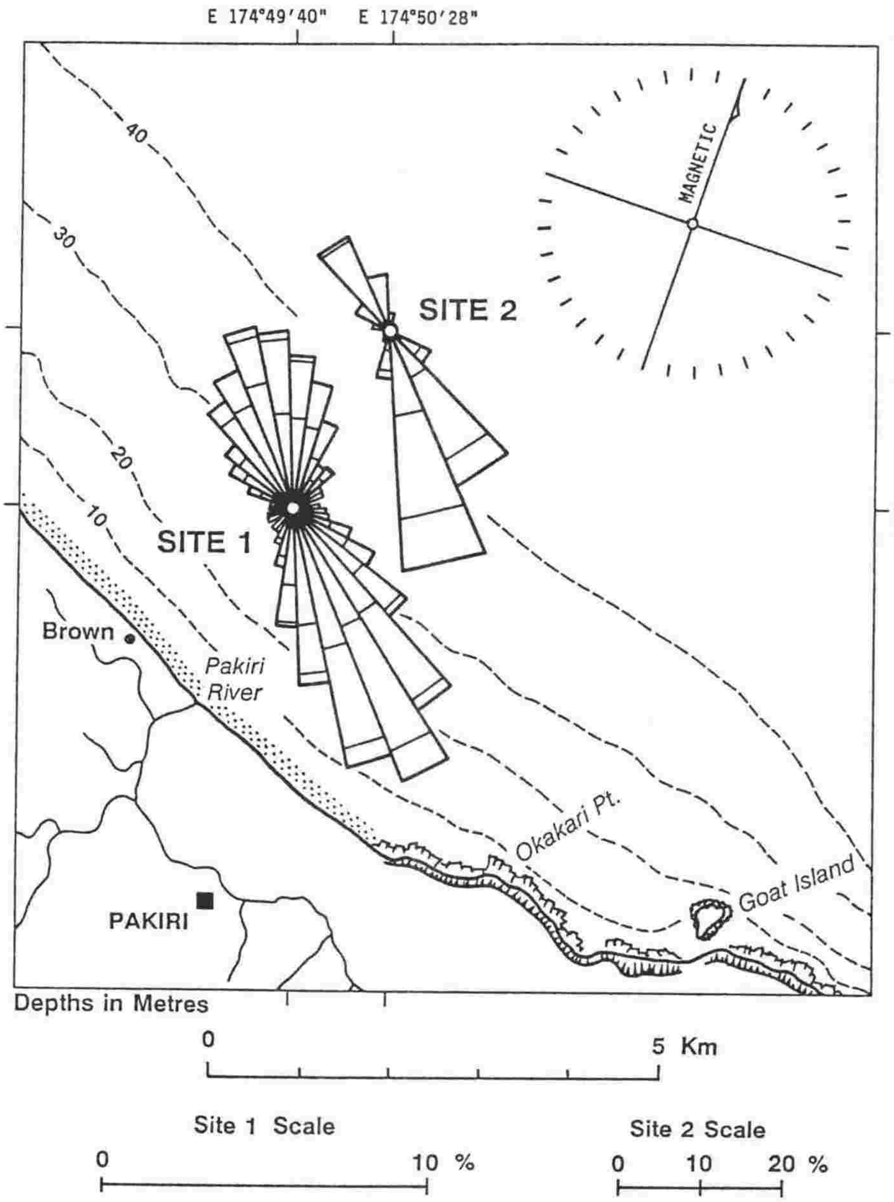



Figure 7.4 Current directions and speeds, site 1 ($10^0$ sectors) and site 2 ($20^0$ sectors), Pakiri Bay (speed increment 0.05 m $s^{-1}$; directions in oceanographic notation; roses derived over period 25.03.86-27.04.86).

Not all the variation in the speed records can be explained in terms of the semi diurnal tidal wave. There remains some unexplained variation at longer periodicities. Disruption of symmetry of the

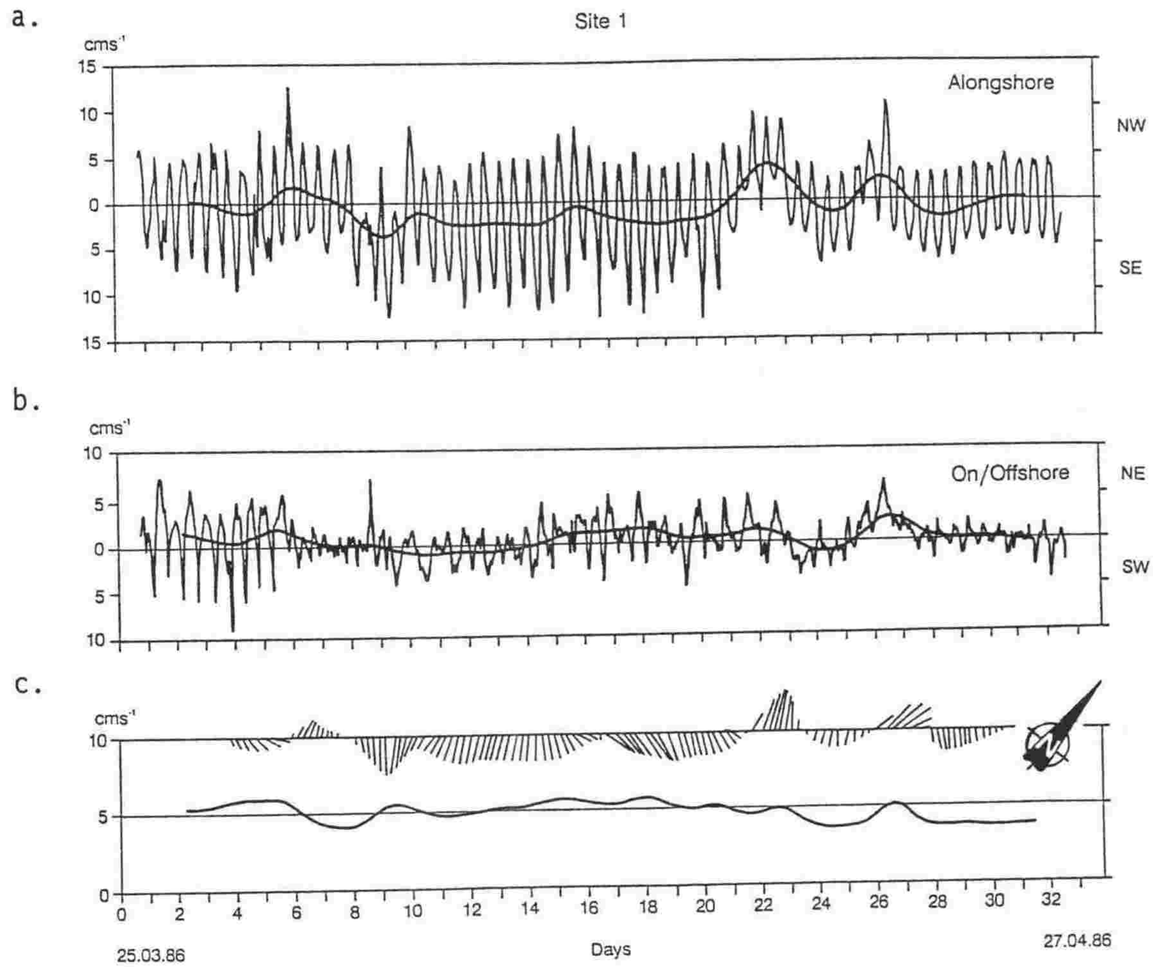



**Figure 7.5** Summary of marine observations, Aanderaa site 1, Pakiri Bay, 25 March-27 April, 1986 showing time series of the (a) alongshore velocity component (320-140°) from low passed (tidal) and sub-tidal data (bold line); (b) onshore-offshore velocity components (050-230°) from the low-passed tidal and sub-tidal data (bold line), and (c) speed values for the low-passed (sub-tidal) data with directional stick plot (source, Bell, 1986).

regular sinusoidal wave of current speeds and direction results from the superimposition of a current with maximum speeds of 6.0 cms$^{-1}$ (Figures 7.5 a,b). This current is persistent throughout the record, flowing primarily alongshore, in a southeast direction, although at times reversing and flowing to the north (Figure 7.5 c). Winds were low and mostly offshore during the deployment. Wave activity observed at the Leigh Marine Laboratory was correspondingly low (Figure 7.3 d). This residual current is most unlikely, therefore, to result from wind forcing. More likely it results from large scale water circulations within the Outer Hauraki Gulf, possibly related to the East Auckland Current.

### 7.1.2 Sediment Transport in Pakiri Bay Due to Tidal and Residual Currents

The potential for tidal and other long period currents to transport sediment in Pakiri Bay may be estimated using the formulae of Miller et al. (1977). For quartz density grains in water at 20°C

$$U_{1cr} = 0.63\ D^{0.29}$$

where D is the grain size in mm and the speed is in $ms^{-1}$. Table 7.2 presents thresholds calculated using this formula for the range of grain diameters encountered on the Pakiri continental shelf. These values exceed the maximum measured speeds at site one (19.40 $cms^{-1}$) and site two (14.90 $cms^{-1}$) for all grain sizes present in Pakiri Bay. Under the (typically) calm conditions experienced during the meter deployments tidal and residual currents are low and sediment transport is unlikely to occur.

**Table 7.2 Critical Threshold Velocities Under Unidirectional Currents (from Miller et al., 1977)**

| | | | | | | |
|---|---|---|---|---|---|---|
| Grain size | | | | | | |
| mm | 0.125 | 0.25 | 0.50 | 1.0 | 2.0 | 4.0 |
| (phi) | 3 | 2 | 1 | 0 | -1 | -2 |
| Critical threshold | | | | | | |
| $U_{1cr}$ ($ms^{-1}$) | 0.34 | 0.42 | 0.51 | 0.63 | 0.77 | 0.94 |

## 7.2 Wave Induced Currents

The study area experiences a wide range of wave heights, periods and wavelengths. Although waves of 1.0 to 1.5 m height and 7 to 8 s period occur for prolonged intervals, waves of up to 5 m height and 8 to 12 s period may occur two to three times each year. Larger waves of 5 to 8 m height and 12 to 15 s period are associated with intense subtropical cyclones and occur approximately every 10-30 years. Periods of maximum wave generation during such events generally last less than 12 to 24 hours. Increasingly smaller waves occur more frequently and last for longer periods. Wave directions are primarily from the east and northeast, directions to which the study area is exposed to a fetch of at least 75 km, and an unlimited fetch, respectively. However, during severe events the fetches within the Gulf facilitate the generation of waves in excess of 5 m from almost any easterly direction. This section investigates the potential for the wide range of waves described to transport sediments on the shoreface and continental shelf in Pakiri Bay.

### 7.2.1 Wave Transformations in the Hauraki Gulf and Study Area

The study area is exposed to swell waves generated beyond the Hauraki Gulf and local wind/swell waves generated within the Gulf. Appendix O describes an investigation of wave transformations due to shoaling and refraction in the Outer Hauraki Gulf generally, and in Pakiri Bay in particular. The approach utilizes the wave refraction programmes of Black and Healy (1981) which calculate the change in wave parameters height (H), direction (θ) and wavelength (λ) and the height and angle of waves at the breaker zone.

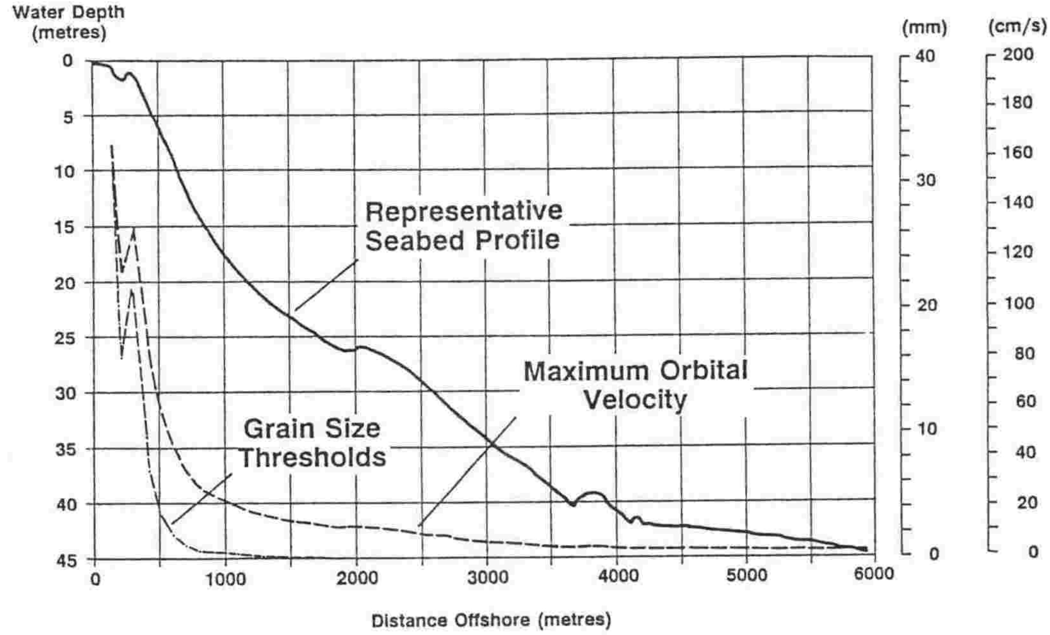
Small waves (H=1.5 m, T=7 s) from a northeasterly direction do not experience significant transformations as they travel across the middle continental shelf in the Outer Hauraki Gulf. The larger 5 and 8 m waves (T=12 and 15 s) are more affected by the bathymetry of the Outer Gulf. Within Pakiri Bay, however, very little converging of wave orthogonals occurs. Wave energy is equally distributed along the coast within Pakiri and Mangawhai Bays. Wave heights increase abruptly in water depths close to the coast, but over much of the width of the Pakiri inner shelf and the Gulf heights remain constant. Waves from an easterly direction experience more pronounced directional and height transformations, resulting in much reduced wave heights at the coast compared with initial heights, and pronounced refraction over the shoreface.

### 7.2.2 Bed Disturbance by Oscillatory Currents

The potential for waves to affect sediment transport in the study area is investigated using the Black and Healy (1981) programmes. These calculate the maximum orbital velocity (using Airy wave theory) and the maximum grain size (using the formulae of Rance and Warren, 1969; and Komar and Miller, 1973, 1975) that can be disturbed. Easterly and northeasterly waves of 1.5, 2.5, 5.0 and 8.0 m height and 7, 9, 12 and 15 s period respectively, were generated over a surface characteristic of the shoreface-inner shelf-mid shelf shore normal profile.

For waves of 1.5 m height and 7 s period grain size thresholds are not surpassed seaward of the 25 m isobath (Figure 7.6 a). The threshold of motion for very fine and fine sands (2-4 $\phi$) are surpassed approximately 1500 m offshore in 25 m water depth. Landward of this point thresholds are surpassed for increasingly larger particles. Large waves, of height 5 m and period 12 s, are able to disturb granule and sand sized sediment (where $D<-2\ \phi$) across the width of the study area. Maximum orbital velocities are constant over the middle continental shelf, but begin to increase in an exponential fashion at the base of the inner shelf (Figure 7.6 b).

These results have two important implications. For about 75 percent of the time the east coast wave climate is characterized by a wave of about 1.0 to 1.5 m height and 6 to 7 s period. Such waves cannot disturb sediments seaward of the 25 m isobath, but are capable of a)




b)

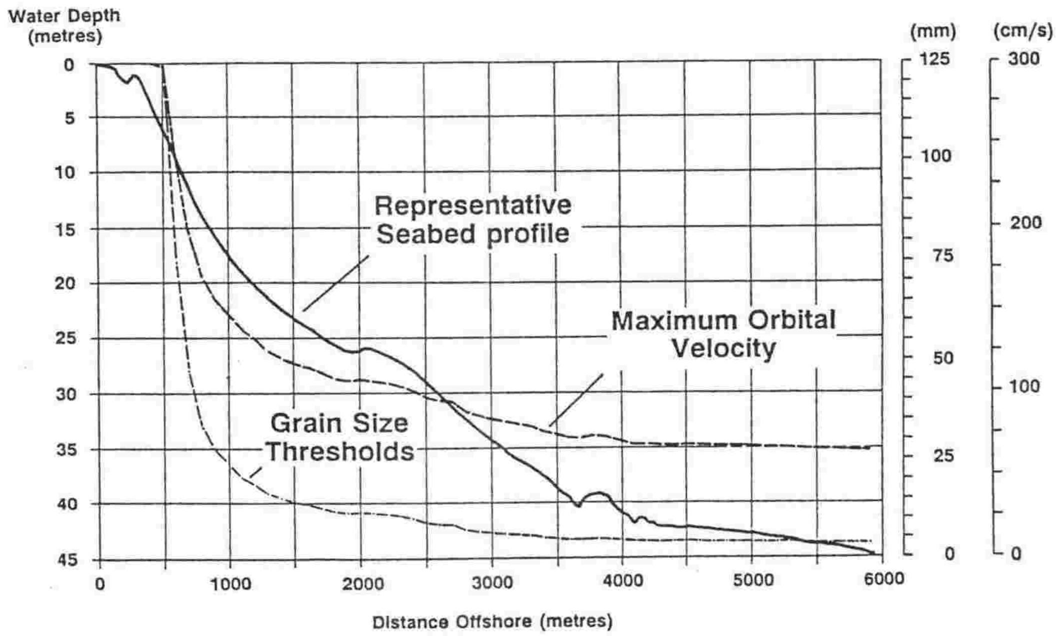



Figure 7.6 Variation in maximum orbital velocity and grain size thresholds across a typical offshore profile, Pakiri Bay, under (a) modal (H=1.5 m, T=7 s) and (b) storm (H=5.0 m, T=12 s) waves.

disturbing sand sized sediments on the shoreface. Disturbance of the shoreface must, therefore, be virtually continuous. Secondly, large waves associated with infrequent storm events have the potential to disturb size sand grades across the entire width of the inner and middle continental shelf. The maximum grain size able to be disturbed decreases with increasing distance offshore as water depth increases (Figure 7.7). Waves of less than 2.5 m height are unable to disturb sand seaward of the base of the shoreface. Progressively larger waves are able to disturb increasingly coarse sediments further offshore in deeper water. However, thresholds for granules are not exceeded over the lower inner shelf.

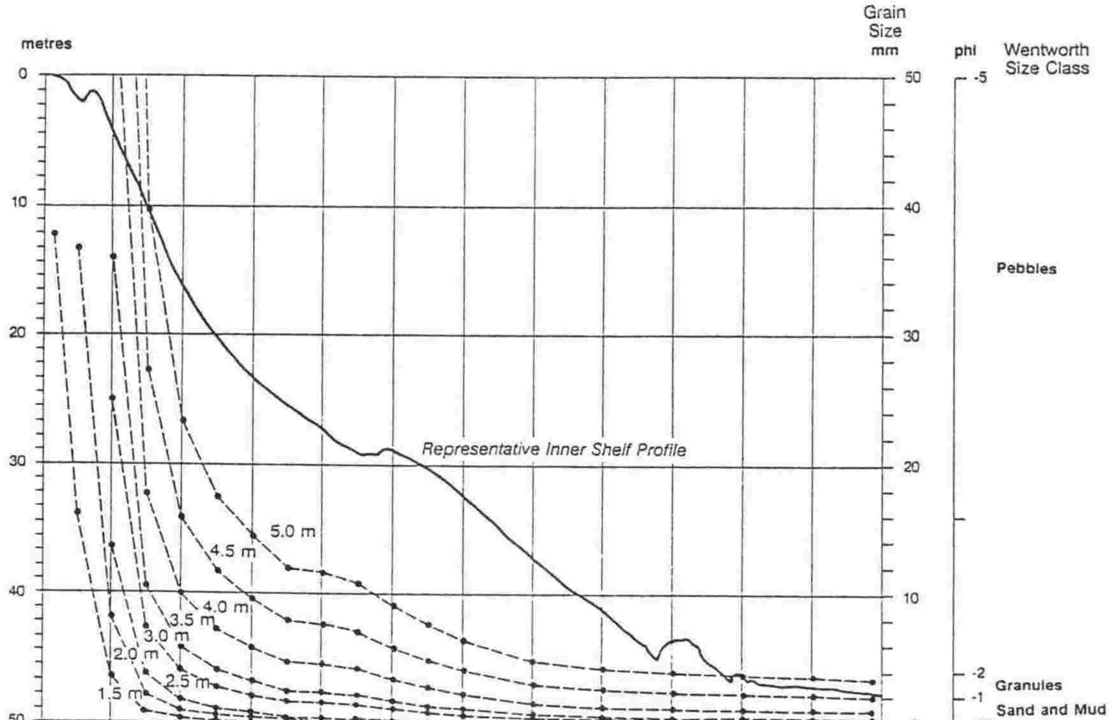



Figure 7.7 Maximum grain size capable of being disturbed by 1.5 to 5.0 m waves (using the formulae of Komar and Miller, 1973,1975) across a representative offshore profile, Pakiri Bay.

### 7.2.3 Sediment Transport By Wave Induced Currents

Progress gravity waves shoaling landward of wave base may induce currents at the bed. These comprise (1) an oscillating component, (2) a weak mass transport current that is either unidirectional (progressive waves) or recirculatory (standing waves), (3) a weak recirculatory current due to bed irregularities and (4) velocity asymmetry due to wave distortion (Allen, 1982, 1985). Collectively they provide a means of detaching grains from the bed (oscillatory currents), forming a rippled bed (recirculatory current) and inducing a unidirectional current in the direction of wave propagation (mass transport and velocity asymmetry).

Mass transport of water under waves can be explained if the assumptions of the Airy wave model that the wave amplitude is negligibly small compared to other lengths, and the fluid is inviscid, are relaxed. Water particle orbits beneath progressive waves are in fact slightly open and allowance for viscosity led to the recognition of an oscillatory boundary layer at the bed (Longuet-Higgins, 1958). A consequence of this motion is that the instantaneous velocity has components both normal and parallel to the bed. The Reynolds stresses created, and those associated with the normal fluctuations, derive within the boundary layer a steady drift in the direction of waves (Allen, 1985).

The total mass transport current is formed from both finite amplitude and viscous effects. At the outer edge of the bottom boundary layer the mass transport velocity ($U_{mt}$) for progressive waves is

$$U_{mt} = \frac{5}{16} \frac{(2\pi H)^2}{LT \sinh^2(2\pi h/L)} \quad ms^{-1}$$

where H = wave height (m), L = wavelength (m), $h$ = water depth (m) and T = wave period (s). The initial wavelength ($L_0$) is determined using the deep water equation

$$L = \frac{gT^2}{2\pi} \quad (m)$$

where g is the acceleration due to gravity. The shallow water wavelengths, for depth stations at which mass transport calculations were undertaken, are derived using the dimensionless transformation curves presented in Pethick (1984).

Mass transport velocities are calculated at 10, 20, 30, 40 and 50 m water depth stations in Pakiri Bay, for calm (H=1.5 m, T=7 s), storm (H=5 m, T=12 s) and severe storm (H=8 m, T=15 s) progressive gravity waves. Waves from a northeasterly or easterly direction undergo relatively minor transformations in height and direction as they shoal across the shoreface and continental shelf in Pakiri Bay. As wave orthogonals approach the Pakiri coast at high angles the effect of mass transport is to generate a unidirectional current onshore.

The mass transport velocities generated by waves typical of relatively calm conditions are low (Table 7.3). Velocities at the 10 and 20 m stations are of similar magnitude to tidal flows recorded from 30 and 45 m water depths in Pakiri Bay. Storm waves of 5 and 8 m height may, however, generate significant mass transport velocities, one or two orders of magnitude greater than combined tidal and residual current flows. Maximum velocities of 0.64 and 1.75 $ms^{-1}$ are generated at the 10 m water depth station by 5 and 8 m waves, respectively.

High mass transport velocities may also be generated on the inner and middle continental shelves. The velocities attained at all depths (10 to 50 m) are of the same order of magnitude as the critical threshold velocities for the sand size sediment grades present (Table 7.2). Currents resulting from mass transport under 5 and 8 m waves may transport fine sand in Pakiri Bay at least to water depths of 30 m.

Table 7.3 Calculation of Mass Transport Velocities Under Calm, Storm and Severe Storm Waves (from Allen, 1985)

| Water Depth (*h*) = | 10 | 20 | 30 | 40 | 50 m |
|---|---|---|---|---|---|
| a) For H = 1.5 m, T = 7 s | | | | | |
| L (m) = | 63 | 70 | 71 | - | - |
| $U_{mt}$ ($ms^{-1}$) = | 0.046 | 0.006 | 0.001 | - | - |
| b) For H = 5.0 m, T = 12 s | | | | | |
| L (m) = | 110 | 135 | 170 | 180 | 200 |
| $U_{mt}$ ($ms^{-1}$) = | 0.643 | 0.166 | 0.083 | 0.039 | 0.024 |
| c) For H = 8.0 m, T = 15 s | | | | | |
| L (m) = | 140 | 160 | 220 | 280 | 340 |
| $U_{mt}$ ($ms^{-1}$) = | 1.746 | 0.436 | 0.257 | 0.179 | 0.137 |

A third wave induced current may result from the velocity asymmetry created as waves are distorted in shallow water. The result of modification to the orbital paths as waves shoal is that the onshore velocities are increased in magnitude but decreased in duration, while the offshore velocities are decreased in magnitude and increased in duration. This asymmetry becomes more pronounced as the waves progress into shallower water. The net effect is an onshore flow of water which inevitably interacts with the mass transport current to produce, in the absence of a larger opposing flow, a combined onshore unidirectional flow (Allen, 1985).

The formation of regular transverse ripples, of the type described in the previous chapter, and the inherent instability of a plane bed under shoaling waves, may be explained in terms of a fourth wave induced current. Irregularities on the bed are sufficient to initiate a series of recirculatory drifts under oscillatory motions which then interact with the grain transport to cause the emergence of a preferred ripple wavelength (Kaneko and Honji, 1979). This current explains the presence of ripples on the Pakiri Bay inner shelf, as well as the differences in the grain size characteristics of the troughs and crests. The recirculatory currents generate flows from trough to crests such that finer, and relatively more transportable grains, will tend to comprise the ripple crests.

Wave induced currents clearly have the capacity to generate onshore water flows and significant sediment transport. The actual amount of sediment transported is not known. However, combinations of such currents provide a mechanism for the onshore transport of sediment in Pakiri Bay. Detachment from the bed results from stresses induced by the horizontal velocity component of the orbital flow and onshore transport by a combination of the mass transport current and net onshore movement due to velocity asymmetry under shoaling waves. Ripples are an indirect expression of the oscillatory currents present at the bed.

### 7.2.4 Infragravity and Internal Waves

Mass transport may also occur as a result of internal and infragravity waves. The former are gravity waves that propagate beneath the sea surface along pycnoclines or thermoclines and within regions of weak or strong vertical density gradients (Wright, 1982). Theoretical studies have shown the potential for both internal (Cacchione and Southard, 1974) and infragravity waves (Boczar-Karakiewicz and Bona, 1986) to transport sediment on the continental shelf, although usually in water depths beyond the influence of surface progressive waves. Such mechanisms of current generation are of undetermined significance in the context of the Hauraki Gulf and the study area in particular. They are unlikely, however, to be of much influence at the relatively shallow depths involved in Pakiri Bay, and given the width of the middle continental shelf in the Outer Gulf (Boczar-Karakiewicz, 1989).

## 7.3 A Model of Shoreface and Continental Shelf Sedimentation

The configuration of the underlying bedrock framework is most probably a major factor in accounting for the overall dimensions of the Pakiri sediment body, and the position of the outer margins of the inshore and inner shelf morphologic components in particular. However, its detailed morphology and sedimentology are interpreted to result from contemporary processes of sedimentation. These processes are dominated by near bed currents induced by shoaling waves, and coastal return currents developed in response to strong onshore winds and waves. Tidal and other long period currents are considered of secondary or lesser importance.

The model of sediment transport envisaged comprises calm and storm weather elements. During the former (Figure 7.8 a), oscillatory currents induced by shoaling swell waves disturb the bed of the shoreface to maximum water depths of about 25 m. Smaller waves (0.5 to 1.5 m) disturb only the upper shoreface/inshore environments, while somewhat larger waves (1.5 to 2.5 m) may disturb the entire shoreface. Sediment transport occurs as sheetflow in response to an onshore current generated by the combination of mass transport flows and asymmetries in the horizontal velocity component of the oscillatory motion. A relatively minor alongshore component may also occur, as a consequence of tidal flows or where waves approach the coast at angles slightly less than 90°. However, these processes are considered minor compared with the shore normal, wave driven, sediment flux.

During storms larger waves disturb the bed seaward of the lower shoreface (Figure 7.8 b). Waves of 2.5 to 5.0 m height, and larger, are able to detach grains from the bed and initiate an onshore-offshore oscillatory motion, evidenced by the extensive development on the inner shelf of linear crested wave ripples. Onshore sediment transport across the continental shelf may then occur as a result of mass translation and horizontal velocity asymmetries. Sediment transport is probably closely associated with ripple formation and migration.

a.

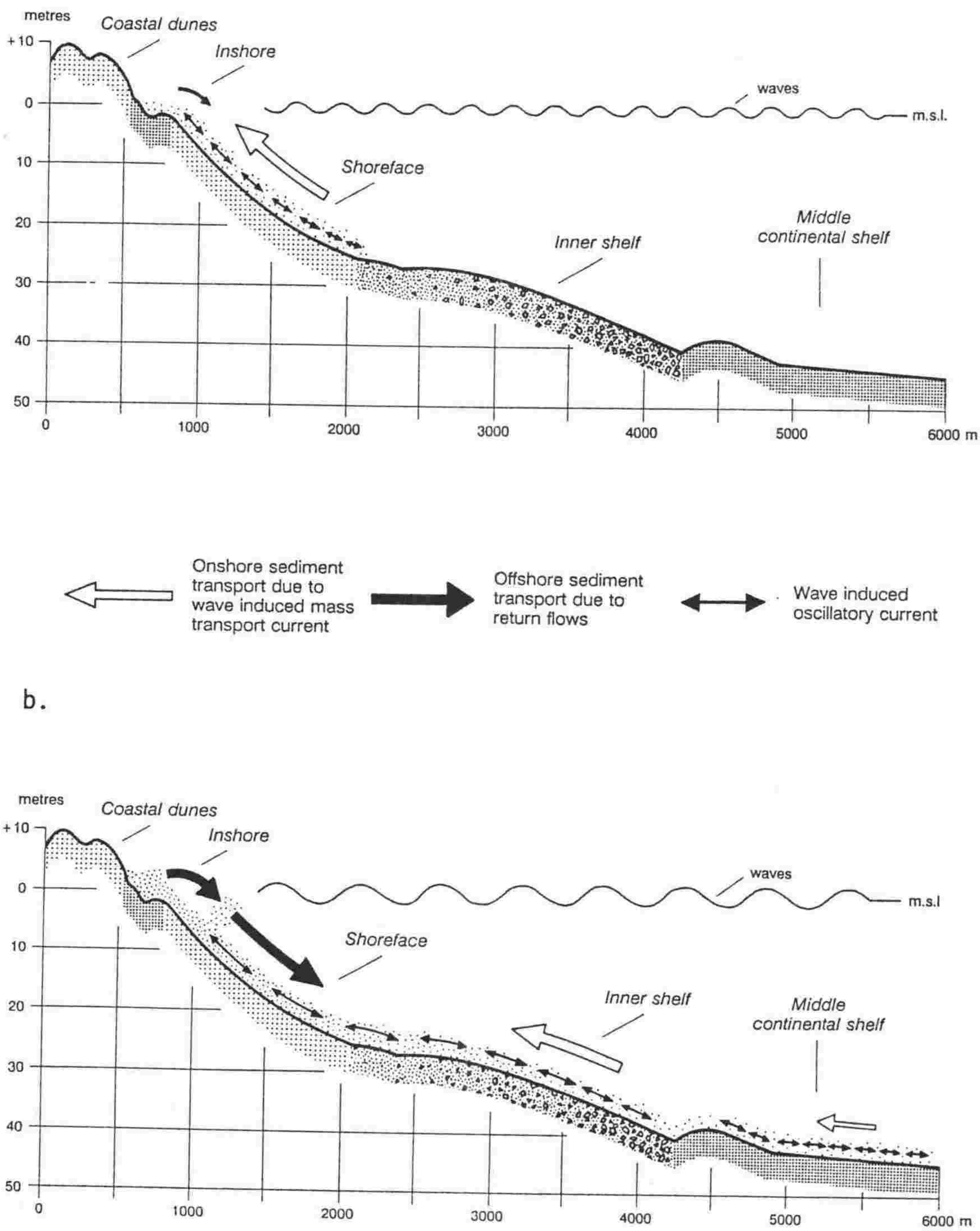



Figure 7.8 Model of sediment transport across the shoreface and continental shelf under (a) calm and (b) storm wave conditions.

In contrast transport of the very fine, well sorted sands of the middle continental shelf almost certainly occurs as sheetflow. Onshore sediment transport is associated with the landward migration of large scale bedforms. The reason for their formation is unclear, but may relate to variations in the sedimentology and/or the topography of the mid shelf surface. These bedforms may transgress the inner shelf-mid shelf juncture, but presumably deteriorate because of higher energy conditions on the inner shelf.

During storm events onshore currents induced by shoaling waves and strong onshore winds are probably counteracted by offshore currents generated by return flows and coastal circulatory cells. These currents may transport sand eroded from the coast offshore to be deposited across the shoreface, as well as sand detached from the bed by oscillatory water motions. During subsequent calm, and relatively calm, sea conditions, wave induced onshore currents return sediment shoreward. It is conceivable that during particularly severe events some sediment is diffused over the surface of the shoreface, and perhaps the inner shelf, and is relatively slowly transported back onshore. Onshore-offshore sediment movements on the shoreface will occur considerably more rapidly than the episodic onshore movements on the inner shelf associated with infrequent storm events.

## 7.4 Discussion

Sedimentation in Pakiri Bay is therefore episodic, occurring in response to variations in the nature of shoaling surface waves. Sediment transport is not thought to occur on the continental shelf in typical (calm weather) wave conditions and hence sedimentation on the shelf can be considered storm wave dominated. The shoreface is thought to experience near continual bed disturbance and onshore sediment transport under a wide range of low to moderate wave conditions. Sediment transport in this environment is cyclic in the sense that during storms sediment may be eroded from the upper shoreface and coast and transported seaward, and then transported back landward by wave induced currents during subsequent calm periods.

Many of the geomorphological and ecological phenomena described in the preceding chapters are explained by the model in terms of spatial and temporal variations in wave induced and storm wave related return currents. The following features of the wave climate are considered of particular importance:- (a) Wave energy is distributed uniformly alongshore within Pakiri Bay, though shows considerable temporal variability; (b) waves orthogonals are orientated at approximately right angles to the coast and experience relatively minor height and directional transformations; (c) a wide range of wave heights and periods occur and (d) disturbance of the bed by wave induced currents diminishes with increasing water depth across the shoreface and inner continental shelf, but remains relatively constant across that portion of the mid shelf studied. These characteristics of the wave climate are key elements of the explanation of the following phenomena.

a. Sediment Characteristics

The sediments of Pakiri Bay (Hauraki B Facies) are thought to be derived from the shelf sediments (Hauraki A Facies) of the Outer Hauraki Gulf (Schofield, 1975, McCabe, 1985). The present investigation has shown the former to be predominantly well sorted sands, with a relatively minor gravel and mud component. In contrast grain size distributions of samples from the Outer Gulf continental shelf are polymodal (Thompson, 1975).

The proposed model predicts the onshore transport of shelf sediments but cannot account for the deposition of the mass of sediment that comprises the Pakiri sediment body (subtidal and coastal). There is no linkage between the very coarse sands of the lower inner shelf and a comparable deposit in the study area to seaward. The very fine sands of the mid shelf are being transported onshore by wave induced currents, but the medium to very coarse fraction of these sediments is insignificant. In any case, the presence of a high mud content in the sediments of the mid shelf suggests disturbance of this surface is infrequent. In all probability the Pakiri sediment body evolved by episodic deposition during the late Quaternary, possibly as predicted by models developed along the comparable New South Wales coast (Roy et al., 1980; Roy and Thom, 1981). The proposed Pakiri model does, however, explain much of the present day character of the Pakiri sediment body, which could feasibly have developed since sea level reached about the present level about 6,500 years ago.

Reworking of the surface of the sediment body by wave induced currents is expressed in the graded bed of the inner continental shelf and the fine sediments of the shoreface. This pattern reflects the inverse relationship between water depth and the magnitude of wave induced currents at the bed. Calculated maximum orbital velocities and the presence of wave ripples evidence the competence of large (storm) waves to transport the very fine sands on the mid shelf at water depths of at least 50 m. Thresholds are not exceeded for the very coarse sand and granule fraction of the sediments of the lower inner shelf, although the fine and medium sand fractions may be transported. Therefore, progressively smaller waves, intermediate between calm and storm types, are able to transport fine and medium sands, increasingly close to shore. As the maximum orbital velocity for any particular wave diminishes with increasing water depth over time this process will result in the preferential transport of fine sediments onshore. The shoreface sediment type is interpreted to result mostly from the deposition of fine sediments eroded from the inner shelf. However, long term they may be so interrelated with the sediments of the coast as to invalidate their identification as a separate sedimentological entity. Evidence of significant sediment exchange between coastal and shoreface environments in historic times was documented in Chapter Five.

The very fine sands ($M_Z$=2.0-2.5 $\phi$) of the middle continental shelf are transported by wave induced currents despite the water depths involved (45-50 m). Such transport is restricted to periods during which waves in excess of 4 to 5 m occur. Waves of this size occur (on average) two or three times each year, but usually last for periods of less than 24 hours. Nevertheless, sediment transport must result in a significant landward movement of sediment to maintain the abrupt contact between the mid shelf and inner shelf sediment types and the textural patterns of the mid shelf.

Differences between the two southern transects (Okakari and Matheson) and those to the north (Brown, Williams, Couldrey, Walkway, Gravel) have been noted. The latter are characterized by a wider range of mean grain sizes and more pronounced boundaries between adjacent sediment types. In addition the morphological components typical of most of Pakiri Bay are absent or poorly expressed south of the Pakiri River mouth.

Two hypotheses are proposed to explain these differences. Cape Rodney may afford the southern Pakiri Bay coast and seabed some shelter from waves originating from the east, such that wave induced currents are less intense over the surface of this part of the sediment body. As a result onshore sediment transport and concomitant textural differentiation does not occur to the same extent.

The characteristics of the southern most transects may also reflect a relationship between the development of the subtidal and subaerial components of the sediment body. Okakari transect borders a rocky, cliffed coast where sand dune development is precluded. Matheson transect extends offshore from the sandy coast, but the proximity of steep hillslopes similarly precludes extensive sand dune development. The implication is that the onshore movement of fine sand across the northern transects, and subsequent coastal deposition and sand dune development, facilitates the textural differentiation of the shoreface-inner shelf sands. The development of a coarse inner shelf sediment type may depend upon the removal of sufficient fine sand from the subtidal sediment system. The quantity of fine sands across Okakari transect may result from the onshore movement of these size grades, as predicted by the model, but not to the extent that intensive sorting occurs and a coarse inner shelf sediment type develops to seaward.

b. Morphology

The morphology of the shoreface and inner shelf components of the subtidal sediment body are interpreted as a response to the wave induced and coastal currents identified in the above model. The convex profile geometry of the inner shelf results from the erosion of the fine and medium sand fractions from the lower inner shelf and the preferential transport of this material landward. Deposition of this sediment occurs at a point where the onshore currents are countered by seaward directed flows during major storm events. These currents are influential in maintaining the concave profile geometry of the shoreface. The location of the transition from convex inner shelf to concave shoreface may be envisaged as representing a balance between onshore sediment transport across the inner shelf and bidirectional transport across the shoreface during storm events.

Secondary variations in the morphology of the inner shelf and middle continental shelf reflect the presence of large scale bedforms comprised of fine and very fine sands. These features are best developed at the juncture between the inner and mid shelf, where the hummocks described are orientated transverse to the wave induced currents, in contrast to the flow parallel orientation of the mid shelf mounds. Both forms are considered to result from active onshore sediment transport, although the volumes and rates of movement involved may be low. Convexities also form on the gently sloping, almost planar, surface between the inner shelf and the shoreface. These are associated with bands of relatively coarse (rippled) and fine sediment and may represent a bed configuration intermediate between shoreface and inner shelf process regimes.

### c. Bedform Configurations

The sequence of bedforms encountered across the shoreface and inner shelf in Pakiri Bay is consistent with the proposed model. Wind waves create a bedform sequence in which ripples at relatively low fluid stresses are succeeded by the plane bed of the shoreface at sufficiently high velocities. Wave ripples become flatter as the orbital velocity is increased, until they eventually merge into a plane or very gently undulating bed associated with intense transport.

The existence and properties of ripples can be determined in terms of near bed water particle orbital velocity and grain size using the empirically derived curves of Allen (1979) and Miller and Komar (1980 b). Velocities on the mid shelf exceed the existence range for ripples under waves of at least 5 m height for the very fine sand size grades present. The same is true for the fine sands of the shoreface for waves of 1.5 to 2.0 m. Ripples on the inner continental shelf however, are predicted and observed to form in the medium to very coarse sands under a wide range of wave conditions.

## 7.5 Conclusions

Aanderaa current meter observations show near bed non oscillatory flows to comprise a tidal bidirectional current and a residual current. The former floods to the south and ebbs to the north, creating a current that is essentially alongshore. The residual current flows mostly to the southeast, but on occasions flows towards the north. Both currents are weak and neither is able to initiate sediment transport. Calculated velocities do not exceed the thresholds necessary to disturb even the fine sands of the shoreface. There is however, the potential for combined tidal wave induced flows. Such currents may contribute to the formation of the alternating bands of fine and coarse sand at the juncture between the inner shelf and shoreface.

Wave transformations in Pakiri Bay result in wave energy being distributed evenly along the coast, with little evidence of wave focusing. The coast south of the Pakiri River mouth may be somewhat sheltered from easterly waves. However, this coast is equally exposed to waves from northeasterly waves. Waves from this direction experience relatively little change in height across the subtidal sediment body.

Waves in excess of 5 m shoaling over the inner shelf and shoreface induce near bottom maximum orbital velocities that exceed the threshold of motion for all but the very coarse sands and granules encountered on the lower inner shelf. However, for periods of from days to weeks the wave climate is dominated by the prevailing 1.0 to 1.5 m, 7 to 8 s swell wave. Under these conditions bed disturbance occurs only over the shoreface, in water depths of less than 25 m. Waves intermediate between these extremes may disturb sediments across the inner shelf.

Sediment transport is interpreted to occur in an onshore direction across the continental shelf. The most probable mechanism entails detachment of particles from the bed by oscillatory water motions under shoaling waves, then net shoreward transport as a result of mass transport and velocity asymmetries. This model is consistent with calculations of mass transport velocities under storm waves, and the observed pattern of bedform configurations. Under storm waves transport of the fine and very fine sands of the shoreface and middle continental shelf respectively occurs as sheetflow. Sediment transport on the inner shelf most likely occurs by migration of ripples.

The preferential transport of fine and medium sands across the inner shelf produces a graded bed in which mean grain size increases offshore. The result of this process is the formation of the fine, very well sorted sands of the shoreface sediment type. The bed of the shoreface must experience more intense onshore fluid stresses during periods of high wave activity, but these are likely counteracted by return flows. No measurements of such flows have been obtained in the study area. However, such currents are known from other exposed sandy coasts (Cacchione et al, 1984; Field and Roy, 1984; Niedoroda et al., 1984; Gordon and Hoffman, 1985). The interpretation of sedimentation on the shoreface is therefore somewhat speculative, although interpretations of echosound data presented in Chapter Five suggest significant movements of sediment has occurred across the upper shoreface in historic times.

The processes described are considered to result mostly in the reworking of the surface of the subtidal sediment body, probably since the culmination of the last marine transgression. It cannot be assumed this event did not impart on the surface of the sediment body particular sedimentological characteristics that are in some way expressed today. However, it is argued that the subtidal environments are characterized by modern processes of sedimentation that are sufficiently intense for the effects of such inheritance to be minor. These processes are evidenced in the morphology of the shoreface and continental shelf, the bedform configurations and the sequence of sediment types. It is proposed these sediment types be designated facies, and referred to as the 'shoreface fine sand' and 'inner shelf coarse sand' facies. The sediments of the mid shelf in Pakiri Bay are designated the 'very fine, muddy, sand facies', but this sediment type is apparently very different to the less well sorted sediments of most of the Outer Gulf mid shelf.

# Chapter 8

# SUMMARY and CONCLUSIONS

## 8.0 Introduction

The beach and dune sands of the embayed east coast of Northland evidence the deposition of marine sediments in late-Quaternary times. Large scale coastal and shelf surveys have shown that these deposits are often contiguous with extensive sub-tidal sediment bodies comprising the shoreface and inner continental shelf. However, there have been few attempts to model processes of sedimentation in such environments, or interpret the geomorphology of the sediment bodies themselves. This is despite the possibility that the development of the coast and the subtidal sediment body are closely interrelated. An understanding of the processes that determine the character and contemporary behaviour of such features may be essential to the explanation of future coastal development.

This study seeks to contribute to such an understanding by empirical investigation of the Pakiri-Mangawhai sediment body. This feature comprises the Holocene sands of the coastal dunes and foreshore and the unconsolidated sediments of the shoreface and inner continental shelf. The geomorphology of the adjacent middle continental shelf has also been investigated.

The study area is located on the east coast of the Northland Peninsula in the Outer Hauraki Gulf. Environmental factors that distinguish this coast from many other coasts include the (1) the high exposure of the study area to swell and storm waves; (2) the weakness of tidal and oceanic-type currents; (3) the dearth of either fluvial or alongshore sediment sources; (4) the tectonic stability of the embayment and (5) the relationship between the steeply-sloping surface of the sediment body and the broad, gently-sloping surface of the middle continental shelf.

## 8.1 Morphological Characteristics of the Pakiri Sediment Body

The overall dimensions of the Pakiri-Mangawhai sediment body appear to reflect the bedrock configuration of the embayment. The Pakiri half of the sediment body extends from the coastal dunes to the juncture between the inner continental shelf and the middle continental shelf, 5 to 6 km offshore in 45 m water depth. There is some sub-bottom sonar evidence that this abrupt change in slope is influenced by the substrata, perhaps associated with a former shoreline. The sandy coast and associated sediment body extend 25 km alongshore between the rocky coasts of Bream Tail and Cape Rodney. South of the Pakiri River the shoreface and inner shelf begin to narrow as the isobaths converge towards the steep rocky coast.

In contrast, the detailed morphology of the subtidal component of the sediment body is little affected by substrata controls. The morphology of the surfaces of the shoreface and inner continental shelf are most likely a response to modern processes of sedimentation. In section the shoreface comprises a curvilinear concave surface, whereas the inner shelf comprises an equally curvilinear convexity. The latter culminates abruptly at the junction with the relatively gently sloping surface of the middle continental shelf. The sub-bottom sonar records obtained, while failing to locate the bedrock-sediment interface, showed that the morphology of the shoreface and inner shelf is independent of subsurface controls.

Secondary variations in the morphology of the sediment body mostly result from the presence of large scale bedforms on the inner and middle continental shelf. These features are present in several forms, but are invariably convex in section. Side-scan sonar records show them to be widespread over the mid shelf, and particularly concentrated at the base of the inner shelf. They have somewhat different forms at these respective locations, however both are considered to be transgressive, and represent onshore sediment movement, albeit at an unknown rate. The origin of the convexities at the transition from the inner shelf to the shoreface is more problematic. They tend to decrease in amplitude and wavelength towards the coast, and produce a regular alongshore ridge and swale topography. Their location may reflect a transition between hydraulic conditions on the shoreface and those on the inner shelf.

## 8.2 Non Carbonate Sediment Patterns

Extensive and intensive sampling of the sea bed in Pakiri Bay over a three year period has facilitated the recognition of a hitherto undescribed pattern of shoreface and continental shelf sediments. Three sediment types comprise the surface of the subtidal sediment body in Pakiri Bay. Each is directly associated with either the shoreface, inner shelf or middle continental shelf environments. The sediments of the shoreface sediment type are fine, very well sorted quartz-feldspathic sands of 2.0 $\phi$ mean grain size. The inner shelf sediment type comprises a gradation of sediment sizes from medium sands to very coarse sands and granules at the base of the inner shelf. At the transition from the inner shelf to the mid shelf the sediments become abruptly finer, with the mean grain size of samples between 2.0 and 2.5 $\phi$. These very fine sands of the mid shelf sediment type are finer than those of the shoreface but not as well sorted. The textural transition from very coarse sands and granules to very fine sands coincides with an abrupt increase in the amount of mud in the samples, from about 0 to 2 percent to between 5 and 15 percent.

Alongshore variations in sedimentology are much less than onshore-offshore variations, such that the three sediment types identified form shore-parallel bands in Pakiri Bay. At the southern end of Pakiri Bay they grade into a locally derived carbonate facies offshore from the rocky Cape Rodney to Okakari Point coast, while data presented by McCabe (1985) suggests the same pattern occurs at the northern end of Managwhai Bay. In general data presented by McCabe (1985) support the northern continuation of the morphological and sedimentological patterns described into Mangawhai Bay. The results of the study of sedimentation in Pakiri Bay are likely to be largely applicable to the interpretation of the geomorphology of Mangawhai Bay.

## 8.3 Patterns of Carbonate Sedimentation

Carbonates comprise up to 30 percent (by weight) of sediments in Pakiri Bay. The distribution of carbonates in the sediments is not random however, but shows a systematic increase offshore. The lowest (1-3 percent) and highest (25-30 percent) concentrations are associated with the fine sands of the upper shoreface and coarse sediments at the base of the inner shelf, respectively. As the concentration of carbonates increases offshore the grain size of the carbonate fragments also increases, commensurate with the grain size variation of the terrigeneous fraction.

Extensive and intensive sampling of the macrobenthos in Pakiri Bay over a three year period has allowed the formulation of a model of species distribution and abundance. This has been used to estimate the extent and location in Pakiri Bay of modern biogenic production. The results show that the living benthos may significantly contribute to the mass of the sediemnts of the shoreface and inner continental shelf. This is in agreement with the regional interpretations of sedimentation on the Northland east coast shelf.

The pattern of carbonate concentration in the sediments of Pakiri Bay does not correlate with the pattern of estimated modern biogenic production. Highest levels of modern shell production occur across the shoreface. In contrast the proportion of carbonates in the sediments is low across the shoreface (1-5 percent), increasing offshore to maximum concentrations of 25 to 30 percent at the base of the inner shelf. Hypotheses have been advanced to explain this dichotomy, but there may be no simple explanation. The tests of recently-dead molluscs may be rapidly degraded, especially across the more frequently disturbed shoreface or transported onshore or offshore. The pattern of carbonate distribution in the sediments may also result from reworking of a former carbonate-rich deposit, and be unrelated to modern patterns of biogenic production.

The model of benthos distribution has also been employed to interpret aspects of the marine environment. The benthic infauna in Pakiri Bay is dominated by molluscs. Other phyla (foraminifera and bryozoa) account for less than 1 percent of the total carbonate material in the sediments. The live fauna of the inner continental shelf is comparable to the **Tawera spissa-Venericardia purpurata** (Venus) community described by McKnight (1969). The **Nemocardium pulchellum-Venericardia purpurata** (Nemocardium) community characterizes the area around the juncture between the inner and mid shelf, where **Tawera** is absent. Associations of species also characterize the alongshore bar and upper shoreface, and the mid shelf environments. The most important factors influencing species distribution are considered to be substrate type and the frequency and intensity of bed disturbance by currents. Species that are diagnostic of high and low energy environments are characteristic of the shoreface and middle continental shelf respectively.

## 8.4 The Hydraulic Regime in Pakiri Bay

Hyrdraulic conditions in Pakiri Bay were investigated by deployment of instruments on the shoreface and continental shelf, the application of existing current models and the interpretation of bedforms. An investigation of wave transformations was also undertaken.

Current meter measurements during calm (low wave) conditions are dominated by bidirectional tidal flows, although a residual current is also present. Both flows are weak, with average combined speeds of less than 10 $cms^{-1}$. The semi-diurnal tidal wave floods to the south and ebbs to the north, inducing a reversing near-bed current that flows alongshore for most of the time. The residual current is of unknown origin, but most likely results from regional-scale circulations in the Outer Hauraki Gulf.

Theoretical calculations indicate that near-bed flows over the continental shelf during storm conditions are dominated by currents induced by shoaling waves. These flows are calculated to be orders of magnitude greater than the currents measured during non-storm conditions. They result from a combination of mass transport of water particles due to non closure of particle orbits and velocities assymetries in the horizontal component of orbital motion. During low wave conditions, characteristic of the wave regime for prolonged periods, such currents are insignificant seaward of the mid to upper shoreface. Under all conditions such currents are directed onshore, and undergo little focusing as a result of wave refraction.

The above wave-induced currents affect the inner and middle continental shelf in storm wave conditions. The nature of currents affecting the shoreface during storm events is probably more complex when water circulations close to the coast almost certainly entail seaward-flowing return currents. These result from the mass landward transport of water by wind forcing and as a consequence of the wave-induced currents identified. Such currents are inferred to occur, but have not been measured in the study area.

## 8.5 An Interpretation of Sedimentation in Pakiri Bay

Processes of sedimentation in Pakiri Bay are most probably dominated by currents induced by shoaling surface waves. Measurements of tidal and other long period currents show such flows are weak and unlikely to transport sediments of the grain sizes present. Calculated maximum orbital velocites under large storm waves surpass threshold velocities for all sand size classes present in Pakiri Bay. Subsequent transport of the disturbed particles may then occur in an onshore direction across the continental shelf as a result of the wave-induced currents already discussed. Sedimentation on the shoreface is probably more complex, and reflects a balance between the above onshore fluid forces and currents that affect the inshore and upper to mid shoreface during severe storms. These latter flows are return flows and coastal cell circulations that tend to transport sediment eroded from the foreshore and inshore seaward.

It is possible that the patterns described are at least in part inherited from former depositional environments, perhaps as a result of the last sea level transgression. However, it is argued that the geomorphic and ecological characteristics of the Pakiri Bay sediment body are explicable in terms of ongoing, wave-induced processes of sediment erosion, transport and deposition. In this respect the surfaces of the shoreface and continental shelf are interpreted to be storm-wave dominated.

Sedimentation in the study area is seen as episodic, and correlated with the incidence and severity of periods of high onshore winds and waves associated with intense depressions. During the study period the sediment and morphologic patterns of the sediment body have remained essentially constant. The bathymetric surveys undertaken since the 1978 storms have shown however, that significant onshore-offshore sediment movements may occur over the mid to upper shoreface. Simultaneous disturbance and sediment transport across the entire width of the inner shelf probably occurs rarely, but increasingly more frequently closer to shore in shallower waters. The pattern of decreasing disturbance with increasing water depth may explain the graded bed of the inner shelf, and is almost certainly an important factor in the distribution of species in Pakiri Bay and the trend of increasing mud content acoss the sediment body.

Both Schofield (1970) and Thompson (1975) have interpreted the well-sorted sands of Pakiri Bay as a coastal derivative of the Hauraki A Sand Facies of the Outer Hauraki Gulf continental shelf. The results of the present investigation indicate this process cannot be occuring contemporaneously. The sediments of the shoreface and inner shelf are isolated from the more variable sediments of most of the middle continental shelf by the very fine, muddy, sands that are characteristic of the mid shelf in Pakiri Bay. These latter sediments are interpreted to result from the winnowing and preferential transport onshore of the very fine sand fraction of the sediments of the mid shelf seaward of Pakiri Bay .

## 8.6 Comparison With Other Models of Shoreface and Continental Shelf Sedimentation

The morphology and sedimentology of the Pakiri Bay sediment body is interpreted to result from modern processes of sedimentation. In this respect the proposed model shares features with some of the interpretations of shelf sedimentation reviewed in Chapter Two (Figure 2.2). In particular, several models (Figure 2.2 a,b,c,e) identify the potential for surface waves to rework palimpsest sediment on the continental shelf.

However, unlike the North Atlantic barrier coasts (Figure 2.2 b,d,f), the east coast of Northland is geologically stable. Sea levels are thought to have been constant, at about the present level, for the last 6,000 years or so. In contrast, the east coast North American models predict the formation of transgressive sediment facies related to a rising sea level. Compared with many other coasts, therefore, the marine environment of the Northland coast has remained relatively constant during the major portion of the Holocene.

Reworking of shoreface and shelf sediments at sites like Pakiri is probably made all the more effective because of the dearth of modern (non carbonate) sediments. The only possible source of modern sediments in Pakiri Bay is erosion of the coastal barrier, a process that has apparently not occurred rapidly in historic times. This lack of modern sediment input distinguishes the Pakiri case from the otherwise comparable southern Bering Sea model (Figure 2.2 e). Both models envisage active reworking of shelf sediments by infrequent storm waves, involving onshore-offshore sediment transport, and the development of a textually graded surface. However, in the Pakiri situation this process entails a finite volume of sediment contained within a well defined embayment.

Little is known of the hydrology of the Outer Hauraki Gulf. However the embayments of the east coast, comprising Omaha, Mangawhai-Pakiri, and Bream Bays, are probably little affected by the tidal and oceanic currents that are important along, for example, the English (Figure 2.2 d) and South African (Figure 2.2 a) coasts. The broad, relatively shallow, embayment of the Outer Gulf may inhibit the strength of oceanic currents near the coast.

The New South Wales shoreface and inner shelf shares a number of morphologic and sedimentological characteristics with those described from Pakiri Bay (See Figure 2.4). These include an offshore sequence of sediment types that are analogous to the shoreface, inner shelf and middle continental shelf types described in the present investigation. The poorly sorted, coarse sands and gravels of the NSW inner shelf are interpreted to be palimpsest, and remote from the modern coastal sediment budget. The sediments of the NSW mid shelf are also comparable to the mid shelf sediments described from Pakiri, although they occur in somewhat deeper water. The model developed in the present study may well have implications for the further interpretation of the New South Wales sequence.

## 8.7 Implications for the Management of Human Activities

The model of shoreface and shelf sedimentation presented may have important implications for the management of human activities in such environments. For example, the fine, well sorted sands of the upper shoreface in Pakiri Bay are presently being mined. The technique employed involves the suction dredging of sand from the sea floor in water depths of 5 to 8 m. Two companies are presently licensed to extract a combined total of 60,000 $m^3$ of sand annually. The sands are pumped directly aboard a barge, and shipped to Auckland where they are utilized in the manufacture of concrete and other construction-related products.

Consent-granting authorities have responsibility under various statutes to ensure mining of the seabed at locations like Pakiri does not unduely affect the natural development of the adjacent coast, and in particular exacerbate erosion. It is feared that in this way the recreational and ecological values of beaches adjacent to mining license areas may be compromised.

At Pakiri the problem is assessing the response of an inherently dynamic exposed sandy coast to the incremental removal of relatively small quantities of sand. Each extraction has an immediate effect on the bed evidenced by the formation of a borrow pit (Figure 5.20, for example), however these are rapidly obliterated by sediment movement on the upper shoreface. The effects of any one extraction are therefore averaged over a much larger area of bed. Compared with the overall dimensions of the subtidal sediment body (assuming at least a 1 m thickness of unconsolidated sediment) the total volume of sand mined (approximately $1.5 \times 10^6$ $m^3$) is small.

Interpreting the effects of mining at Pakiri is further complicated by the history of coastal land use. Sand mining (both directly from the beach and offshore) has not been the only human activity along the Pakiri coast. Disturbance and modification of the coastal dune system and foreshore has been severe. South of the Poutawa Stream (Figure 1.4) the natural sand binding vegetation has been much disturbed by European agricultural activities, and possibly as a result of prehistoric Maori habitation. This length of coast has several active blowouts, apparently formed as a result of the disturbance of foredune vegetation. North of the Poutawa Stream the formerly extensive area of natural sand dunes (dune type 3, Figure 1.4) has been stabilized and afforested to form part of Mangawhai State Forest. Part of the afforestation process involved the construction of an artificial foredune and leveling the former dune surface up to 150 m inland from the foredune. These impacts must significantly disrupt the natural cycling of sand that occurs between foreshore and backshore environments along the Pakiri coast, especially as the prevailing winds are offshore. Collectively they may have a far greater affect on the development of the Pakiri coast.

However, mining at Pakiri does result in a persistent and unequivocal loss of sand from the active sediment system that might otherwise contribute to coastal development. The model of sedimentation presented in the present study identifies the potential for sediment exchange between the shoreface and coast as a result of natural processes of coastal erosion and deposition. In this respect the location of the present mining operations at Pakiri and elsewhere may be of much greater significance than the quantities extracted. The actual impacts of mining on the geomorphology of this, and similar moderate to high energy coasts, may be impossible to isolate. However, assuming the objective is to minimise the risk of unnecessarily disturbing the natural development of the Pakiri coast the existing license areas entail the greatest risk of disturbance of the coastal sediment system. The medium to long term consequences may be no different than if direct mining of the beach were permitted.

The present mining operations at Pakiri are licensed by Government agencies in response to the entrepreneurial initiatives of individual companies. In the past there has been little critical evaluation of these operations, or consideration of resource options. Hilton (1989) (Appendix P) proposes that a more enlightened management strategy would entail the identification of appropriate sites by consent granting authorities, and their subsequent promotion using the licensing system. The present study has demonstrated that with regard to the Pakiri sediment body alternative resource options may well exist. The textural characteristics of the sediments of the inner continental shelf are compatible with their use as aggregate for the maunfacture of concrete. These sediments are in deeper water (25-45 m) than those presently mined, but represent a potential resource of voluminous proportions. Sedimentation on the surface of the inner shelf is thought to be dominated by the landward transport of sediments over medium to long-term time periods. Their extraction would invariably entail some environmental damage, especially in terms of the ecology of the bed, but considerably less risk of interfering with the natural development of the Pakiri coast.

## 8.8 Future Research

This study has presented the results of a detailed geomorphic investigation of an embayed east coast sediment body about which little was previously known. However, although there is much evidence in support of the proposed model there remains ample scope for further work.

This investigation has identified the directions of sediment transport, but has been unable to quantify the rates involved. Clearly these must be considerable across the shoreface during particularly severe storm events, during which thousands to hundreds of thousands of cubic metres of sand may be eroded from the coast and inshore and deposited on the shoreface. Subsequent landwards movement of the sediment back onshore may however, take several years. Such a pattern is suggested to have occurred following the July 1978 storms.

Little can be inferred from the investigation about transport rates on the inner shelf and the middle continental shelf, and future work might profitably involve field observations of bed stability. The water depths involved beyond the shoreface may render sediment tracing and similar techniques impractical. A structure deployed on the seabed, containing photographic and current-metering devices, might be effective, although the risk of equipment loss would be high. Whatever approach is employed, however, will be subject to the severe limitation that for long periods marine conditions are calm, and over much of the study area near-bed velocities insignificant. Sediment transport on the middle shelf is thought to occur only under extreme conditions, such that sediment movement may be nil for periods of months or years.

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# Appendix A

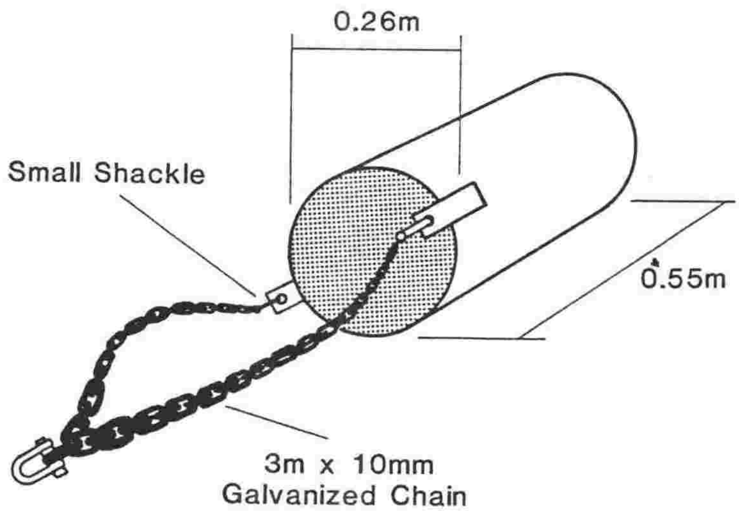
## SAMPLING TECHNIQUE

Samples were obtained by one of two methods. Dune and intertidal samples were collected by driving a 20 cm length of 75 mm diameter PVC piping into the substrate at a $45^0$ angle, and withdrawing the sample by excavation of the pipe. A pipe dredge was preferred to grab type samplers for offshore work, since it was found to provide better retention of fines. The device, and the system of dredging is portrayed in Figure 1. The dredge was towed behind the University of Aucklands' Research Vessel Proteus, an 11 m, 60 horse power vessel. A Neilson drum winch with a pull of 1000 kg, holding 200 m of 20 mm polyester rope, breaking strain 2000 kg, was employed to tow the dredge. The operation was effective with depth to rope-length ratios of between 1:3 and 1:4. With greater ratios the effectiveness of the dredge increases, however the time required to winch the dredge to the boat becomes a disadvantage.

The dredging operation entailed positioning the Proteus over the predetermined sampling station according to the technique outlined in Appendix B. The clutch on the winch was disengaged and the dredge apparatus permitted to fall rapidly to the seabed. At this point in the operation the vessel is moved gradually forward until the required rope length to water depth ratio is attained. Care is needed to ensure the dredge remained stationary on the seabed. When sufficient line was lost from the drum the clutch was engaged and the vessel powered forward. In water shallower than about 25 m sampling is instantaneous due to the large line length to depth ratio. In deeper water, especially beyond 45 m depth, sampling required tow durations of up to and exceeding 30 s at about one knot boat speed. Hence, samples from the shoreface and most of the inner shelf can be considered spot samples, whereas the results from deeper water samples reflect conditions over an area of seabed.

The volume of sediment obtained using this apparatus is usually two or three litres less than the 30 l capacity of the dredge. The top 5 l of sediment were discarded, and the next 1.2 l retained for analysis. Since subsequent splitting would greatly increase the error and compromise the representativeness of the sample, the whole of the 1.2 l sample is analyzed for percent mud and carbonate content. Samples are pretreated in the field with 25 ml of Janola to retard biological activity.

a.




b.

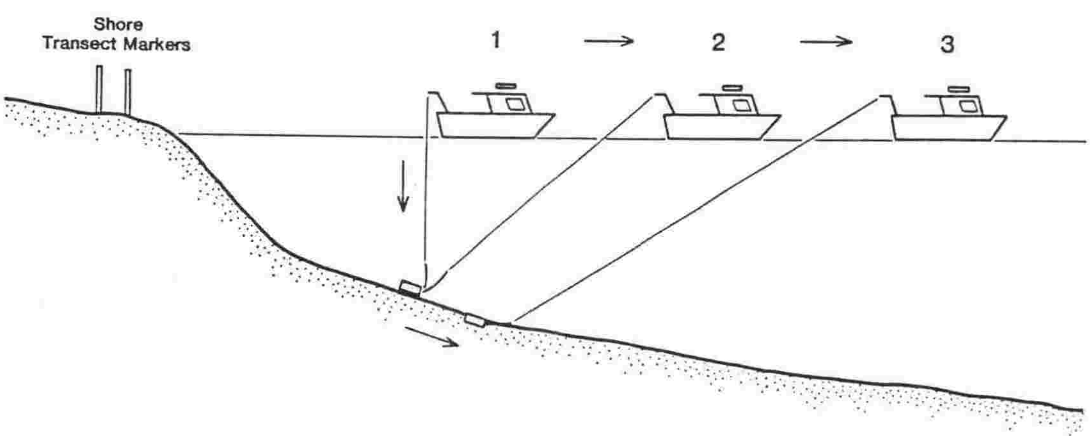



Figure 1 (a) Pipe dredge employed and (b) method of use.

# Appendix B

## OFFSHORE NAVIGATION AND STATION LOCATION

All sediment samples, echosound, sub-bottom and photographic stations were located along transects by means of two semi-permanent shore markers (Figure 1). The distance of the vessel from the shore along these transects was determined using a Furuno 2400 radar range-finder. The accuracy of this instrument is within approximately 25 m of the range discrimination. At distances of 6000 m this error was considered acceptable. The position of the shore markers relative to surveyed datums was determined, and auxiliary datums installed at the shore marker sites. The location and reduced level of datums used during the present investigation is described in Appendix D. The depth at each sample station was obtained at the moment of sampling using a Furuno FE 881 echosounder, with an instantaneous accuracy of +/- 1 percent for sound velocity at 1500 $ms^{-1}$.

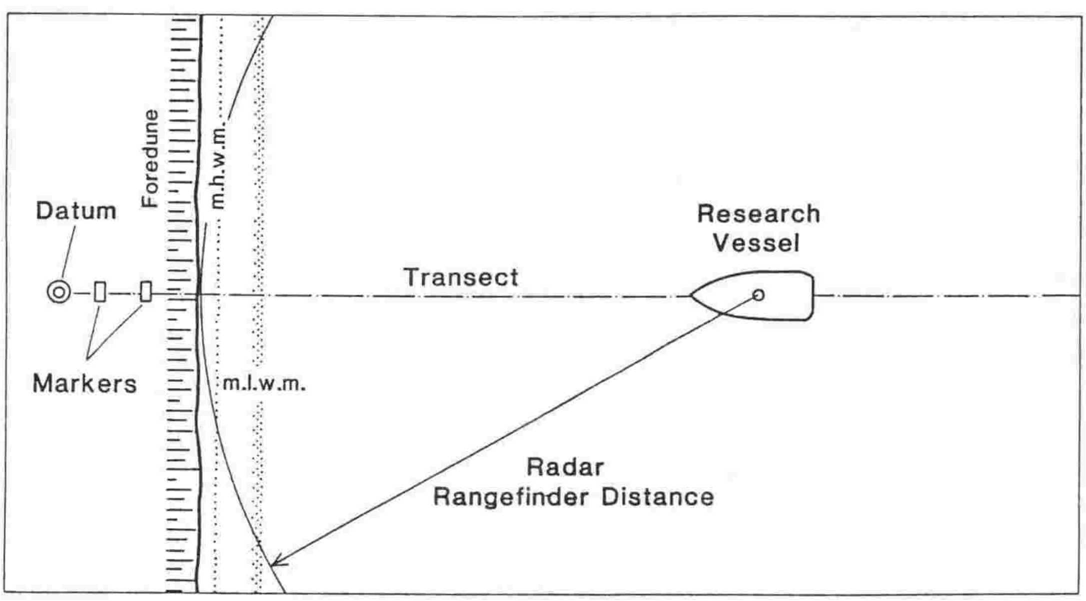



Figure 1 Method of navigation using radar and transect markers

As a check on the accuracy of the range finder/marked-transect method independent radar range-finder and compass observations of prominent features were obtained and the vessel positions plotted by triangulation. Figure 2 compares the results of the two methods along one transect during an occasion of low swell waves and no significant cross winds. Beyond 4000 m offshore the results of

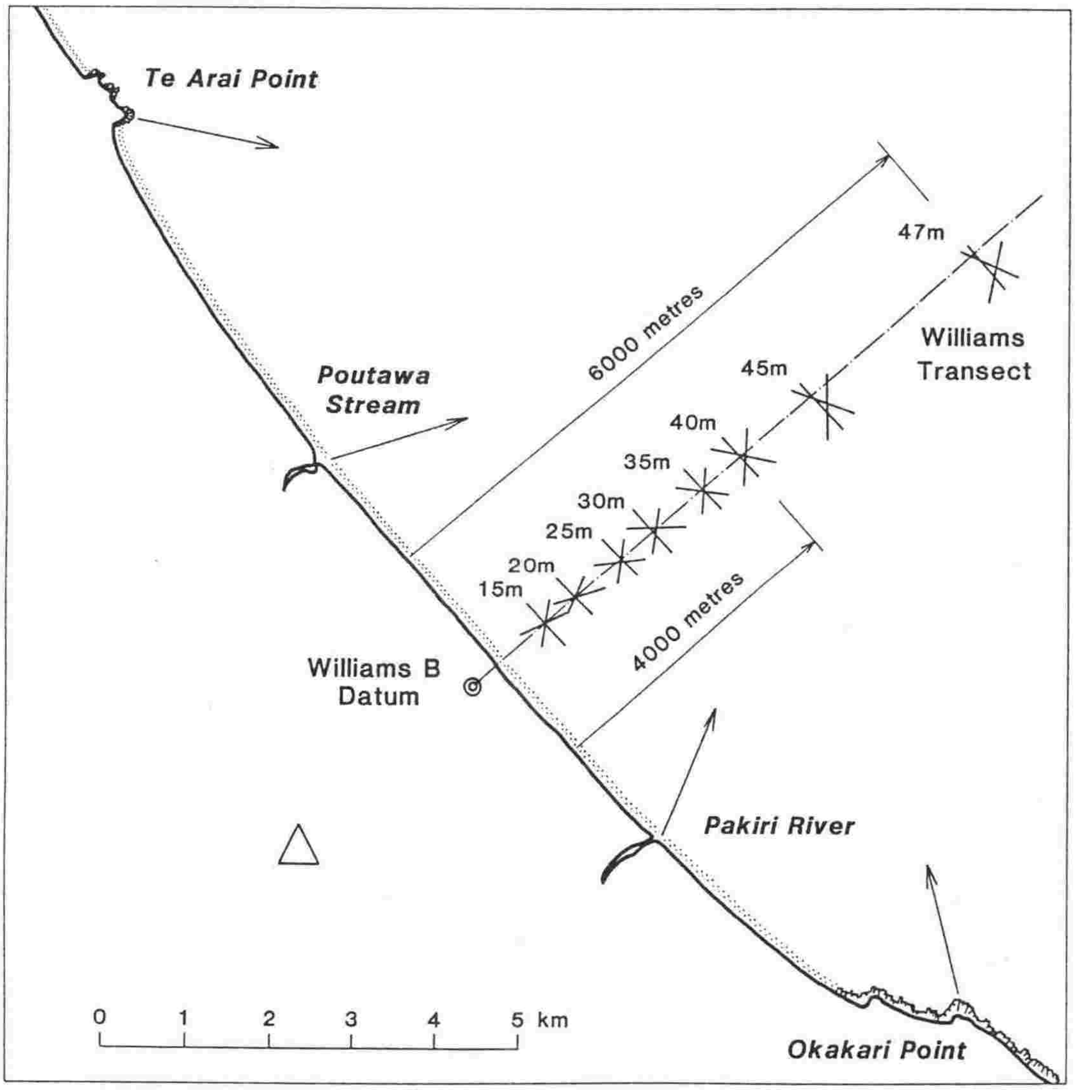



Figure 2 Comparison of radar range-finder/shore marker technique and range-finder triangulation, 22 September 1986

the two techniques become increasingly disparate. Between zero and 4000 m discrepancies were generally less than 50 m, a level of error considered acceptable given the scale of the phenomenon under investigation and the nature of the sediment sampling technique. Beyond 4000 m correct alignment of the markers became increasingly difficult, with a corresponding increase in error. Locational errors were probably in excess of +/- 50 m in adverse weather conditions, especially during cross-winds in excess of 15 knots.

# Appendix C

## LABORATORY TECHNIQUES

### Laboratory Treatments

The sequence of laboratory treatments employed is portrayed in Figure 1 and is based on the standard methods described by Carver (1971) and Folk (1974). Samples were pretreated with 15 ml of Janola (active ingredient sodium hyperchloride) to inhibit organic decomposition. Large fragments of shell material were removed in the laboratory by hand with the help of a coarse sieve. Further separation of the remaining organic material was not attempted because of the probable and unnecessary loss of clay and silt mineral particles. The total weight of fines was determined after the sample was dispersed with calgon (sodium hexametaphosphate), wet sieved and the sand and fine fractions dried. In general, every effort was made to standardize error where it could not be removed. Samples were treated in batches, usually comprising an entire transect. The same methods were applied to each transect or batch, however, variations in results due to slightly differing treatments no doubt occurred. These are not considered significant.

After wet sieving through a 63 micron ($\mu$) sieve the fines fraction, containing particles of silt and clay finer than 63 $\mu$, was dried to derive an estimate of total fines. The sand fraction was split to provide sub-samples (approx 120 g) for settling tube analysis of grain size, and another for carbonate determination. The settling tube sample was then split two or more times to allow multiple trials for the same sample. At least two subsamples were settled and the results averaged for each sample. Following digestion and determination of the percent carbonate the subsample was again split to provide fractions for sieving using a range of Endecotts Ltd test sieves, and settling tube determination of grain size, without shell. The sieved fractions were maintained and utilized in studies of particle composition.

Grain size analysis was undertaken using the Department of Geography, University of Aucklands', rapid sediment analyzer. This

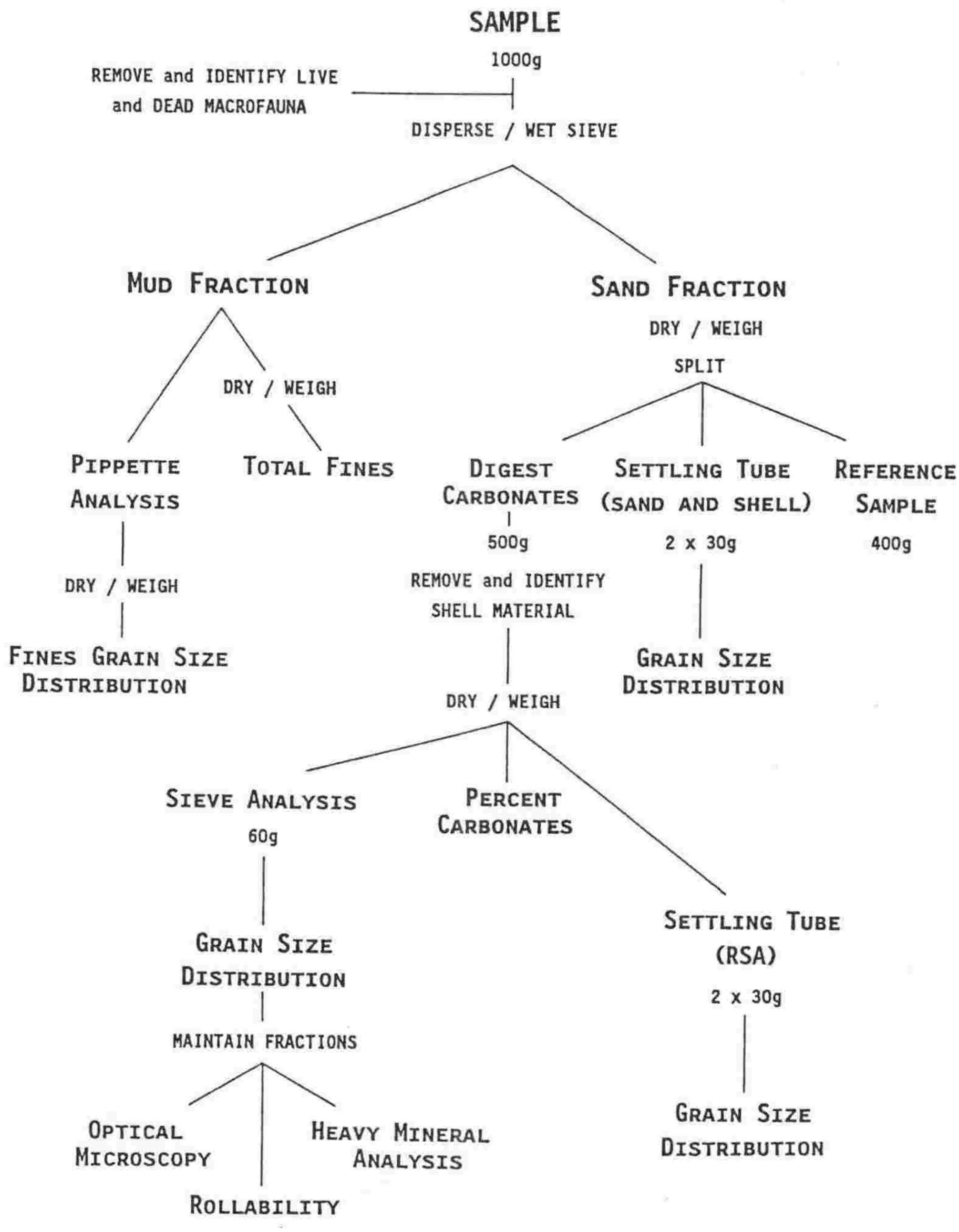



Figure 1 Sequence of laboratory treatments

device can produce a result in terms of the settling velocity as well as particle size. Settling velocity is analyzed in terms of the Chi parameter discussed by May (1981). This can be defined as

$$\mathrm{Chi} = -\log_2(s/so)$$

where, so = standard settling velocity of 1 $ms^{-1}$

and, s is the standardized settling velocity given by

s = sm + (K) * (20 - t) * sm

where, k is a temperature correction factor given by

sm > 0.177 k=0

0.002 > sm > 0.177 k = -0.00555 * ln(sm)-0.00961

sm < 0.002 k=0.025

The resulting Chi values are for spherical quartz grains falling through pure water at 20°C. Hence it is possible to compare the Chi results for different sediments under different conditions.

Particle size is analyzed in terms of the phi parameter, defined as

$$\mathrm{Phi} = -\log^2(d)$$

where d = grain diameter in millimeters. The program uses the Gibbs <u>et</u> <u>al</u>. (1971) equation to convert the settling velocity distribution to a particle size distribution, by determining the settling velocity for the required phi values, and then obtaining the cumulative weight for that velocity using

$$V = \frac{-3 * U + SR\ (9*U*U+G*R*R*W*(S-W)*(0.015476 + 0.19841 *R))}{W * (0.011607 + 0.14881 * R)}$$

where V = velocity (cm $s^{-1}$),

U = water dynamic viscosity (poise),

G = acceleration due to gravity (cm $s^{-2}$),

R = radius of a sphere (cm),

W = water density (g $cm^{-3}$),

and, S = particle density (g $cm^{-3}$).

To allow a wide range of sediment types to be processed, the density correction factors proposed by Komar (1981) are employed. Therefore, the results are for equivalent spheres with the water specified density (quartz). The results are analyzed using among others, the graphical method of Folk and Ward (1957) to derive the mean, median, sorting, skewness and kurtosis.

## Sources of Error

An attempt was made to experimentally determine the errors associated with the laboratory treatments. Of the potential errors those associated with determination of total fines and total carbonates are considered most important. In general it is suspected that the proportion of fines tends to be underestimated, while the proportion of carbonates in some samples tends to be overestimated. The wet sieve technique of fines separation following dispersal requires the washings to be collected, dried and weighed. With particularly muddy samples this operation may be less efficient as fine particles are retained in the matrix, although these are subsequently rinsed from the sand fraction with copious water before drying, splitting and RSA analysis. Even in the worse cases however, this error is not thought to exceed 10 percent of the total fines weight.

## Grain Size Determination

Grain size determinations were derived using both sieve and settling tube methods. That these two techniques measure fundamentally different properties is pointed out by Komar and Cui (1984). Sieving sorts the sediment grains by shape as well as by size, and the assumption is commonly made while sieving that the particles are spherical such that their 'diameters' correspond to the width of the square sieve openings. Treating sieved grains as spheres introduces a systematic error in the results which causes some uncertainty when using the grain-size data in investigations of sediment transport processes. For this and reasons of efficiency, the settling tube technique was preferred, although this method is also affected by variations in grain size and density. An appreciation of the effect of the technique on the results is important if the results are to be compared to those of other studies, and within the present study.

The results of settling tube determinations of grain size are thought to better indicate the hydrodynamic properties of sediments, in that those factors that influence a particle during erosion, transportation and sedimentation, size, porosity, density, shape, roundness and sphericity, are taken into account (Komar and Cui, 1984). Standard practice is to convert the settling velocities into 'equivalent sedimentation diameters', the diameter of a sphere having the same settling rate as measured for the non-spherical, natural grain, as per the formula of Gibbs et al. (1971).

The results of Komar and Cui demonstrate the two methods yield nearly the same size distributions as long as the sample is composed almost entirely of quartz and feldspar and is well sorted. Comparisons of the two techniques indicate that this is not necessarily the case with samples analyzed during the present investigation (Figure 2 a,b). Grain size distributions obtained by settling tube tend to have a lower mean grain size (coarser) and have a lower standard deviation (better sorted). Further, these trends are not necessarily consistent across a transect. As discussed in Chapter Three the mineralogical composition of samples, and in particular the proportion of mafic minerals, commonly varies across the transects. For example, samples obtained from the mid shelf are coarser by settling than sieving. This result may partly reflect the higher mafic content of these samples, since the sieve results are less influenced by differences in particle density.

An investigation was undertaken to assess the effect of varying mineralogy on the RSA results. Size-controlled particles, of either felsic or mafic particles, or a mix of both, were analyzed using a variety of specific gravity formulas. In the first four trials

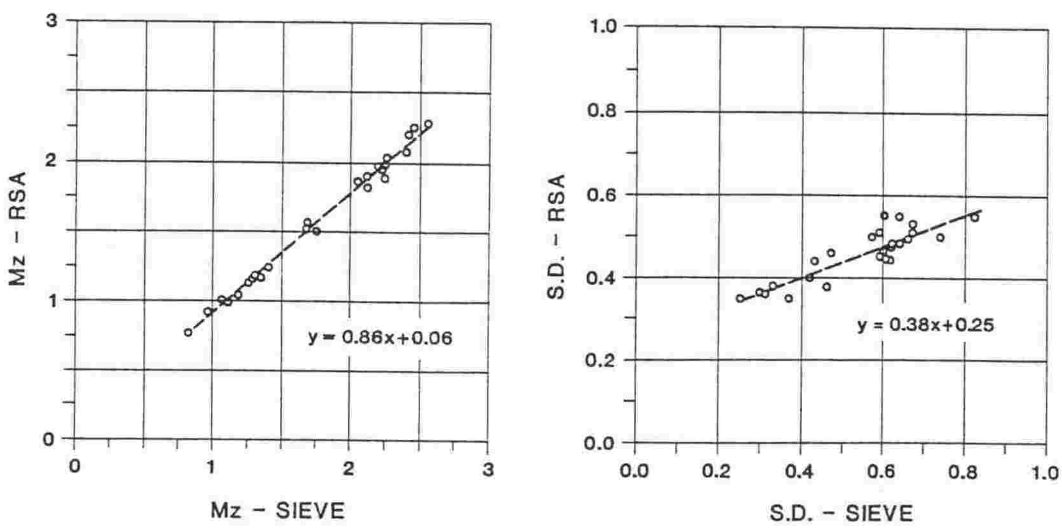



**Figure 2** Comparison of sample mean grain size (a) and standard deviation (b) (phi units) derived by sieve and settling tube (RSA) methods.

(E1-4) the specific gravity of silica (2.65) was employed for both silica and titanomagnetite sands. The results were markedly different in mean grain size, and comparable for standard deviation and skewness (Table 1). The implication is that the more dense mafic particles settled faster than the lighter felsic particles, and this was not allowed for in the choice of a specific gravity. Gradually increasing the specific gravity (E5-7) of the titanomagnetite provides mean grain size results more in accordance with the ideal size-controlled 100% silica sample, even though the former tend to be rod-shaped and the latter spherical. Similarly, when the two sediments are mixed in equal proportions, and an intermediate specific gravity selected, the results are closer to the ideal. The conclusion is that the selection of an appropriate specific gravity value, for use in the settling velocity formula, is important.

However, it is not practical to determine the ideal specific gravity to be employed for each sample analyzed by RSA technique during the present investigation. It is sufficient to appreciate that coarse

**Table 1 Effect of Varying Mineralogy (Specific Density) on Grain Size Distributions Derived by Rapid Sediment Analysis**

| Sample Ref. | Grain Size (phi) | Composition (percent) | Specific Density Employed | Mz (phi) | SD (phi) |
|---|---|---|---|---|---|
| E1 | 2.50 | 100 Qtz | 2.65 | 2.11 | 0.26 |
| E2 | " | " | " | 2.05 | 0.28 |
| mean | | | | 2.08 | 0.27 |
| S.E. | | | | 0.03 | 0.01 |
| E3 | 2.50 | 100 Ti | 2.65 | 1.69 | 0.27 |
| E4 | " | " | " | 1.61 | 0.32 |
| mean | | | | 1.65 | 0.29 |
| S.E. | | | | 0.04 | 0.02 |
| E5 | 2.50 | 100 Ti | 3.00 | 1.85 | 0.28 |
| E6 | " | " | 4.00 | 2.25 | 0.25 |
| E7 | " | " | 5.20 | 2.45 | 0.26 |
| mean | | | | 2.18 | 0.26 |
| S.E. | | | | 0.18 | 0.01 |
| E8 | 2.50 | Qtz 50 Ti | 3.92 | 2.22 | 0.33 |
| E9 | " | " | " | 2.20 | 0.29 |
| E10 | " | " | " | 2.22 | 0.32 |
| mean | | | | 2.21 | 0.31 |
| S.E. | | | | 0.01 | 0.01 |

Notes:- 1. Qtz - Quartz
2. Ti - Titanomagnetite

sediments are probably even coarser than measured, where they contain rock fragments with low specific gravities, and fine sediments are probably even finer than measured where they contain a high proportion of mafic minerals.

# Appendix D

## LOCATION AND REDUCED LEVELS OF PAKIRI-MANGAWHAI DATUMS

A system of datums was installed along the Pakiri-Mangawhai coast by the Auckland Regional Water Board following the severe storms of July 1978. They were used for beach surveys from 1978 until 1983 when a project to monitor the beaches of the Auckland Region was discontinued. These datums provided the necessary locational and elevational control for many of the investigations reported in this thesis. All datums have been surveyed, via local Lands and Survey datums, relative to the Mt Eden circuit metric grid and mean sea level Auckland (1.743 m). Sea level observations at the University of Aucklands' Leigh Marine Laboratories indicate local mean sea is at least 0.1 m above this level (Evans, 1987). The location of the datums on the metric grid and their elevation relative to Auckland mean sea level is given in Table 1. The location of the datums in the Mangawhai-Pakiri embayment is portrayed in Figure 1.

The Regional Water Board datums consist of 2 m lengths of 50 mm (diameter) galvanised steel piping. They are easily distinguished from the 'M' series of datums installed by the New Zealand Forest Service in 1977 for forest management purposes. The Regional Water Board datums are often located in the middle of a square of wooden pegs. These pegs were used to support black and white-painted markers erected prior to aerial photography in June 1982. The Forest Service datums consist of steel waratahs inserted into a steel pipe.

The datums had not been used since October 1983, and required considerable time to relocate or reestablish. The original network consisted of one or more inland datums (designated A), supporting a single datum on the foredune (designated B). In several instances the foredune mark had been subsequently covered by wind-blown sand. Picnic B and SB1 B[1] (Walkway transect) could not be relocated, and

Table 1 Reduced Level and Location of Pakiri-Mangawhai Datums

| Datum | Transect | Reduced Level (m) | Grid Location north (m) | Grid Location east (m) | Grid Ref. NZMS 260 R08 |
|---|---|---|---|---|---|
| 2941 | Mangawhai | 15.28 | 784 622.80 | 286 496.68 | 559 638 |
| 2941 Aux. | - | 9.71 | 784 399.19 | 286 625.38 | - |
| Picnic A | Picnic | 14.70 | 781 873.24 | 287 953.24 | 575 612 |
| Pic. Aux. | - | - | 781 499.54 | 288 244.47 | - |
| SB1 $B^2$ | Gravel | 8.10 | 777 995.88 | 290 744.86 | 595 573 |
| SB1 $B_N$ | - | 13.18 | - | - | - |
| SB2 A | Walkway | 16.15 | 776 177.33 | 291 362.09 | 609 551 |
| M7 | - | 23.36 | 776 736.32 | 291 005.49 | 603 558 |
| Could. B | Couldrey | 13.10 | 774 016.51 | 293 187.69 | 624 531 |
| 2972 N | - | 16.40 | 774 550.92 | 292 778.66 | - |
| Will. B | Williams | 15.76 | 772 578.45 | 294 498.71 | 636 516 |
| Brown N | - | 28.96 | 772 062.32 | 294 847.94 | 642 509 |
| Brown B | Brown | 14.61 | 771 454.40 | 295 522.41 | 647 504 |
| 2971 A | - | 33.07 | 770 037.00 | 296 905.02 | 661 491 |
| 2971 $S^2$ | Matheson | 15.50 | 769 414.43 | 297 665.19 | 667 484 |

Source: Chief Surveyor, Auckland Regional Authority

were reestablished with steel waratahs. Subsequent movements of sand in the area of the foredune revealed SB1 $B^2$, an earlier attempt by the Auckland regional Water Board to maintain a datum above the foredune surface. The inland datum SB2 A (Gravel transect) had been destroyed, as had the seaward datum near trig station 2971, to the south of the Pakiri River. Because the landward datum could not be located a new transect, Matheson, was constructed adjacent to

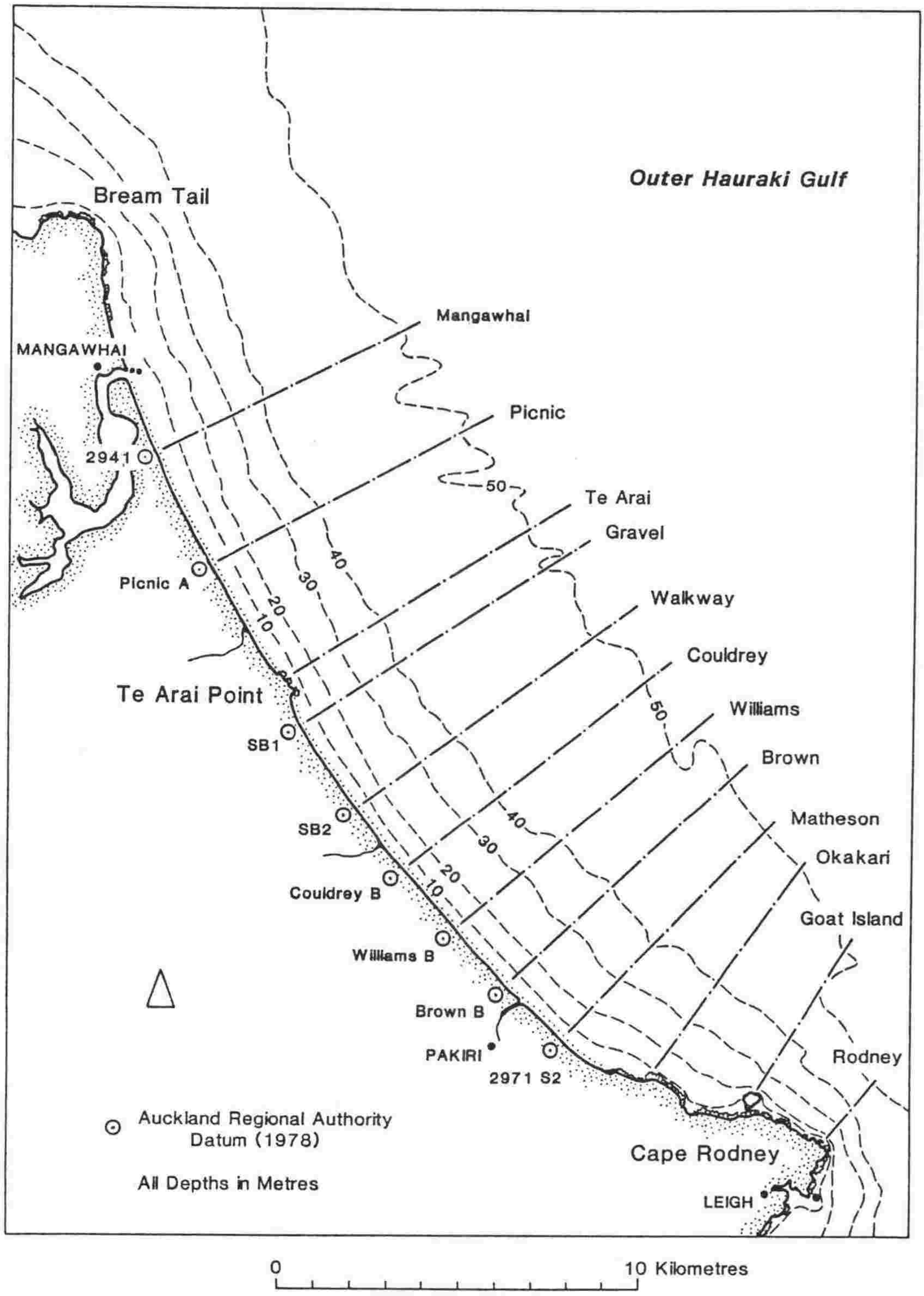



Figure 1 Location of Auckland Regional Water Board datums

auxiliary datum 2971 $S^2$, 700 m to the south. The landward 2971 datum has since been located (pers.comm., Mr Ian Smith, Chief Surveyor, Auckland Regional Authority).

Auxiliary datums were originally installed by the Regional Water Board to serve as photo-control points between the eight major datums. However, because they bisect adjacent transects, are surveyed relative to the metric grid and are located on prominent hummocks, they are ideally located for survey instrument observations during offshore echosound surveys. Datums M6 and M7, installed by the New Zealand Forest Service, are well placed to perform the same function.

Several types of additional datums and markers were installed during the study. To facilitate beach and foredune surveys two waratahs were installed along the shore-normal transect line seaward of the Water Board (foredune) datum. Landward of the foredune a white tanalised fence post has been installed along most transects, especially where the original landward datum was missing, to provide a means of reestablishing the transect in the event of a major storm and the loss of the foredune and waratah datums. In addition, two brightly painted (orange) markers were installed along each of the six transects south of Te Arai Point. These consisted of 2.0 x 0.4 m lengths of treated marine plywood attached to posts buried at least 1.4 m deep. They were placed along the transect so they could be aligned to locate a vessel on the transect line up to 6000 m offshore. In most instances the survey of new datums was facilitated by reference to one of several visible trig station datums in the Pakiri-Mangawhai district; the trig station on Te Arai Point being of particular value.

# Appendix E

## SUMMARY OF SEDIMENT ANALYSES

In the following tables distance offshore refers to the distance from the foredune datum to the vessel at the moment of sampling. Water depth is relative to regional mean sea level (1.7 m). The following symbols are used in the tables:- Carbs - carbonate material, Fines - silt and clay fraction, $M_Z$ - mean grain size, SD - standard deviation of sample, K - kurtosis and Sk - skewness. Along some transects grain size analysis involved fully treated, sand-only samples, as well as part-treated samples containing both shell and sand. Both mean grain size values for the sand only (Sa), and sand and shell (Sh) are included in the tables where applicable. Kurtosis, standard deviation and skewness values however, refer to the sand only analysis. Reference samples are housed in the sediment store, Department of Geography, University of Auckland.

### 1. Okakari Transect (26.09.86)

| Sample Ref. | Distance Offshore (metres) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics $M_Z$ Sa | $M_Z$ Sh | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|---|
| 0 1 | 185 | 14 | 72.7 | 2.9 | 1.94 | 0.37 | 0.95 | -0.39 | 2.25 |
| 0 2 | 278 | 16 | 9.7 | 0.8 | 2.23 | 2.15 | 0.34 | 0.07 | 0.88 |
| 0 3 | 370 | 17 | 8.5 | 0.6 | 2.26 | 2.12 | 0.31 | 0.03 | 0.90 |
| 0 4 | 463 | 18 | 7.6 | 0.7 | 2.27 | 2.29 | 0.32 | 0.13 | 0.93 |
| 0 5 | 556 | 19 | 6.8 | 0.6 | 2.25 | 2.14 | 0.31 | 0.10 | 0.93 |
| 0 6 | 648 | 20 | 6.4 | 0.7 | 2.28 | 2.20 | 0.32 | 0.15 | 0.95 |
| 0 7 | 741 | 21 | 6.4 | 1.4 | 2.25 | 2.15 | 0.61 | 0.15 | 0.95 |
| 0 8 | 833 | 22 | 10.1 | 1.1 | 2.27 | 2.17 | 0.32 | 0.12 | 0.97 |
| 0 9 | 926 | 23 | 8.6 | 1.2 | 2.27 | 2.18 | 0.31 | 0.17 | 0.99 |
| 0 10 | 1185 | 26 | 10.1 | 0.7 | 2.28 | 2.13 | 0.31 | 0.15 | 0.95 |
| 0 11 | 1445 | 28 | 10.0 | 0.4 | 2.26 | 2.20 | 0.32 | 0.14 | 0.96 |
| 0 12 | 1704 | 30 | 12.2 | 1.5 | 2.25 | 2.24 | 0.35 | 0.12 | 0.94 |
| 0 13 | 1963 | 33 | 14.2 | 1.6 | 2.20 | 2.16 | 0.37 | 0.05 | 0.91 |
| 0 14 | 2222 | 35 | 21.9 | 1.8 | 2.15 | 2.05 | 0.35 | 0.13 | 0.92 |
| 0 15 | 2482 | 37 | 57.8 | 1.5 | 1.32 | 0.92 | 0.55 | 0.47 | 0.93 |
| 0 16 | 2741 | 37 | 60.6 | 1.4 | 2.07 | 1.08 | 0.49 | -0.08 | 0.97 |
| 0 17 | 3000 | 38 | 12.4 | 5.8 | 2.39 | 2.37 | 0.33 | 0.08 | 0.89 |

Okakari Transect (continued)

| Sample Ref. | Distance Offshore (metres) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics $M_Z$ Sa | $M_Z$ Sh | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|---|
| 0 18 | 3260 | 40 | 12.9 | 5.8 | 2.40 | 2.24 | 0.28 | 0.13 | 0.88 |
| 0 19 | 3519 | 42 | 12.9 | 6.6 | 2.32 | 2.21 | 0.36 | 0.07 | 0.91 |
| 0 20 | 3778 | 44 | 13.3 | 7.3 | 2.35 | 2.28 | 0.33 | 0.11 | 0.92 |

## 2. Matheson Transect (05.11.86)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics (phi units) $M_Z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| Y 81 | 185 | 4 | 4.4 | 0.7 | 1.88 | 0.34 | 0.14 | 0.90 |
| Y 82 | 278 | 5 | 5.0 | 0.7 | 2.02 | 0.36 | 0.12 | 0.89 |
| Y 83 | 370 | 8 | 6.8 | 0.9 | 2.02 | 0.32 | 0.07 | 0.99 |
| Y 84 | 463 | 10 | 6.4 | 0.9 | 2.06 | 0.34 | 0.09 | 0.98 |
| Y 85 | 556 | 10 | 12.6 | 0.8 | 1.94 | 0.33 | 0.14 | 0.91 |
| Y 86 | 648 | 12 | 6.7 | 0.8 | 2.17 | 0.29 | 0.11 | 0.89 |
| Y 87 | 741 | 15 | 5.8 | 1.3 | 2.15 | 0.33 | 0.07 | 0.89 |
| Y 88 | 833 | 15 | 5.1 | 1.5 | 2.15 | 0.33 | 0.10 | 0.88 |
| Y 89 | 926 | 16 | 6.3 | 2.0 | 2.12 | 0.34 | 0.09 | 0.91 |
| Y 90 | 1185 | 18 | 8.4 | 2.4 | 2.15 | 0.34 | 0.06 | 0.93 |
| Y 91 | 1445 | 21 | 8.7 | 2.6 | 2.09 | 0.38 | 0.02 | 3.05 |
| Y 92 | 1704 | 25 | 7.5 | 2.7 | 2.04 | 0.40 | 0.03 | 0.93 |
| Y 93 | 1963 | 25 | 8.5 | 3.6 | 1.92 | 0.47 | 0.03 | 0.94 |
| Y 94 | 2222 | 28 | 5.7 | 1.7 | 1.92 | 0.40 | 0.15 | 0.96 |
| Y 95 | 2482 | 30 | 7.9 | 2.4 | 1.71 | 0.40 | 0.18 | 1.04 |
| Y 96 | 2741 | 33 | 6.9 | 2.5 | 1.57 | 0.42 | 0.18 | 1.05 |
| Y 97 | 3000 | 35 | 20.7 | 3.6 | 1.01 | 0.47 | 0.37 | 1.26 |
| Y 98 | 3260 | 38 | 7.1 | 3.7 | 1.89 | 0.45 | 0.28 | 0.99 |
| Y 99 | 3519 | 40 | 13.1 | 7.0 | 2.28 | 0.41 | 0.02 | 1.04 |
| Y 100 | 3778 | 43 | 9.5 | 6.2 | 2.39 | 0.38 | 0.05 | 0.92 |

3. Brown Transect (07.11.86)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_Z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| | | | | | Summary Statistics (phi units) | | | |
| BB 1 | 175 | 3 | 4.7 | 0.9 | 2.09 | 0.37 | 0.10 | 0.89 |
| 2 | 268 | 3 | 5.0 | 0.2 | 1.98 | 0.40 | 0.03 | 1.00 |
| 3 | 360 | 4 | 9.1 | 0.8 | 1.84 | 0.41 | 0.11 | 0.99 |
| 4 | 453 | 6 | 8.3 | 0.7 | 1.99 | 0.37 | 0.07 | 1.07 |
| 5 | 546 | 8 | 6.4 | 0.6 | 2.02 | 0.34 | 0.15 | 0.90 |
| 6 | 638 | 10 | 7.8 | 0.8 | 2.03 | 0.36 | 0.12 | 0.88 |
| 7 | 731 | 12 | 6.7 | 0.8 | 2.13 | 0.35 | 0.03 | 0.92 |
| 8 | 823 | 14 | 6.5 | 0.8 | 2.18 | 0.33 | 0.08 | 0.87 |
| 9 | 916 | 15 | 6.4 | 0.8 | 2.20 | 0.43 | -0.02 | 0.91 |
| 10 | 1175 | 18 | 6.6 | 1.0 | 2.21 | 0.31 | 0.09 | 0.87 |
| 11 | 1434 | 21 | 11.2 | 1.1 | 2.05 | 0.43 | -0.02 | 0.91 |
| 12 | 1693 | 24 | 9.2 | 1.1 | 2.01 | 0.44 | -0.02 | 0.94 |
| 13 | 1953 | 27 | 7.9 | 1.2 | 1.98 | 0.41 | 0.08 | 0.90 |
| 14 | 2212 | 28 | 7.0 | 1.4 | 2.02 | 0.39 | 0.10 | 0.93 |
| B 1 | 2471 | 30 | 5.8 | 1.5 | 1.58 | 0.50 | 0.12 | 0.96 |
| 2 | 2731 | 32 | 6.4 | 1.2 | 0.92 | 0.51 | 0.13 | 1.08 |
| 3 | 2990 | 35 | 25.9 | 1.1 | 0.90 | 0.63 | 0.19 | 1.10 |
| 4 | 3249 | 35 | 5.6 | 1.8 | 1.99 | 0.43 | 0.14 | 0.93 |
| 5 | 3509 | 37 | 5.5 | 1.5 | 1.17 | 0.42 | 0.32 | 1.08 |
| 6 | 3768 | 38 | 6.3 | 1.8 | 1.64 | 0.84 | -0.28 | 3.74 |
| 7 | 4027 | 40 | 8.4 | 2.1 | 2.07 | 0.48 | -0.03 | 1.10 |
| 8 | 4287 | 42 | 10.6 | 2.8 | 2.06 | 0.47 | 0.16 | 0.94 |
| 9 | 4545 | 43 | 9.8 | 3.7 | 2.08 | 0.44 | 0.17 | 1.00 |
| 10 | 4805 | 45 | 10.8 | 3.7 | 2.18 | 0.43 | 0.03 | 1.14 |

4a. Williams Transect (22.09.86)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_Z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| | | | | | Summary Statistics (phi units) | | | |
| Y 1 | 185 | 5 | 2.3 | 0.0 | 2.03 | 0.35 | 0.16 | 0.93 |
| 2 | 278 | 4 | 4.5 | 0.8 | 1.87 | 0.38 | 0.09 | 0.94 |
| 3 | 370 | 7 | 4.2 | 0.8 | 1.96 | 0.38 | 0.07 | 0.92 |
| 4 | 463 | 9 | 5.5 | 0.6 | 1.90 | 0.36 | 0.14 | 0.92 |
| 5 | 556 | 10 | 4.9 | 0.8 | 2.00 | 0.37 | 0.13 | 0.94 |
| 6 | 648 | 13 | 3.7 | 1.1 | 2.00 | 0.36 | 0.10 | 0.90 |
| 7 | 741 | 15 | 4.1 | 0.8 | 1.24 | 0.45 | 0.23 | 1.00 |

Williams Transect (continued)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_Z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| | | | | | Summary Statistics (phi units) | | | |
| 8 | 833 | 17 | 6.2 | 0.8 | 1.20 | 0.47 | 0.23 | 1.03 |
| 11 | 926 | 19 | 6.6 | 1.9 | 1.60 | 0.51 | 0.22 | 1.01 |
| 12 | 1185 | 22 | 10.8 | 0.8 | 1.04 | 0.46 | 0.25 | 1.05 |
| 13 | 1444 | 24 | 6.5 | 1.0 | 1.08 | 0.44 | 0.28 | 1.03 |
| 14 | 1703 | 25 | 5.7 | 0.7 | 1.19 | 0.45 | 0.20 | 1.05 |
| 15 | 1963 | 26 | 21.7 | 0.9 | 1.04 | 0.52 | 0.35 | 1.00 |
| 16 | 2222 | 27 | 11.1 | 1.5 | 1.05 | 0.51 | 0.34 | 0.97 |
| 17 | 2481 | 30 | 10.2 | 0.7 | 1.19 | 0.49 | 0.23 | 0.98 |
| 18 | 2741 | 33 | 7.9 | 1.1 | 0.92 | 0.50 | 0.33 | 1.24 |
| 19 | 3000 | 36 | 10.7 | 1.0 | 0.83 | 0.55 | 0.20 | 1.11 |
| 20 | 3259 | 37 | 4.9 | 1.3 | 1.22 | 0.49 | 0.23 | 1.01 |
| 21 | 3519 | 39 | 23.1 | 1.4 | 1.00 | 0.43 | 0.32 | 1.10 |
| 22 | 3778 | 40 | 8.9 | 2.0 | 1.88 | 0.69 | -0.66 | 1.16 |
| 23 | 4037 | 41 | 9.0 | 4.8 | 1.50 | 0.52 | 0.29 | 1.05 |
| 24 | 4297 | 43 | 11.2 | 6.1 | 2.33 | 0.41 | 0.10 | 0.93 |
| 25 | 4555 | 45 | 18.8 | 4.9 | 2.35 | 0.50 | 0.02 | 0.90 |
| 26 | 4815 | 45 | 14.7 | 6.8 | 2.15 | 0.55 | 0.05 | 0.92 |
| 27 | 5074 | 45 | 15.3 | 6.9 | 1.81 | 0.49 | 0.33 | 0.89 |
| 28 | 5333 | 45 | 13.2 | 2.6 | 1.51 | 0.51 | 0.23 | 1.01 |
| 29 | 5593 | 46 | 9.2 | 4.0 | 1.90 | 0.49 | 0.15 | 0.90 |
| 30 | 5852 | 46 | 11.7 | 2.6 | 2.10 | 0.48 | 0.10 | 1.00 |
| 31 | 6112 | 47 | 10.3 | 9.8 | 2.25 | 0.40 | 0.11 | 0.90 |

**4b. Williams Transect (07.05.86)**

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_Z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| | | | | | Summary Statistics (phi units) | | | |
| Z 1 | 278 | 4 | 2.4 | 0.0 | 1.84 | 0.35 | 0.09 | 0.95 |
| 2 | " | " | 4.3 | 0.0 | 1.86 | 0.36 | 0.12 | 0.93 |
| 3 | " | " | 6.9 | 0.0 | 1.49 | 0.54 | 0.00 | 0.85 |
| 4 | " | " | 18.1 | 0.0 | 1.45 | 0.55 | -0.05 | 0.94 |
| 5 | " | " | 5.5 | 0.0 | 1.63 | 0.46 | -0.01 | 0.97 |
| 6 | 574 | 10 | 5.8 | 1.6 | 2.00 | 0.34 | 0.09 | 0.90 |
| 7 | " | " | 5.7 | 1.8 | 1.99 | 0.33 | 0.17 | 0.98 |
| 8 | " | " | 6.3 | 1.7 | 1.93 | 0.36 | 0.11 | 0.88 |
| 9 | " | " | 5.9 | 2.4 | 1.91 | 0.35 | 0.09 | 0.87 |

Williams (continued)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_Z$ | Summary Statistics SD (phi units) | Sk | K |
|---|---|---|---|---|---|---|---|---|
| 10 | " | " | 5.9 | 1.1 | 1.88 | 0.36 | 0.08 | 0.92 |
| 11 | 778 | 15 | 1.7 | 0.7 | 1.47 | 0.47 | 0.17 | 0.93 |
| 12 | " | " | 2.4 | 0.8 | 1.68 | 0.43 | 0.13 | 1.00 |
| 13 | " | " | 3.3 | 1.0 | 1.93 | 0.41 | 0.09 | 0.94 |
| 14 | " | " | 4.2 | 1.0 | 2.00 | 0.37 | 0.08 | 0.90 |
| 15 | " | " | 2.8 | 0.6 | 1.83 | 0.46 | -0.01 | 1.01 |
| 16 | 1241 | 20 | 7.2 | 1.1 | 1.70 | 0.56 | 0.07 | 0.94 |
| 17 | " | " | 3.2 | 0.7 | 1.61 | 0.47 | 0.19 | 0.95 |
| 18 | " | " | 5.2 | 0.9 | 1.58 | 0.51 | 0.22 | 0.97 |
| 19 | " | " | 7.1 | 0.9 | 1.67 | 0.44 | 0.11 | 0.96 |
| 20 | " | " | 8.1 | 0.9 | 1.36 | 0.52 | 0.13 | 1.01 |
| 21 | " | " | 6.6 | 1.0 | 1.61 | 0.46 | 0.18 | 1.00 |
| 22 | " | " | 10.1 | 2.0 | 1.75 | 0.48 | 0.03 | 0.96 |
| 23 | " | " | 4.7 | 0.9 | 1.33 | 0.50 | 0.13 | 0.96 |
| Z 24 | 1963 | 25 | 8.3 | 1.7 | 1.13 | 0.49 | 0.25 | 1.01 |
| 25 | " | " | 8.6 | 1.4 | 1.16 | 0.43 | 0.24 | 1.10 |
| 26 | " | " | 5.9 | 0.8 | 1.15 | 0.45 | 0.23 | 1.00 |
| 27 | " | " | 8.6 | 0.8 | 1.17 | 0.46 | 0.27 | 1.07 |
| 28 | " | " | 7.7 | 1.1 | 1.17 | 0.46 | 0.27 | 1.02 |
| 29 | " | " | 7.4 | 0.7 | 1.28 | 0.47 | 0.25 | 0.98 |
| 30 | " | " | 11.5 | 1.0 | 1.16 | 0.43 | 0.22 | 1.09 |
| 31 | " | " | 9.2 | 1.1 | 1.12 | 0.48 | 0.27 | 1.02 |
| Z 32 | 2500 | 30 | 6.0 | 0.9 | 1.27 | 0.42 | 0.20 | 1.07 |
| 33 | " | " | 4.9 | 2.7 | 1.38 | 0.43 | 0.15 | 1.00 |
| 34 | " | " | 6.4 | 2.2 | 1.42 | 0.44 | 0.13 | 0.98 |
| 35 | " | " | 14.4 | 1.3 | 1.07 | 0.53 | 0.16 | 1.08 |
| 36 | " | " | 11.6 | 0.8 | 1.18 | 0.52 | 0.21 | 1.06 |
| 37 | " | " | 15.5 | 1.5 | 1.16 | 0.54 | 0.12 | 1.02 |
| Z 38 | 3223 | 35 | 12.8 | 1.3 | 0.85 | 0.64 | 0.19 | 0.92 |
| 39 | " | " | 13.6 | 0.9 | 0.69 | 0.60 | 0.27 | 1.08 |
| 40 | " | " | 11.3 | 2.1 | 0.66 | 0.64 | 0.10 | 1.11 |
| 41 | " | " | 10.1 | 1.7 | 0.68 | 0.65 | 0.18 | 0.99 |
| 42 | " | " | 11.4 | 1.4 | 0.44 | 0.65 | 0.17 | 1.20 |
| 43 | " | " | 9.1 | - | 0.67 | 0.64 | 0.15 | 1.06 |
| Z 44 | 3852 | 40 | 21.8 | 1.3 | 0.54 | 0.54 | 0.33 | 1.26 |
| 45 | " | " | 32.0 | 1.4 | 0.61 | 0.51 | 0.33 | 1.20 |
| 46 | " | " | 22.9 | 1.3 | 0.71 | 0.50 | 0.29 | 1.14 |
| 47 | " | " | 6.2 | 3.6 | 1.61 | 0.52 | 0.17 | 0.92 |
| 48 | " | " | 10.0 | 1.7 | 1.92 | 0.49 | 0.08 | 0.96 |
| 49 | " | " | 12.4 | 2.1 | 1.40 | 0.52 | 0.34 | 1.03 |

Williams (continued)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_Z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| | | | | | Summary Statistics (phi units) | | | |
| Z 50 | 4963 | 45 | 15.9 | 4.4 | 1.95 | 0.68 | 0.06 | 0.70 |
| 51 | " | " | 17.5 | 6.4 | 2.13 | 0.71 | -0.33 | 0.89 |
| 52 | " | " | 16.1 | 6.2 | 2.14 | 0.50 | 0.08 | 0.98 |
| 53 | " | " | 17.4 | 3.8 | 2.16 | 0.56 | -0.06 | 0.93 |
| 54 | " | " | 16.1 | 3.3 | 2.16 | 0.49 | 0.03 | 0.98 |
| 55 | " | " | 14.4 | 3.8 | 2.14 | 0.51 | 0.01 | 0.85 |
| Z 56 | 7450 | 47 | 19.6 | 3.2 | 2.12 | 0.46 | -0.01 | 1.01 |
| 57 | " | " | 14.8 | 3.0 | 2.16 | 0.43 | 0.00 | 1.03 |
| 58 | " | " | 10.3 | 5.5 | 2.18 | 0.42 | 0.05 | 0.98 |
| 59 | " | " | 14.4 | 3.8 | 2.09 | 0.47 | 0.00 | 1.05 |

## 5. Couldrey Transect (25.09.86)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_Z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| | | | | | Summary Statistics (phi units) | | | |
| C 1 | 185 | 4 | 3.9 | 0.0 | 1.98 | 0.37 | 0.09 | 0.97 |
| 2 | 278 | 3 | 4.6 | 0.0 | 1.90 | 0.36 | 0.11 | 0.97 |
| 3 | 370 | 5 | 5.0 | 0.0 | 2.09 | 0.34 | 0.13 | 1.02 |
| 4 | 463 | 7 | 3.3 | 0.0 | 2.08 | 0.32 | 0.05 | 0.96 |
| 5 | 556 | 9 | 2.1 | 0.8 | 2.05 | 0.35 | -0.01 | 0.90 |
| 6 | 648 | 11 | 1.6 | 0.5 | 2.11 | 0.32 | 0.12 | 0.91 |
| 7 | 741 | 13 | 3.4 | 0.8 | 2.13 | 0.48 | 0.08 | 0.86 |
| 8 | 833 | 15 | 4.1 | 1.2 | 1.30 | 0.43 | 0.18 | 0.95 |
| 9 | 926 | 17 | 5.5 | 0.9 | 1.82 | 0.48 | 0.28 | 0.99 |
| 10 | 1185 | 20 | 8.9 | 1.2 | 1.87 | 0.54 | 0.15 | 1.08 |
| 11 | 1444 | 23 | 7.3 | 0.7 | 1.66 | 0.48 | 0.21 | 0.96 |
| 12 | 1703 | 25 | 12.9 | 0.6 | 1.21 | 0.45 | 0.19 | 1.13 |
| 13 | 1963 | 26 | 14.6 | 0.8 | 1.65 | 0.46 | 0.25 | 1.00 |
| 14 | 2222 | 27 | 11.5 | 0.1 | 1.95 | 0.33 | 0.16 | 0.96 |
| 15 | 2481 | 28 | 13.8 | 1.1 | 1.97 | 0.30 | 0.06 | 0.97 |
| 16 | 2744 | 32 | 15.0 | 0.9 | 1.66 | 0.55 | 0.21 | 0.96 |
| 17 | 3000 | 34 | 14.4 | 1.8 | 1.49 | 0.38 | 0.28 | 1.05 |
| 18 | 3259 | 36 | 16.2 | 2.1 | 1.72 | 0.45 | 0.11 | 1.06 |
| 19 | 3519 | 38 | 12.7 | 1.2 | 1.68 | 0.56 | 0.20 | 1.12 |
| 20 | 3778 | 39 | 19.6 | 1.6 | 1.17 | 0.47 | 0.29 | 1.06 |
| 21 | 4037 | 42 | 15.8 | 2.3 | 1.30 | 0.43 | 0.16 | 1.16 |

Couldrey (continued)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics $M_Z$ | SD (phi units) | Sk | K |
|---|---|---|---|---|---|---|---|---|
| 22 | 4297 | 43 | 10.4 | 3.1 | 0.76 | 0.68 | 0.10 | 0.91 |
| 23 | 4555 | 43 | 11.9 | 4.6 | 1.74 | 0.47 | 0.11 | 1.06 |
| 24 | 4815 | 44 | 8.9 | 3.5 | 1.64 | 0.41 | 0.25 | 1.00 |
| 25 | 5074 | 44 | 6.1 | 5.2 | 1.29 | 0.48 | 0.18 | 0.95 |
| 26 | 5333 | 44 | 5.4 | 4.7 | 1.55 | 0.40 | 0.22 | 1.01 |
| 27 | 5593 | 44 | 7.5 | 6.2 | 2.13 | 0.31 | 0.12 | 0.97 |
| 28 | 5852 | 45 | 6.4 | 6.5 | 2.03 | 0.40 | 0.02 | 0.98 |
| 29 | 6112 | 45 | 6.6 | 6.0 | 2.06 | 0.39 | 0.11 | 0.91 |
| 30 | 6372 | 45 | 4.4 | 7.6 | 2.11 | 0.32 | 0.14 | 0.97 |

## 6. Walkway Transect (24.09.86)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics $M_Z$ Sa | $M_Z$ Sh | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|---|
| Y 51 | 185 | 5 | 2.3 | 0.7 | 1.82 | 1.84 | 0.37 | 0.08 | 0.92 |
| 52 | 278 | 5 | 2.5 | 0.7 | 1.89 | 1.87 | 0.37 | 0.12 | 0.98 |
| 53 | 370 | 6 | 2.7 | 0.7 | 1.83 | 1.85 | 0.39 | 0.15 | 1.01 |
| 54 | 463 | 7 | 4.3 | 0.8 | 1.92 | 1.90 | 0.33 | 0.13 | 0.96 |
| 55 | 556 | 10 | 3.4 | 1.1 | 2.07 | 2.04 | 0.33 | 0.16 | 1.00 |
| 56 | 648 | 12 | 2.8 | 0.7 | 1.97 | 2.01 | 0.39 | 0.13 | 0.90 |
| 57 | 741 | 15 | 2.2 | 1.2 | 2.04 | 2.05 | 0.35 | 0.15 | 0.95 |
| 58 | 833 | 16 | 2.5 | 1.8 | 1.96 | 1.93 | 0.40 | 0.09 | 0.99 |
| 59 | 926 | 20 | 2.3 | 1.3 | 1.94 | 2.00 | 0.35 | 0.16 | 0.95 |
| 60 | 1185 | 24 | 3.7 | 1.7 | 1.81 | 1.68 | 0.36 | 0.14 | 1.00 |
| 61 | 1444 | 26 | 4.9 | 1.6 | 1.39 | 1.37 | 0.50 | 0.21 | 1.02 |
| 62 | 1703 | 28 | 11.0 | - | 1.24 | 1.26 | 0.52 | 0.14 | 0.90 |
| 63 | 1963 | 30 | 6.5 | 1.1 | 1.32 | 1.33 | 0.46 | 0.20 | 1.00 |
| 64 | 2222 | 31 | 10.7 | 1.3 | 0.87 | 1.33 | 0.68 | 0.36 | 0.87 |
| 65 | 2481 | 31 | 16.7 | 1.4 | 1.43 | 1.32 | 0.44 | 0.30 | 1.04 |
| 66 | 2741 | 34 | 15.1 | 1.0 | 1.03 | 0.96 | 0.50 | 0.11 | 1.68 |
| 67 | 3000 | 36 | 17.4 | 2.6 | 0.89 | 0.88 | 0.45 | 0.31 | 1.53 |
| 68 | 3259 | 38 | 18.7 | 1.2 | 0.78 | 0.49 | 0.51 | 0.32 | 1.78 |
| 69 | 3519 | 40 | 15.2 | 1.2 | 0.51 | 0.40 | 0.53 | 0.22 | 1.57 |
| 70 | 3778 | 41 | 28.0 | 1.8 | 1.04 | 0.96 | 0.58 | 0.29 | 1.06 |
| 71 | 4037 | 45 | 12.7 | 0.9 | 0.13 | 0.05 | 0.46 | 0.23 | 1.36 |
| 72 | 4297 | 45 | 16.0 | 2.8 | 1.73 | 1.64 | 0.49 | 0.17 | 0.97 |
| 73 | 4555 | 47 | 9.0 | 4.3 | 2.02 | 1.97 | 0.44 | 0.14 | 0.93 |

Walkway (continued)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics $M_Z$ Sa | $M_Z$ Sh | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|---|
| Y74 | 4815 | 46 | 11.3 | 10.3 | 2.22 | 2.15 | 0.45 | 0.07 | 0.85 |
| 75 | 5074 | 46 | 11.1 | 8.5 | 2.23 | 2.19 | 0.41 | 0.10 | 0.95 |
| 76 | 5333 | 46 | 7.9 | 5.1 | 2.17 | 2.18 | 0.42 | 0.11 | 1.02 |
| 77 | 5593 | 49 | 10.9 | 3.8 | 2.13 | 1.99 | 0.59 | -0.07 | 0.90 |
| 78 | 5852 | 50 | 14.4 | 12.1 | 2.21 | 2.10 | 0.52 | -0.07 | 0.95 |
| 79 | 6112 | 51 | 6.5 | 10.0 | 2.09 | 1.87 | 0.51 | 0.04 | 0.90 |

## 7. Gravel Transect (04.11.86)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics $M_Z$ | SD (phi units) | Sk | K |
|---|---|---|---|---|---|---|---|---|
| G 1 | 185 | 4 | 4.2 | 2.2 | 2.08 | 0.37 | -0.19 | 0.99 |
| 2 | 278 | 5 | 3.9 | 2.9 | 2.13 | 0.34 | -0.18 | 1.23 |
| 3 | 370 | 6 | 2.9 | 2.2 | 2.02 | 0.47 | -0.21 | 1.05 |
| 4 | 463 | 8 | 3.6 | 2.7 | 2.17 | 0.34 | -0.11 | 1.35 |
| 5 | 556 | 10 | 3.2 | 3.0 | 2.21 | 0.32 | -0.06 | 1.41 |
| 6 | 648 | 13 | 3.6 | 2.6 | 2.23 | 0.31 | -0.03 | 1.43 |
| 7 | 741 | 15 | 4.3 | 1.6 | 2.15 | 0.39 | -0.09 | 1.30 |
| 8 | 833 | 17 | 5.8 | 2.1 | 1.96 | 0.51 | -0.06 | 0.99 |
| 9 | 926 | 18 | 3.2 | 2.1 | 1.87 | 0.53 | 0.04 | 0.97 |
| 10 | 1185 | 23 | 4.2 | 2.4 | 1.48 | 0.50 | 0.25 | 1.05 |
| 11 | 1444 | 26 | 8.8 | - | 1.47 | 0.50 | 0.20 | 1.06 |
| 12 | 1703 | 28 | 12.7 | 1.9 | 1.29 | 0.55 | 0.19 | 1.23 |
| 13 | 1963 | 31 | 4.7 | 3.8 | 1.18 | 0.62 | 0.11 | 1.17 |
| 14 | 2222 | 31 | 7.9 | 3.3 | 1.53 | 0.52 | 0.27 | 0.99 |
| 15 | 2481 | 33 | 6.7 | 3.0 | 1.15 | 0.49 | 0.19 | 1.13 |
| 16 | 2741 | 35 | 10.5 | 2.6 | 1.00 | 0.47 | 0.45 | 1.17 |
| 17 | 3000 | 37 | 12.9 | 2.8 | 0.90 | 0.48 | 0.34 | 1.90 |
| 18 | 3259 | 38 | 18.0 | 3.8 | 0.74 | 0.53 | 0.05 | 1.86 |
| 19 | 3519 | 41 | 23.6 | 2.9 | 0.36 | 0.72 | -0.11 | 1.34 |
| 20 | 3778 | 43 | 12.0 | 5.1 | 2.42 | 0.47 | 0.06 | 1.33 |
| 21 | 4037 | 44 | 13.7 | 14.7 | 2.60 | 0.40 | -0.01 | 1.00 |
| 22 | 4297 | 47 | 8.9 | 13.7 | 2.66 | 0.38 | -0.08 | 1.27 |
| 23 | 4555 | 46 | 14.8 | 11.8 | 2.25 | 0.54 | -0.13 | 1.65 |

## 8. Grain-Size Analysis of Dune Sands (from Schofield, 1970)

| Sample Reference | Grid Reference NZMS 1 (N29) | Median Diameter (mm) | (phi) |
|---|---|---|---|
| N29 102 | 148461 | 0.23 | 2.25 |
| 107 | 235350 | 0.23 | 2.25 |
| 112 | 166431 | 0.24 | 2.00 |
| 116 | 160428 | 0.27 | 2.00 |
| 119 | 198378 | 0.26 | 2.00 |
| 122 | 203383 | 0.25 | 2.00 |

## 9. Pakiri Beach Samples (18.07.87)

Samples from mean high water mark (a) and low water mark (b).

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | Summary Statistics $M_Z$ | SD (phi units) | Sk | K |
|---|---|---|---|---|---|---|---|---|
| 1a | - | - | - | - | 1.17 | 0.57 | 0.23 | 0.82 |
| b | - | - | - | - | 1.65 | 0.46 | -0.03 | 1.02 |
| 2a | - | - | - | - | 1.18 | 0.61 | 0.12 | 0.83 |
| b | - | - | - | - | 1.33 | 0.62 | 0.04 | 0.81 |
| 3a | - | - | - | - | 1.61 | 0.48 | 0.00 | 0.86 |
| b | - | - | - | - | 1.74 | 0.43 | 0.02 | 0.93 |
| 4a | - | - | - | - | 1.66 | 0.39 | 0.11 | 0.91 |
| b | - | - | - | - | 1.81 | 0.37 | 0.05 | 0.85 |
| 5a | - | - | - | - | 1.70 | 0.40 | 0.10 | 0.87 |
| b | - | - | - | - | 1.70 | 0.38 | 0.06 | 0.89 |
| 6a | - | - | - | - | 1.79 | 0.38 | 0.05 | 0.82 |
| b | - | - | - | - | 1.75 | 0.40 | 0.08 | 0.86 |
| 7a | - | - | - | - | 1.74 | 0.35 | 0.14 | 0.90 |
| b | - | - | - | - | 1.67 | 0.38 | 0.11 | 0.90 |
| 8a | - | - | - | - | 1.71 | 0.40 | 0.04 | 0.87 |
| b | - | - | - | - | 1.71 | 0.41 | 0.02 | 0.88 |
| 9a | - | - | - | - | 1.74 | 0.37 | 0.09 | 0.87 |
| b | - | - | - | - | 1.65 | 0.40 | 0.07 | 0.87 |
| 10a | - | - | - | - | 1.69 | 0.39 | 0.06 | 0.91 |
| b | - | - | - | - | 1.80 | 0.35 | 0.09 | 0.91 |
| 11a | - | - | - | - | 1.74 | 0.40 | 0.03 | 0.90 |
| b | - | - | - | - | 1.78 | 0.34 | 0.10 | 0.90 |
| 12a | - | - | - | - | 1.76 | 0.37 | 0.09 | 0.84 |
| b | - | - | - | - | 1.64 | 0.44 | 0.00 | 0.85 |

Beach Samples (continued)

| Sample Ref. | Distance Offshore (m) | Water Depth (m) | % Carbs. | % Fines | $M_z$ | SD | Sk | K |
|---|---|---|---|---|---|---|---|---|
| | | | | | Summary Statistics (phi units) | | | |
| 13a | - | - | - | - | 1.60 | 0.42 | 0.02 | 0.87 |
| b | - | - | - | - | 1.65 | 0.39 | 0.08 | 0.89 |
| 14a | - | - | - | - | 1.65 | 0.37 | 0.08 | 0.88 |
| b | - | - | - | - | 1.62 | 0.42 | 0.03 | 0.83 |
| 15a | - | - | - | - | 1.72 | 0.40 | 0.07 | 0.90 |
| b | - | - | - | - | 1.73 | 0.42 | 0.03 | 0.87 |
| 16a | - | - | - | - | 1.71 | 0.41 | 0.00 | 0.92 |
| b | - | - | - | - | 1.63 | 0.43 | 0.04 | 0.82 |
| 17a | - | - | - | - | 1.69 | 0.40 | 0.10 | 0.91 |
| b | - | - | - | - | 1.69 | 0.41 | 0.09 | 0.91 |
| 18a | - | - | - | - | 1.78 | 0.39 | 0.01 | 0.86 |
| b | - | - | - | - | 1.61 | 0.45 | 0.05 | 0.86 |
| 19a | - | - | - | - | 1.68 | 0.42 | 0.11 | 0.92 |
| b | - | - | - | - | 1.63 | 0.40 | 0.10 | 0.89 |
| 20a | - | - | - | - | 1.83 | 0.36 | 0.10 | 0.90 |
| b | - | - | - | - | 1.66 | 0.47 | 0.01 | 0.87 |
| 21a | - | - | - | - | 1.82 | 0.37 | 0.04 | 0.86 |
| b | - | - | - | - | 1.83 | 0.38 | 0.08 | 0.90 |
| 22a | - | - | - | - | 1.81 | 0.40 | 0.11 | 0.84 |
| 23a | - | - | - | - | 1.78 | 0.37 | 0.11 | 0.89 |

# Appendix F

## METHOD OF BENTHOS SAMPLING

The sampling technique employed involved trawling using a basket dredge. Stations were located according to the method described in Appendix B, except that to ensure multiple samples were obtained from approximately the same location stations were marked by a moored dan buoy. Trawls were in an alongshore direction commencing at the dan buoy. Samples were obtained using a basket dredge, towed across the seabed for 60 s at approximately 2.5 kts. Given that the width of the basket dredge is 0.55 m, the area of seabed sampled during each trawl is therefore 55 $m^2$.

The technique employed has a number of limitations. Diver observation of the basket dredge under tow indicates penetration of the seabed can be spasmodic. Penetration is dependent upon the bulk characteristics of the sediments, with maximum penetration (of about 10 cm) in coarse sands and fine gravels. There is thus likely to be a bias in the results towards the epifauna and infauna that inhabit the upper benthic boundary layer. For example, it is known from strandline faunas and SCUBA diver collections that the bivalve Dosinia anus is present across the lower shoreface. Yet live specimens were rarely recovered by the dredge, and these tended to be juveniles, which might be expected to live closer to the surface. Adult specimens may not have been present at the stations sampled, but more likely lived beyond the penetrative depth of the dredge. The results presented in this chapter are therefore likely to provide relatively poor estimates of the epifauna that live deeper than 5 to 10 cm.

The dredge employed was constructed with 1 cm diameter mesh, so that in practice only the benthic macrofauna was sampled. Practical difficulties were encountered where the volume of coarse sediment was high, or the number of live benthos abundant. In these cases the dredge might fill rapidly. Trial trawls of 15 and 30 s yielded maximum dredge loads of the gastropod **Umbonium zelandicum** in water depths of 3 to 5 m, in the vicinity of the crest of the alongshore bar. While this species is present in tremendous numbers its relative abundance compared with other species is probably in part due to the ease with which it is dredged. This species lives lightly buried in the surface few centimeters of relatively uncompacted sand, in shallow water depths at which the dredge is probably most efficient. In terms of its vulnerability to sampling this species is the antithesis of **Dosinia anus**.

Apart from the physical difficulties of capture the macrobenthos present some specific sampling problems. Benthic communities may not be evenly distributed within a habitat, and are known to fluctuate in distribution and abundance over time. While individual species were usually present in (multiple) samples from the same station, the relative abundance in each sample sometimes varied by orders of magnitude. This is particularly true of species such as **Umbonium zelandicum**, that occupy a highly localised habitat. With the method employed three dredge hauls at each station are considered the minimum necessary to permit an estimate of the variance. And as discussed previously, the results will in part reflect the substrate type and the relative areas of seabed sampled. Except for the deep middle continental shelf stations all stations were dredged for 60 s. The mid shelf stations were dredged for 120 s because of the paucity of live mollusca present.

# Appendix G

## SYSTEMATICS AND RELATIVE ABUNDANCE

## OF LIVING BIVALVES AND GASTROPODS DREDGED FROM PAKIRI BAY

| | Abundance |
|---|---|
| PHYLUM Mollusca, CLASS Bivalvia | |
| ORDER Nuculoida | |
| FAMILY Nuculidae, GENUS Nucula | |
| - **Nucula hartvigiana** (Powell, p.356) | Common |
| ORDER Mytiloida | |
| FAMILY Pinnidae, GENUS Atrina | |
| - **Atrina zelandica** (Powell, p.375) | Rare |
| FAMILY Mytilidae, GENUS Modiolarca | |
| - **Modiolarca impacta** | Rare |
| ORDER Pterioida | |
| FAMILY Pectinidae, GENUS Pecten | |
| - **Pecten novazelandiae** (Powell, p.377) | Common |
| GENUS Chlamys | Rare |
| ORDER Veneroida | |
| FAMILY Lucinidae, GENUS Divaricella | |
| - **Divaricella (Divalucina) huttoniana** | Rare |
| FAMILY Ungulinidae, GENUS Diplodonta | |
| - **Diplodonta (Zemysina) globus** (Powell, p.388) | Rare |
| FAMILY Carditidae, GENUS Venericardia | |
| - **Venericardia purpurata** (Powell, P.406) | Common |
| FAMILY Cardiidae, GENUS Nemocardium | |
| - **Nemocardium (Pratulum) pulchellum** (p.413) | Rare |
| FAMILY Mactridae, GENUS Longimactra | |
| - **Longimactra elongata** (Powell, p. 414) | Rare |
| GENUS Scalpomactra | |
| - **Scalpomactra scalpellum** (Powell, p.414) | Rare |
| GENUS Zenatia | |
| - **Zenatia acinaces** (Powell, p.414) | Rare |
| FAMILY Psammobiidae, GENUS Gari | |
| - **Gari lineolata** (Powell, p.418) | Rare |
| - **Gari strangeri** (Powell, p.418) | Rare |

CLASS Bivalvia, ORDER Veneroida (continued)

| | |
|---|---|
| FAMILY Veneridae, GENUS Dosinia | |
| - **Dosinia (Phacosoma) subrosea** (p.423) | Rare |
| - **Dosinia (Austrodosinia) anus** (p.423) | Rare |
| GENUS Tawera | |
| - **Tawera spissa** (Powell, p.424) | Abundant |
| FAMILY Veneridae (continued) | |
| GENUS Notocallista | |
| - **Notocallista (Striacallista) multistriata** | Common |
| GENUS Bassina | |
| - **Bassina yatei** (Powell, p.427) | Rare |

ORDER Myoida

| | |
|---|---|
| FAMILY Corbullidae, GENUS Corbula | |
| - **Corbula (Anisocorbula) zelandica** (p.428) | Common |

ORDER Pholadomyoida

| | |
|---|---|
| FAMILY Myochamidae, GENUS Myodora | |
| - **Myadora striata** (Powell, p.432) | Common |

<u>CLASS Gastropoda</u>

ORDER Archaeogastropoda

| | |
|---|---|
| FAMILY Fissurellidae, GENUS Emarginula | |
| - **Emarginula striatula** (Powell, p.38) | Scarce |
| FAMILY Trochidae, GENUS Umbonium | |
| - **Umbonium (Zethalia) zelandicum** (p.65) | Abundant |

ORDER Mesogastropoda

| | |
|---|---|
| FAMILY Turritellidae, GENUS Maoricolpus | |
| - **Maoricolpis roseus roseus** (Powell, p.125) | Scarce |
| GENUS Zeacolpus | |
| - **Zeacolpus (Stiracolpus) pagoda pagoda** | Scarce |
| FAMILY Struthiolariidae, GENUS Struthiolaria | |
| - **Struthiolaria papulosa** (Powell, p.142) | Common |
| - **Struthiolaria (Pelicaria) vermis vermis** | Scarce |
| FAMILY Calyptraeidae, GENUS Sigapatella | |
| - **Sigapatella novaezelandiae** (Powell, p.148) | Scarce |
| GENUS Zegalerus | |
| - **Zegalerus tenuis** | Scarce |
| FAMILY Xenophoridae, GENUS Xenophora | |
| - **Xenophora neozelandica** | Scarce |
| FAMILY Naticidae, GENUS Tanea | |
| - **Tanea zelandica** (Powell, p.154) | Common |
| FAMILY Cassidae, GENUS Xenophalium | |
| - **Xenophalium pyrum pyrum** (Powell, p.159) | Scarce |

CLASS Gastropoda (continued)

ORDER Neogastropoda

| | |
|---|---|
| FAMILY Muricidae, GENUS Poirieria | |
| - **Poirieria zelandica** (Powell, p.170) | Scarce |
| FAMILY Buccinidae, GENUS Cominella | |
| - **Cominella adspersa** (Powell, p.192) | Common |
| - **Cominella (Josepha) guoyana guoyana** | Common |
| - **Cominella (Josepha) virgata virgata** | Scarce |
| GENUS Austrofusus | |
| - **Austrofusus glans** | Common |
| GENUS Penion | |
| - **Penion dilatatus dilatatus** | Common |
| FAMILY Fasciolariidae, GENUS Glaphyrina | |
| - **Glaphyrina vulpicolor** | Rare |
| FAMILY Olividae, GENUS Amalda | |
| - **Amalda australis** (Powell, p.208) | Common |
| - **Amalda mucronata** | Rare |
| FAMILY Volutidae, GENUS Alcithoe | |
| - **Aecithoe arabica** (Powell, p.211) | Scarce |

# Appendix H

## SPECIES COMPOSITION AND ABUNDANCE
## INITIAL SURVEYS - ROCKY COAST AND PAKIRI BAY

### A. Cape Rodney Transect

| Species | Station / Depth (1) 40 metres Dead | (1) 40 metres Live | (2) 50 metres Dead | (2) 50 metres Live |
|---|---|---|---|---|
| BIVALVIA | | | | |
| Atrina zelandica ............ | - | - | - | - |
| Corbula zelandica ........... | 25 | - | - | 35 |
| Divaricella huttoniana ...... | - | - | - | - |
| Dosinia anus ................ | 4 | - | - | - |
| GENUS Chlamys ............... | 29 | - | 118 | - |
| Gari strangeri .............. | 8 | - | - | - |
| Glycymeris laticostata ...... | 38 | - | - | - |
| Myadora striata ............. | 7 | - | - | - |
| Nemocardium pulchellum ...... | - | - | 22 | - |
| Notocallista multistriata ... | - | - | 35 | 2 |
| Pecten novazelandiae ........ | 4 | - | 3 | - |
| Tellina charlottae .......... | - | - | - | - |
| Tawera spissa ............... | 10 | - | 50 | - |
| Venericardia purpurata ...... | 8 | - | 24 | - |
| Zearcopagia disculus ........ | 12 | - | 20 | - |
| Zenatia acinaces ............ | - | - | - | - |
| GASTROPODA | | | | |
| Amalda australis ............ | - | - | - | - |
| Cominella adspersa .......... | - | - | - | - |
| Struthiolaria papulosa ...... | 2 | - | - | - |
| Umbonium zelandicum ......... | - | - | - | - |
| Zegalerus tenuis ............ | - | - | - | - |
| ECHINODERMATA | | | | |
| Fellasten zelandiae ......... | - | - | - | - |
| Echinocardiun cordatum ...... | - | - | - | - |
| BRACHIOPODA | | | | |
| Waltonia inconspicua ........ | - | - | 2 | - |

Cape Rodney transect (continued)

| Species | (1) 40 metres Dead | (1) 40 metres Live | (2) 50 metres Dead | (2) 50 metres Live |
|---|---|---|---|---|
| **Solitary Corals** | | | | |
| Flabellum rubrum ............ | - | - | 40 | - |
| Culicia rubeola ............. | - | - | - | - |
| Proportion of unidentified shell residue in sample ........ | 0.73 | | 0.66 | |
| Substrate Type ................. | Carbonate gravels, with less than 10% coarse sand and gravel. | | | |

## B. Goat Island Transect

| Species | (1) 24m D | (1) 24m L | (2) 34m D | (2) 34m L | (3) 40m D | (3) 40m L | (4) 47m D | (4) 47m L | (5) 56m D | (5) 56m L |
|---|---|---|---|---|---|---|---|---|---|---|
| **BIVALVIA** | | | | | | | | | | |
| Atrina zelandica ...... | 1 | - | - | - | - | - | 2 | - | - | - |
| Corbula zelandica ..... | 4 | - | - | - | 55 | - | 25 | - | 83 | - |
| Divaricella huttoniana | 1 | - | - | - | 18 | - | 8 | - | - | - |
| Dosinia anus .......... | - | - | - | - | 2 | - | - | - | - | - |
| GENUS Chlamys ......... | - | - | - | - | 112 | - | 46 | - | 42 | - |
| Gari strangeri ........ | - | - | - | - | - | - | - | - | - | - |
| Glycymeris laticostata | 25 | - | 6 | - | 12 | - | 20 | - | - | - |
| Myadora striata ....... | - | - | - | - | - | - | - | - | - | - |
| Nemocardium pulchellum | - | - | - | - | 8 | - | - | - | 28 | - |
| Notocallista multistriata | - | - | - | - | 56 | - | 5 | - | 58 | - |
| Pecten novazelandiae .. | 10 | - | - | - | 14 | - | 14 | - | 4 | - |
| Tellina charlottae .... | - | - | - | - | - | - | - | - | - | - |
| Tawera spissa ......... | 140 | - | 20 | - | 150 | - | 114 | - | 310 | - |
| Venericardia purpurata | - | - | 8 | - | 60 | - | 15 | - | 85 | - |
| Zearcopagia disculus .. | - | - | - | - | - | - | - | - | - | - |
| Zenatia acinaces ...... | - | - | - | - | 4 | - | 2 | - | 3 | - |

Goat Island Transect (continued)

| Species | (1) 24m D | (1) 24m L | (2) 34m D | (2) 34m L | (3) 40m D | (3) 40m L | (4) 47m D | (4) 47m L | (5) 56m D | (5) 56m L |
|---|---|---|---|---|---|---|---|---|---|---|
| GASTROPODA | | | | | | | | | | |
| Amalda australis ...... | - | - | - | - | 1 | - | - | - | 1 | - |
| Cominella adspersa .... | - | - | - | - | - | - | - | - | - | - |
| Struthiolaria papulosa | - | - | 1 | - | 8 | - | - | - | - | - |
| Umbonium zelandicum ... | - | - | - | - | - | - | - | - | - | - |
| Zegalerus tenuis ...... | - | - | - | - | 55 | - | 15 | - | 45 | - |
| ECHINODERMATA | | | | | | | | | | |
| Fellasten zelandiae ... | - | - | - | - | - | - | - | - | - | - |
| Echinocardium cordatum | - | - | - | - | - | - | - | - | - | - |
| BRACHIOPODA | | | | | | | | | | |
| Terebratella inconspicua | - | - | - | - | - | - | - | - | - | - |
| Solitary Corals | | | | | | | | | | |
| Flabellum rubrum ...... | - | - | - | - | 12 | - | 20 | - | 4 | - |
| Culicia rubeola ....... | - | - | - | - | - | - | - | - | 6 | - |
| Proportion of unidentified shell residue in sample | 0.70 | | 0.55 | | 0.66 | | 0.75 | | 0.67 | |
| Substrate ............... | Carbonate gravels, with less than 20 % coarse sand and terrigenous gravel | | | | | | | | | |

C. Couldrey Transect, Pakiri Bay

| Species | Station / Depth | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | (1) 10m | | (2) 15m | | (3) 20m | | (4) 30m | | (5) 40m | |
| | D | L | D | L | D | L | D | L | D | L |
| BIVALVIA | | | | | | | | | | |
| Atrina zelandica ...... | - | - | - | - | - | - | 3 | - | - | - |
| Corbula zelandica ..... | - | - | - | - | - | - | - | - | - | - |
| Divaricella huttoniana | - | - | - | - | - | - | - | - | - | - |
| Dosinia anus .......... | - | - | 2 | 1 | - | - | - | - | - | - |
| GENUS Chlamys ......... | - | - | - | - | - | - | - | - | - | - |
| Gari strangeri ........ | - | - | - | - | - | - | - | - | - | - |
| Glycymeris laticostata | - | - | - | - | - | - | - | - | - | - |
| Myadora striata ....... | - | - | 4 | 5 | - | - | - | - | - | - |
| Nemocardium pulchellum | - | - | - | - | - | - | - | - | - | - |
| Notocallista multistriata | - | - | - | - | - | - | - | - | - | - |
| Pecten novazelandiae .. | - | - | - | - | - | - | 1 | - | - | - |
| Tellina charlottae .... | - | - | - | - | - | - | - | - | - | - |
| Tawera spissa ......... | - | - | 2 | 4 | 6 | - | 40 | 288 | - | - |
| Venericardia purpurata | - | - | - | - | - | - | - | - | - | 9 |
| Zearcopagia disculus .. | - | - | - | - | - | - | - | - | - | - |
| Zenatia acinaces ...... | - | - | - | - | 3 | - | - | - | - | - |
| GASTROPODA | | | | | | | | | | |
| Amalda australis ...... | - | - | 2 | 14 | 17 | 10 | 8 | - | - | - |
| Cominella adspersa .... | - | - | 2 | 5 | 3 | 9 | - | 8 | - | - |
| Struthiolaria papulosa | 1 | - | 15 | - | 92 | 6 | 5 | 16 | - | - |
| Umbonium zelandicum ... | - | - | 19 | - | 4 | - | - | - | - | - |
| Zegalerus tenuis ...... | - | - | - | - | - | - | - | - | - | - |
| ECHINODERMATA | | | | | | | | | | |
| Fellasten zelandiae ... | - | 3 | - | - | - | - | - | - | - | - |
| Echinocardiun australe | - | - | - | - | - | 10 | - | 4 | - | - |
| BRACHIOPODA | | | | | | | | | | |
| Terebratella inconspicua | - | - | - | - | - | - | - | - | - | - |
| Solitary Corals | | | | | | | | | | |
| Flabellum rubrum ...... | - | - | - | - | - | - | - | - | - | - |
| Culicia rubeola ....... | - | - | - | - | - | - | - | - | - | - |
| Proportion of unidentified shell residue in sample | 0.00 | | 0.12 | | 0.21 | | 0.34 | | 0.63 | |
| Substrate Type ............ | Fine Sand | | Medium Sand | | Medium Sand | | Coarse Sand | | Carb Gravel | |

D. Te Arai Transect, Pakiri Bay

| Species | Station / Depth (1) 20m Dead | (1) 20m Live | (2) 30m Dead | (2) 30m Live | (3) 40m Dead | (3) 40m Live |
|---|---|---|---|---|---|---|
| BIVALVIA | | | | | | |
| Atrina zelandica ........ | - | - | - | - | - | - |
| Corbula zelandica ....... | - | - | - | - | - | - |
| Divaricella huttoniana .. | - | - | - | - | - | - |
| Dosinia anus ........... | 1 | - | - | - | - | - |
| GENUS Chlamys ........... | - | - | - | - | 38 | - |
| Gari strangeri .......... | - | - | - | - | - | - |
| Glycymeris laticostata .. | - | - | - | - | - | - |
| Myadora striata ......... | - | - | - | - | - | - |
| Nemocardium pulchellum .. | - | - | - | - | - | - |
| Notocallista multistriata | - | - | - | - | - | - |
| Pecten novazelandiae .... | - | - | - | - | - | - |
| Tellina charlottae ...... | 23 | - | - | - | - | - |
| Tawera spissa ........... | 30 | - | - | - | 4 | - |
| Venericardia purpurata .. | - | - | 5 | 2 | 4 | 5 |
| Zearcopagia disculus .... | - | - | - | - | - | - |
| Zenatia acinaces ........ | - | - | - | - | - | - |
| GASTROPODA | | | | | | |
| Amalda australis ........ | 17 | 16 | - | - | 3 | - |
| Cominella adspersa ...... | 7 | 7 | - | - | - | - |
| Struthiolaria papulosa .. | 23 | - | - | - | - | - |
| Umbonium zelandicum ..... | 7 | - | - | - | - | - |
| Zegalerus tenuis ........ | - | - | - | - | - | - |
| ECHINODERMATA | | | | | | |
| Fellasten zelandiae ..... | - | - | - | - | - | - |
| Echinocardiun cordatum .. | - | - | - | - | - | 2 |
| BRACHIOPODA | | | | | | |
| Terebratella inconspicua | - | - | - | - | - | - |
| Solitary Corals | | | | | | |
| Flabellum rubrum ........ | - | - | - | - | - | - |
| Culicia rubeola ......... | - | - | - | - | - | - |
| Proportion of unidentified shell residue in sample .... | 0.17 | | 0.29 | | 0.75 | |
| Substrate ................. | Medium Sand | | Coarse Sand | | Carb. Gravel & Coarse Sand | |

# Appendix I

## OFFSHORE ECHOSOUND SURVEY TECHNIQUE AND SOURCES OF ERROR

### a) R.V. Proteus Echosound Surveys

The techniques of vessel navigation and location across the transects are the same as those described in Appendix B. Survey runs were undertaken on calm days at or close to high tide, such that the 11 m Research Vessel Proteus was usually able to commence the survey run landward of the alongshore bar, in water depths of about 3 m. The distance of the vessel from the seaward shoremarker, which was located atop the foredune scarp, was determined at regular intervals using the radar rangefinder. Distances were determined to an accuracy of +/- 18.5 m every 92.5 or 185 m. The continuous paper recording was marked electronically at the moment the rangefinder distance was confirmed.

Depth recordings derived by this method are not corrected to chart datum or mean sea level. True depths, given a maximum tidal range of about 3.0 m and atmospheric pressure effects of about 30 cm, are within 1.5 m of the plotted depths for this type of survey. However, since all R.V. Proteus surveys were conducted at or within one hour either side of high water, all resulting depths are approximately 0.5 to 1.0 m shallower than plotted. In practice, all depths are correct relative to each other, since sea level can be assummed to be constant during the 12 to 15 minute survey period.

The surveys conducted in November 1978 and July 1984 for the Marine Division of the Ministry of Transport involved a different method of position fixing. The distance of the vessel from shore datum was determined trigonometrically by a shore party using a theodolite. The technique is essentially the same as the one described for the following Avon surveys.

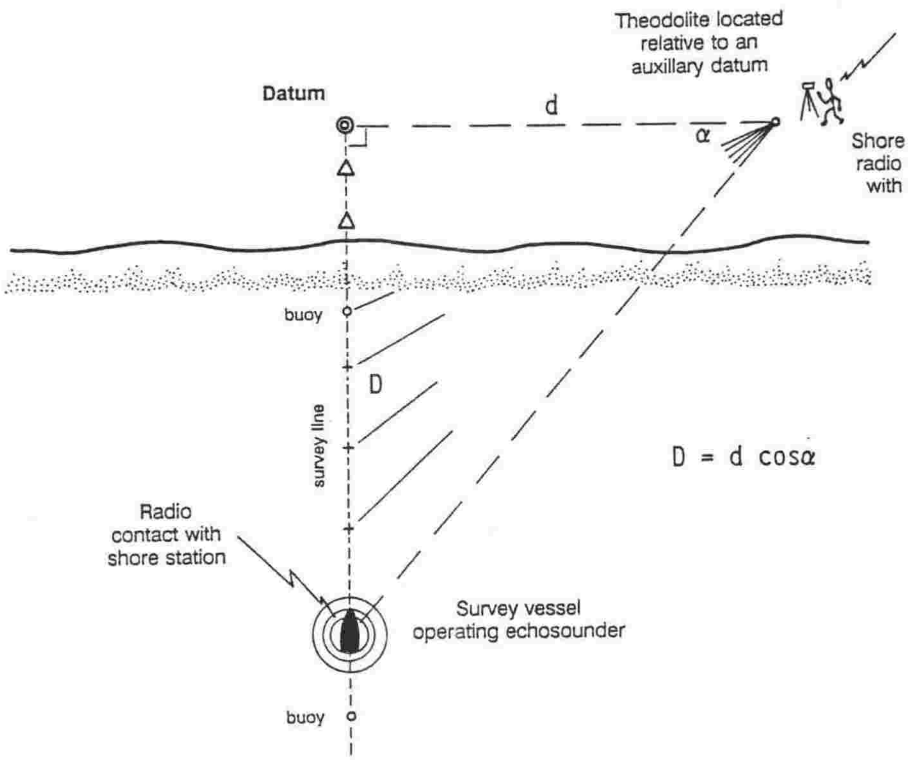
**b) Avon Echosound Surveys**

The technique employed during the offshore surveys involved deployment of a FE-450 Furuno echosounder mounted on a 2.8 m hard-hulled Avon inflatable, powered by a 25 h.p. outboard motor. The basic method employed is similar to that described by Goetsch and Smith (1978). A single survey is comprised of both offshore vessel and beach surveys, involving a minimum of two shore personnel. The offshore segment is surveyed between two (or preferably more) buoys placed beforehand along the transect line, by reference to the aligned shore markers. The horizontal distance of the boat from the shore datum is determined using a theodolite placed over an auxiliary datum located at right angles to the transect line (Figure 1 a). The helmsperson and theodolite observer communicate by two-way radio. At regular intervals (usually 30 s) a 'fix' is determined by the instantaneous determination of angle '$\alpha$' and the marking of the echosound trace. When the vessel reaches the inshore buoy the final fix is made. The shore party then survey across the beach to the buoy using either a theodolite or dumpy level, culminating the shore survey with the staff precisely beside the buoy weight. The difference in elevation at this point, between echosound and beach surveys, is determined and all echosounding levels corrected accordingly. Ideally the survey is repeated a number of times and average values calculated. The echosound survey is completed at high tide and the beach survey on the falling tide, to provide a maximum overlap.

The accuracy of this technique is largely dependent upon marine conditions. Along the Pakiri Coast ideal conditions occur about one day in 20. Replicate surveys, suggest the error margin is approximately +/- 0.5 m, somewhat less than the calculated potential error of 0.9 m.

Variations of this method were attempted when lack of personnel or equipment necessitated, although none were considered as reliable. An attempt to survey a line of deployed buoys along the transects was successful for a short period, until they were destroyed by a

a.




b.

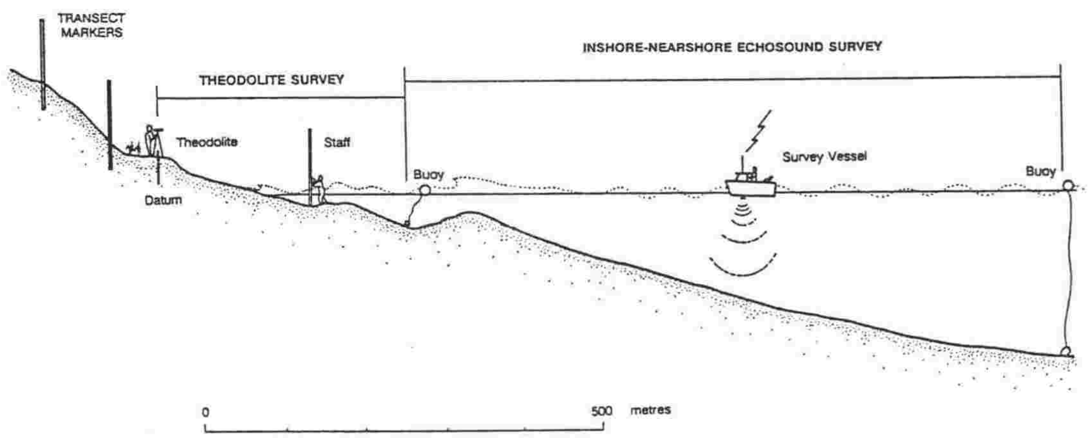



**Figure 1** Beach-echosound survey technique employing shore party and theodolite (a) and beach-echosound surveys using radar rangefinder and optional shore party (b) (after Goetsch and Smith, 1978).

storm. A promising method involved the installation of a series of pairs of pre-surveyed shoremarkers, that when aligned located the vessel a certain distance offshore along the transect. Both of these methods have the disadvantage of providing relatively few surveyed locations along the transect, but nevertheless provided usable bathymetric data with a minimum of preparation. With both methods a buoy was deployed at the end of the survey run (Figure 1 b). At low tide the datum to buoy segment of the transect was surveyed to allow the offshore survey levels to be reduced relative to datum.

## Sources of Error

Regardless of the technique employed the results are subject to identifiable sources of error. Errors associated with echosound surveys have been reviewed by Irwin (1977) and Goetsch and Smith (1978). They may result from changes in the environment, involving water salinity, temperature and pressure, which may effect the velocity of sound in water, and changes in water depth due to sediment movement. Sea water parameters are measured daily in the study area at the Leigh Marine Laboratory, and an extensive data set from 1967 has been analyzed (see Evans and Ballantine, 1986). According to the tables calculated by Mathews (1939) the error due to annual variations in salinity (1.0 ‰) and temperature (8°C) during the Pakiri investigation is small, estimated as +/- 10 cm. Taking the mean annual variation in temperature and salinity at Leigh involves a departure from the assumed velocity of sound (1500 m $s^{-1}$) of 12 m $s^{-1}$, giving a potential error of +/- 1.5 percent. In the depth ranges involved (0-50 m) the effects of variations in pressure are insignificant.

The surveys were inevitably carried out during very calm conditions, when breaking wave height was between 0.0 and 0.5 m. Sediment movement, therefore, was assummed to be insignificant, particularly during the process of linking the offshore echosound surveys and beach instrument survey. Similarly, water level and water conditions were assummed to be constant during the relatively short duration of the Avon surveys (<10 minutes) which were always conducted within one hour either side of high water. Periodic calibration of the instrument reading against a survey staff indicated instrument errors were minimal.

Operational errors are considered to be of greater significance. In particular, errors related to the procedure by which the offshore echosound levels are related to the shore datum, and the navigation of the Avon along the transect. The former procedure assumes the final depth recorded on the echosound trace corresponds to the position of the final theodolite reading. Repeating the survey three times on two separate occasions indicates an error margin of +/- 20 cm using this method. This error is most probably due to disturbance of the weight, to which the buoy is attached, between offshore echosound and onshore theodolite surveys. A more accurate method involves the observation of a staff held against the side of the boat at the end of the offshore survey, although this was seldom an option available.

The permanent shoremarkers were successful in demarcating the transect line offshore. However, alongshore currents close to shore would at times cause deviations in the vessels path of several metres from the transect line. Irwin (1977) has calculated the depth recording error due to various positional errors across surfaces of known slope. Using these calculations the maximum error that might be expected if the vessel stayed within 10 m of the survey line is +/- 0.30 m. This error will not be constant across the transect, since departures from the survey line will be greatest at either end of the transect. This is due to the difficulty in aligning the shoremarkers when far offshore, and to current action close to the coast. For this reason Avon surveys generally commenced less than 2500 m offshore, in water depths of approximately 30 m.

Table 1 summarizes the estimates of errors associated with each procedure. An allowance has also been made for the effect of bedforms. This analysis applies to surveys linked to shore datums, that were surveyed with the intention of deriving a time series data set of seabed elevations and distances offshore. While it was not possible to remove all errors it was found that confidence in the results could be greatly increased by repeat surveys.

**Table 2 Summary of Sources of Error Involved in Echosound Surveys**

| Variables | Maximum Variation +/- (cm) |
|---|---|
| Echosounder | |
| - salinity, temperature of water | 10 |
| Tidal variation | 10 |
| Seabed variations (ripples) | 20 |
| Positional errors | |
| - transfer of reduced level | 20 |
| - location on transect | 30 |
| TOTAL POTENTIAL ERROR | +/- 90 |

# Appendix J

## SPECIFICATIONS OF THE KLEIN SIDE-SCAN SONAR SYSTEM AND ORE SUB-BOTTOM PROFILER AS DEPLOYED AT PAKIRI

Standard Model 530T Hydroscan System Components

| | |
|---|---|
| Recorder | 531TH multihelix, 1-, 2-, 3-channel. |
| Paper | 19A-100 'wet' recording paper. |
| Towfish | 422S-101EF 500 kHz, 0.2 degrees, very high resolution. |

Operational Parameters

| | |
|---|---|
| Range | 100 m |
| Frequency | 375 kHz |
| Beam Angles | Horizontal 1.2°, Vertical 50° |
| Pulse Length | 100 milliseconds |

Klein Model 531T Graphic Recorder Specifications

| | |
|---|---|
| Range Scales | 100 m |
| Paper Speed | 60 lines/cm |
| Scale Lines | Preset every 15 m |
| Time Mark | Every 2 minutes |
| Recording Colour | Sepia (wet paper) |
| Side-scan Frequencies | 500 kHz |

Klein Sub-bottom Profiler 532S-001

| | |
|---|---|
| Frequency | 3.5 kHz |

ORE Sub-bottom Profiler

| | |
|---|---|
| Transceiver | Model 140, 10 kW |
| Transducer | Model 136 |

# Appendix K

## HISTORICAL SHORELINE FLUCTUATIONS, PAKIRI BAY

In an investigation of historic shoreline changes Lees (1982) compared aerial photographs of the Pakiri coast covering the period 1942 to 1981. The photographic record is relatively poor, with infrequent coverage at varying scales. The results are expressed as annual rates of change (in metres), calculated by dividing the total change in metres by the time interval (in years) between the times of photography.

The results (Figure 1) are not consistent with the conclusion that '...the long-term change at Pakiri-Mangawhai Beach is towards progradation' (Lees, 1982, p.29). Accretion between Te Arai Point and the Poutawa Stream (Figure 1 b) in the period 1976/77 to 1980/81 is not natural, rather the result of foredune reconstruction by the New Zealand Forest Service following erosion in the storms of July and August 1978 (see Wishnowsky, 1981). The pattern of accretion and erosion presented in Figure 1 c might also have been misinterpreted. Calculation of net rates of change between the Poutawa Stream and the Pakiri River mouth do not incorporate the effects of the 1978 storms - which, as has been mentioned, resulted in regional foreshore recession. Omitting the Mangawhai inlet-spit complex, which is extraneous to this discussion, only 3 of the 21 photo reference points between the Mangawhai spit and the Poutawa Stream show accretion. If the 1978 shoreline erosion data were included the trend for the southern Pakiri coast would almost certainly be towards erosion, a pattern consistent with the remainder of the Mangawhai-Pakiri coast (excluding the Mangawhai Harbour entrance). This proposition is supported by Lees (1982, p.27) in an interpretation of Figures 1 a,b, and c:-

> The information in these ... figures shows that from 1942-53 and 1942-61 those sections of the beach covered by aerial photographs were generally eroding at moderate rates. In

> contrast, for the 15-20 years preceding 1976-78 the beach tended towards accretion at moderate rates. Post 1976-78, however, a large proportion of the shoreline eroded at rapid rates ... The rapid shoreline recession from 1976/78 to the present (1981) reflects the dynamic nature of the beach.

Hence, excluding the complex Mangawhai Harbour-spit area, analysis of consecutive beach changes for the Pakiri and Mangawhai Beaches, for the period 1942 to 1981, indicates a trend of net erosion. Using Lees (1982) 'moderate' rate of change (0.8 to 5.0 m/yr) the net width of coast eroded in the 20 year period 1961 to 1981 is between 16 (0.8 m/yr) and 100 (5.0 m/yr) m.

The configuration of the Pakiri coast in 1982 (Figure 1.4, for example) shows no evidence of differential rates or directions of shoreline development, consistent with a pattern of erosion north of the Poutawa Stream and accretion south of the stream. The coastal outline in this figure is based on purpose flown, photo point-controlled aerial photographs, at a photo scale of 1:10,000. The map supports analysis of shore profiles from 1978 to 1988, that significant shoreline fluctuations during periods of erosion and deposition are uniform alongshore within Pakiri Bay.

Lees (1982, p.25) states that between 1953 and 1961 and 1976 and 1978 Pakiri-Mangawhai Beach had a positive balance '... with the average rate of accretion being a high 1.03 m/yr'. The Mangawhai portion accreted at an average rate of 2.07 m/yr, while the Pakiri section accreted at 0.26 m/yr'. This contradicts a later statement in which Lees (1982, p.76) states '...the 1950s storms created further instability and recession as protective foredunes were wholly or partly destroyed thus facilitating further erosion. Shoreline changes 1942-61/63 [Figure 1] illustrate this'. The basis for the 1.03 m/yr rate of accretion is not clear. If it is derived from average net accretion rates for the periods 1953 to 1961 and 1976 to 1978 the 1.03 m/yr accretion rate should be considered specific to those two periods, and not indicative of either the direction or magnitude of shoreline development over the entire period for which photo coverage exists (1942 to 1981). Further, rapid and marked fluctuations in the position of mean high water

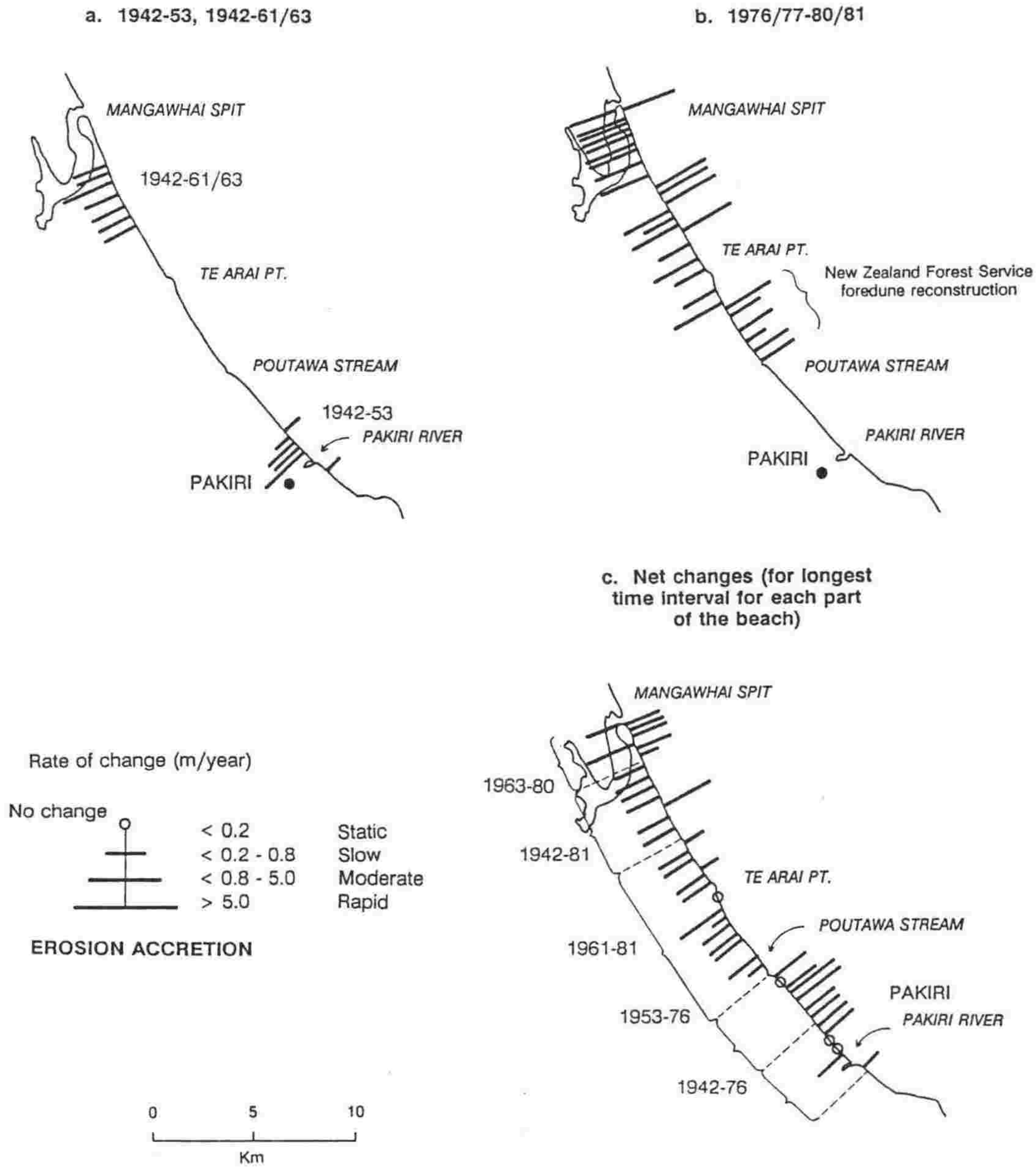



**Figure 1** Consecutive beach changes derived from comparison of aerial photographs, 1942-1981 (from Lees, 1982).

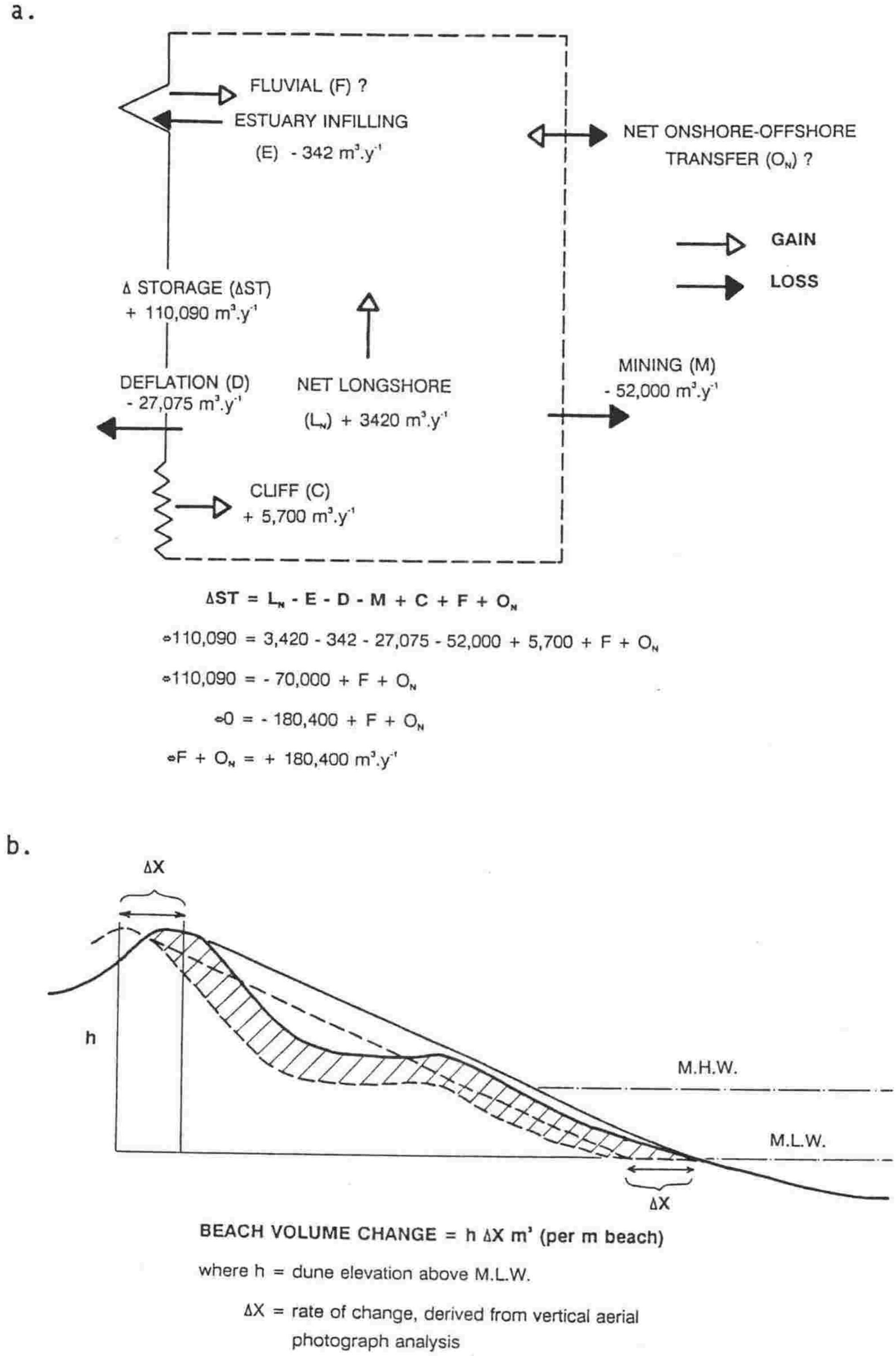



Figure 2 (a) Schematic presentation of the Pakiri-Mangawhai beach sediment budget, and (b) method of calculating beach storage volume change (from Lees, 1982).

mark would be expected in the vicinity of a sand spit/harbour mouth complex. Rates of change obtained from the vicinity of the Mangawhai Spit/Harbour may have little relevance to rates of change along the exposed Mangawhai and Pakiri coasts.

Lees (1982, p.25) calculates a beach sediment budget for the Mangawhai-Pakiri Coast (see Figure 2) in which onshore-offshore sediment transport, in addition to fluvial inputs, accounts for the transfer of 180,000 $m^3$ of sand per year into the beach sediment system. Inputs and losses from the beach budget are expressed as annual rates from calculations '...mostly covering the period of the aerial photograph analysis' (Lees, 1982, p.78). The use of data in the equation covering differing time periods introduces a significant source of error. Assuming the period of the aerial photograph analysis is the interval 1942 to 1981, the sediment budget is intended to apply to a period of 39 years. However the deflation factor (D) (from Wishnowsky, 1981) applies to a much shorter period during foredune reconstruction. Modern deflation from the backshore and foredune areas is confined to two isolated blowouts and the Mangawhai dune area, and is presumably a small fraction of the deflation prior to the establishment of artificial foredunes and Mangawhai State Forest.

The factor 'change in storage' was calculated using the beach volume change method in Figure 2 b, for the period 1978 to 1979. Firstly, the method of calculating beach storage volume change is crude. Translation of the entire profile as envisaged has not been observed during the present study. Secondly, the 1978-79 Water Board surveys used by Lees (1982) represent a measure of net beach volume change over only a six, or possibly 12 month period. Whatever the period, the volumes can only be used in a sediment budget for that period. A change in beach volume storage of 110,090 $m^3$, calculated over a 12 month period (1978-79) cannot be taken as representative of average annual rates of change along an exposed, highly dynamic sandy coast. Beach volume changes of 210,000 $m^3$ were observed to occur during a period of relatively moderate erosion of the berm over a several day period in September 1985. The Pakiri-Mangawhai Beach sediment budget (Lees, 1982, p.78) can, therefore, not be reasonably used to identify the factors of fluvial input (F) and onshore-offshore sediment transfer (On).

# Appendix L

## OPERATING PARAMETERS OF THE REMOTE-CONTROLLED PHOTOGRAPHIC SYSTEM

| | |
|---|---|
| 1. Camera | Nikon |
| 2. Flash | C & C |
| 3. Wide Angle lens | Nikon 28 mm |
| Field of view | 1.50 x 1.20 m |
| Film type/ASA | Ektachrome 200 |
| Aperture | F 5.6 |
| Flash strength | 1/2 |
| Shutter speed | 1/60 s |
| 4. Normal Angle Lens | Nikon 35 mm |
| Field of view | 1.10 x 0.70 m |
| Film type/ASA | Ektachrome 100 |
| Aperture | F 4 |
| Flash strength | 1/2 |
| Shutter speed | 1/60 s |

### Operation

The camera has an auto advance capability so that the device need not be raised to the surface between exposures, and multiple exposures of the same or adjacent locations may be obtained. The camera and flash are triggered from the surface by means of a cable. The system is tested to water depths of 50 m, and can be deployed in cross winds of up to 20 kts. In addition to the skipper of the R.V. Proteus two people are required to operate the winch and feed out and retrieve the triggering cable.

## Appendix M

### A. CHARACTERISTICS OF RIPPLES DERIVED FROM PHOTOGRAPHIC IMAGES

| No. | X[1] (m) | Y[2] (m) | Bed[3] | D[4] (mm) | h[5] (m) | n[6] (m) | β[7] (m) | Sy.[8] β/h | St.[9] n/h | Sp.[10] h/D |
|---|---|---|---|---|---|---|---|---|---|---|
| Okakari Transect (29.09.87) | | | | | | | | | | |
| 1 | 185 | 11 | Mit | 0.26 | - | - | - | - | - | - |
| 2 | 370 | 16 | " | 0.21 | - | - | - | - | - | - |
| 3 | 555 | 17 | " | 0.21 | - | - | - | - | - | - |
| 4 | 740 | 19 | " | 0.21 | - | - | - | - | - | - |
| 5 | 925 | 21 | " | 0.21 | - | - | - | - | - | - |
| 6 | 1110 | 24 | " | 0.21 | - | - | - | - | - | - |
| 7 | 1295 | 26 | " | 0.21 | - | - | - | - | - | - |
| 8 | 1480 | 28 | " | 0.21 | - | - | - | - | - | - |
| 9 | 1665 | 30 | " | 0.21 | - | - | - | - | - | - |
| 10 | 1850 | 32 | " | 0.21 | - | - | - | - | - | - |
| 11 | 2035 | 33 | " | 0.21 | - | - | - | - | - | - |
| 12 | 2220 | 35 | " | 0.21 | - | - | - | - | - | - |
| 13 | 2405 | 36 | " | 0.42 | - | - | - | - | - | - |
| 14 | 2590 | 38 | " | 0.25 | - | - | - | - | - | - |
| 15 | 2775 | 39 | " | 0.25 | - | - | - | - | - | - |
| 16 | 2960 | 40 | " | 0.18 | - | - | - | - | - | - |
| 17 | 3145 | 41 | " | 0.18 | - | - | - | - | - | - |
| 18 | 3330 | 42 | " | 0.18 | - | - | - | - | - | - |
| 19 | 3515 | 43 | " | 0.21 | - | - | - | - | - | - |
| 20 | 3700 | 44 | " | 0.21 | - | - | - | - | - | - |
| 21 | 3885 | 46 | " | - | - | - | - | - | - | - |
| 22 | 4255 | 47 | " | - | - | - | - | - | - | - |
| 23 | 4625 | 47 | " | - | - | - | - | - | - | - |
| 24 | 4810 | 48 | " | - | - | - | - | - | - | - |
| Brown Transect (29.09.87) | | | | | | | | | | |
| 25 | 851 | 20x3 | " | 0.21 | - | - | - | - | - | - |
| 26 | 1295 | 25x3 | " | 0.21 | - | - | - | - | - | - |
| 27 | 1961 | 30x3 | " | 0.25 | - | - | - | - | - | - |
| 28 | 2645 | 35x3 | Ri | 0.50 | 0.50 | 0.10 | 0.25 | 0.5 | 0.2 | 1000 |
| 29 | 3552 | 40x3 | Mit | 0.42 | - | - | - | - | - | - |
| 30 | 5550 | 50x3 | " | - | - | - | - | - | - | - |
| 31 | 277 | 5 | " | 0.25 | - | - | - | - | - | - |
| 32 | 370 | 6 | " | 0.30 | - | - | - | - | - | - |
| 33 | 555 | 11 | " | 0.25 | - | - | - | - | - | - |
| 34 | 740 | 15 | " | 0.21 | - | - | - | - | - | - |

| No. | X[1] (m) | Y[2] (m) | Bed[3] | D[4] (mm) | h[5] (m) | n[6] (m) | β[7] (m) | Sy.[8] β/h | St.[9] n/h | Sp.[10] h/D |
|---|---|---|---|---|---|---|---|---|---|---|
| Brown transect (continued) | | | | | | | | | | |
| 35 | 925 | 19 | " | 0.21 | - | - | - | - | - | - |
| 36 | 1110 | 21 | " | 0.21 | - | - | - | - | - | - |
| 37 | 1295 | 24 | " | 0.21 | - | - | - | - | - | - |
| 38 | 1480 | 26 | " | 0.25 | - | - | - | - | - | - |
| 39 | 1665 | 27 | Ri | 0.25 | 0.50 | 0.12 | 0.25 | 0.5 | 0.24 | 2000 |
| 40 | 1850 | 28 | Mit | 0.25 | - | - | - | - | - | - |
| 41 | 2035 | 29 | Ri | 0.25 | 0.60 | 0.10 | 0.30 | 0.5 | 0.17 | 2400 |
| 42 | 2220 | 31 | " | 0.25 | 0.50 | 0.10 | 0.25 | 0.5 | 0.20 | 2000 |
| 43 | 2405 | 32 | " | 0.30 | 0.50 | 0.10 | 0.25 | 0.5 | 0.20 | 1660 |
| 44 | 2590 | 34 | " | - | - | - | - | - | - | - |
| 45 | 2775 | 36 | " | 0.50 | 0.55 | 0.10 | 0.27 | 0.5 | 0.18 | 1100 |
| 46 | 2960 | 36 | Lat | 0.50 | 0.40 | 0.14 | 0.20 | 0.5 | 0.35 | 800 |
| 47 | 3145 | 37 | " | 0.25 | - | - | - | - | - | - |
| 48 | 3330 | 38 | N | 0.25 | - | - | - | - | - | - |
| 49 | 3515 | 40 | Mit | 0.42 | - | - | - | - | - | - |
| 50 | 3700 | 40 | N | 0.30 | - | - | - | - | - | - |
| 51 | 3885 | 41 | " | 0.30 | - | - | - | - | - | - |
| 52 | 4070 | 42 | " | 0.25 | - | - | - | - | - | - |
| 53 | 4255 | 43 | " | 0.25 | - | - | - | - | - | - |
| 54 | 4440 | 44 | " | 0.25 | - | - | - | - | - | - |
| 55 | 4625 | 46 | " | 0.25 | - | - | - | - | - | - |
| 56 | 4810 | 46 | " | 0.21 | - | - | - | - | - | - |
| 57 | 4995 | 47 | " | - | - | - | - | - | - | - |
| 58 | 5180 | 48 | Mit | - | - | - | - | - | - | - |
| 59 | 5365 | 49 | N | - | - | - | - | - | - | - |
| Williams Transect (20.06.87) | | | | | | | | | | |
| 60 | 555 | 11 | Mit | 0.25 | - | - | - | - | - | - |
| 61 | 647 | 13 | " | 0.25 | - | - | - | - | - | - |
| 62 | 740 | 16 | " | 0.42 | - | - | - | - | - | - |
| 63 | 832 | 17 | N | 0.42 | - | - | - | - | - | - |
| 64 | 926 | 18 | Mit | 0.35 | - | - | - | - | - | - |
| 65 | 1184 | 21 | N | 0.50 | - | - | - | - | - | - |
| 66 | 1443 | 24 | Mit | 0.50 | - | - | - | - | - | - |
| 67 | 1702 | 25 | N | 0.42 | - | - | - | - | - | - |
| 68 | 2220 | 29 | N | 0.50 | - | - | - | - | - | - |
| 69 | 2479 | 31 | Mit | 0.42 | - | - | - | - | - | - |
| 70 | 2738 | 34 | Ri | 0.50 | 0.70 | 0.12 | 0.06 | 0.5 | 0.17 | 1400 |
| 71 | 2997 | 35 | " | 0.59 | 0.80 | 0.12 | 0.06 | 0.5 | 0.15 | 1355 |
| 72 | 3256 | 38 | Mit | 0.42 | - | - | - | - | - | - |
| 73 | 3515 | 39 | " | 0.50 | - | - | - | - | - | - |
| 74 | 3774 | 42 | N | 0.25 | - | - | - | - | - | - |
| 75 | 4033 | 43 | " | 0.35 | - | - | - | - | - | - |
| 76 | 4292 | 45 | " | 0.21 | - | - | - | - | - | - |
| 77 | 4551 | 45 | " | 0.21 | - | - | - | - | - | - |

| No. | X[1] (m) | Y[2] (m) | Bed[3] | D[4] (mm) | h[5] (m) | n[6] (m) | $\beta$[7] (m) | Sy.[8] $\beta$/h | St.[9] n/h | Sp.[10] h/D |
|---|---|---|---|---|---|---|---|---|---|---|
| Williams transect (continued) | | | | | | | | | | |
| 78 | 4810 | 47 | " | 0.21 | - | - | - | - | - | - |
| 79 | 5069 | 47 | " | 0.30 | - | - | - | - | - | - |
| 80 | 5328 | 48 | " | 0.35 | - | - | - | - | - | - |
| 81 | 5587 | 48 | Mit | 0.25 | - | - | - | - | - | - |
| 82 | 5846 | 47 | N | 0.25 | - | - | - | - | - | - |
| 83 | 6105 | 47 | Mit | 0.21 | - | - | - | - | - | - |
| Couldrey Transect (30.09.87) | | | | | | | | | | |
| 84 | 1480 | 26 | Mit | 0.30 | - | - | - | - | - | - |
| 85 | 1850 | 29 | Ri | 0.30 | 0.80 | 0.12 | 0.06 | 0.5 | 0.15 | 2660 |
| 86 | 2035 | 30 | " | 0.70 | 0.30 | 0.12 | 0.06 | 0.5 | 0.40 | 430 |
| 87 | 2220 | 30 | N | 0.25 | - | - | - | - | - | - |
| 88 | 2775 | 35 | Lat | 0.30 | 0.50 | - | 0.25 | 0.5 | - | 1670 |
| 89 | 3145 | 39 | " | 0.30 | - | - | - | - | - | - |
| 90 | 3515 | 42 | " | 0.30 | - | - | - | - | - | - |
| 91 | 3700 | 43 | Ri | 0.42 | 0.75 | 0.12 | 0.27 | 0.5 | 0.16 | 1785 |
| 92 | 3792 | 44 | Mit | 0.42 | - | - | - | - | - | - |
| 93 | 3885 | 44 | " | 0.42 | - | - | - | - | - | - |
| 94 | 4440 | 46 | " | 0.30 | - | - | - | - | - | - |
| 95 | 4625 | 46 | " | 0.30 | - | - | - | - | - | - |
| Walkway Transect (30.09.87) | | | | | | | | | | |
| 96 | 370 | 5 | Mit | 0.30 | - | - | - | - | - | - |
| 97 | 555 | 10 | " | 0.25 | - | - | - | - | - | - |
| 98 | 740 | 15 | " | 0.25 | - | - | - | - | - | - |
| 99 | 925 | 19 | " | 0.25 | - | - | - | - | - | - |
| 100 | 1110 | 22 | " | 0.30 | - | - | - | - | - | - |
| 101 | 1295 | 25 | " | 0.35 | - | - | - | - | - | - |
| 102 | 1480 | 26 | " | 0.35 | - | - | - | - | - | - |
| 103 | 1665 | 27 | N | 0.42 | - | - | - | - | - | - |
| 104 | 1850 | 28 | Lat | 0.42 | - | - | - | - | - | - |
| 105 | 2035 | 29 | Mit | 0.50 | - | - | - | - | - | - |
| 106 | 2220 | 30 | Lat | 0.59 | - | - | - | - | - | - |
| 107 | 2405 | 31 | " | 0.42 | - | - | - | - | - | - |
| 108 | 2590 | 33 | " | 0.42 | - | - | - | - | - | - |
| 109 | 2775 | 35 | " | 0.50 | - | - | - | - | - | - |
| 110 | 2960 | 37 | " | 0.50 | - | - | - | - | - | - |
| 111 | 3145 | 38 | " | 0.59 | - | - | - | - | - | - |
| 112 | 3330 | 39 | Ri | 0.65 | 0.60 | 0.14 | 0.30 | 0.5 | 0.23 | 920 |
| 113 | 3515 | 41 | Mit | 0.71 | - | - | - | - | - | - |
| 114 | 3700 | 43 | " | 0.50 | - | - | - | - | - | - |
| 115 | 3885 | 44 | Ri | 1.00 | 0.50 | 0.14 | 0.25 | 0.5 | 0.28 | 500 |
| 116 | 3700 | 43 | N | 0.50 | - | - | - | - | - | - |
| 117 | 3885 | 44 | N | 1.00 | - | - | - | - | - | - |

| No. | X[1] (m) | Y[2] (m) | Bed[3] | D[4] (mm) | h[5] (m) | n[6] (m) | β[7] (m) | Sy.[8] β/h | St.[9] n/h | Sp.[10] h/D |
|---|---|---|---|---|---|---|---|---|---|---|
| Walkway transect (continued) | | | | | | | | | | |
| 118 | 3885 | 42 | Mit | 1.00 | - | - | - | - | - | - |
| 119 | 3977 | 41 | " | 1.00 | - | - | - | - | - | - |
| 120 | 3885 | 42 | " | 1.00 | - | - | - | - | - | - |
| 121 | 3977 | 43 | Lat | 1.00 | - | - | - | - | - | - |
| 122 | 4070 | 43 | " | 1.00 | - | - | - | - | - | - |
| 123 | 4162 | 45 | " | 0.30 | - | - | - | - | - | - |
| 124 | 4255 | 46 | Ri | 0.30 | 0.50 | 0.12 | 0.25 | 0.5 | 0.24 | 1670 |
| 125 | 4440 | 47 | N | 0.25 | - | - | - | - | - | - |
| 126 | 4625 | 46 | Mit | 0.21 | - | - | - | - | - | - |
| 127 | 4810 | 46 | N | 0.21 | - | - | - | - | - | - |
| <u>Gravel Transect</u> (28.09.87) | | | | | | | | | | |
| 128 | 370 | 6 | Mit | 0.25 | - | - | - | - | - | - |
| 129 | 555 | 11 | " | 0.21 | - | - | - | - | - | - |
| 130 | 740 | 15 | " | 0.21 | - | - | - | - | - | - |
| 131 | 925 | 19 | N | 0.30 | - | - | - | - | - | - |
| 132 | 1110 | 22 | Mit | 0.35 | - | - | - | - | - | - |
| 133 | 1295 | 24 | " | 0.35 | - | - | - | - | - | - |
| 134 | 1480 | 27 | Lat | 0.42 | - | - | - | - | - | - |
| 135 | 1665 | 29 | Ri | 0.42 | 0.40 | 0.14 | 0.20 | 0.5 | 0.35 | 950 |
| 136 | 1850 | 30 | Lat | 0.42 | - | - | - | - | - | - |
| 137 | 1942 | 31 | Ri | 0.42 | 0.40 | 0.14 | 0.20 | 0.5 | 0.35 | 950 |
| 138 | 2035 | 32 | Lat | 0.42 | - | - | - | - | - | - |
| 139 | 2127 | 32 | " | 0.42 | - | - | - | - | - | - |
| 140 | 2220 | 32 | " | 0.35 | - | - | - | - | - | - |
| 141 | 2312 | 33 | " | 0.42 | - | - | - | - | - | - |
| 142 | 2405 | 34 | Ri | 0.42 | 0.40 | 0.14 | 0.20 | 0.5 | 0.35 | 950 |
| 143 | 2590 | 35 | " | 0.50 | 0.50 | 0.14 | 0.25 | 0.5 | 0.28 | 1000 |
| 144 | 2775 | 36 | Lat | 0.50 | - | - | - | - | - | - |
| 145 | 2960 | 37 | " | 0.54 | - | - | - | - | - | - |
| 146 | 3145 | 38 | " | 0.59 | - | - | - | - | - | - |
| 147 | 3330 | 40 | Ri | 0.71 | 0.45 | 0.12 | 0.27 | 0.5 | 0.27 | 630 |
| 148 | 3515 | 42 | Ri | 0.84 | 0.60 | 0.12 | 0.30 | 0.5 | 0.20 | 710 |
| 149 | 3700 | 43 | N | 0.18 | - | - | - | - | - | - |
| 150 | 3885 | 44 | Mit | 0.15 | - | - | - | - | - | - |
| 151 | 4070 | 45 | N | 0.18 | - | - | - | - | - | - |
| 152 | 4162 | 48 | Mit | 0.15 | - | - | - | - | - | - |
| 153 | 4255 | 48 | N | 0.15 | - | - | - | - | - | - |
| 154 | 4440 | 49 | " | 0.17 | - | - | - | - | - | - |
| 155 | 4625 | 49 | " | " | - | - | - | - | - | - |
| 156 | 4810 | 48 | " | " | - | - | - | - | - | - |
| 157 | 4995 | 48 | " | " | - | - | - | - | - | - |

Notes:

1. Distance from datum (in metres).
2. Water depth (approximately relative to mean sea level).
3. Bed configuration; N - no discernible topography, Mit - minor irregular topography, Ri - linear crested ripples and megaripples, and Lat - non-linear, latticed bed.
4. Estimated mean grain size diameter (mm), derived from sediment survey results.
5. Ripple wavelength (metres).
6. Estimated vertical distance between ripple crests and troughs (cm).
7. Average distance from ripple crest to leading trough (cm).
8. Ripple symmetry (β/h).
9. Ripple steepness (n/h).
10. Ration of mean grain diameter to ripple wavelength (h\D).

**B. CHARACTERISTICS of RIPPLES DERIVED FROM SIDE-SCAN SONAR WALKWAY to OKAKARI TRANSECTS, 15.03.87**

| Time[1] | Dis.[2] (m) | Depth[3] (m) | D[4] (mm) | Crests[5] /15m | h[6] (m) | Tone[7] (Inferred sediments) |
|---|---|---|---|---|---|---|
| 1710-1741 | | | | | | Shore-normal leg |
| 1742 | 2300 | 27 | 0.25 | - | | light |
| 1744 | 2105 | 25 | " | - | | " |
| 1746 | 2100 | " | " | - | | " |
| 1748 | 1950 | " | " | - | | " |
| 1750 | 1800 | " | " | - | | " |
| 1752 | " | " | " | - | | " |
| 1754 | " | " | " | - | | " |
| 1756 | " | " | " | 13 | 1.15 | ribbons/dark |
| 1758 | " | " | " | 17 | 0.88 | " |
| 1800 | " | 26 | " | 17 | 0.88 | broad area/light |
| 1802 | " | " | " | 17 | 0.88 | " |
| 1804 | " | " | " | 18 | 0.83 | " |
| 1806 | " | " | " | 19 | 0.79 | " |
| 1808 | " | " | " | 13 | 1.15 | ribbons/dark |
| 1810 | " | 27 | " | 17 | 0.88 | broad area/light |
| 1812 | 1700 | " | " | 14 | 1.07 | ribbons/dark |
| 1814 | " | " | 0.42 | 12 | 1.25 | " |
| 1816 | 1900 | " | 0.50 | 17 | 0.88 | broad area/light |
| 1818 | 2050 | 28 | " | 14 | 1.07 | ribbons/dark |
| 1820 | 2100 | " | " | 13 | 1.15 | " |
| 1822 | 2150 | " | " | 20 | 0.75 | broad area/light |
| 1824 | " | " | " | 19 | 0.79 | " |
| 1826 | 2200 | " | 0.25 | 16 | 0.93 | " |
| 1828 | " | 29 | " | 18 | 0.83 | " |
| 1830 | " | 28 | " | 18 | 0.83 | " |

| Time[1] | Dis.[2] (m) | Depth[3] (m) | D[4] (mm) | Crests[5] /15m | h[6] (m) | Tone[7] (Inferred Sediments) |
|---|---|---|---|---|---|---|
| 1832 | 2150 | " | " | 15 | 1.00 | ribbons/dark |
| 1834 | " | " | " | - | | light |
| 1836 | " | " | " | 12 | 1.25 | ribbons/dark |
| 1838 | " | " | " | - | | " |
| 1840 | 2140 | " | " | 12 | 1.25 | " |
| 1842 | 2150 | 29 | 0.50 | - | | light |
| 1844 | 2200 | 30 | " | 13 | 1.15 | ribbons/dark |
| 1846 | 2210 | " | " | 13 | 1.15 | " |
| 1848 | 2220 | " | " | 14 | 1.07 | " |
| 1850-1915 | | | | | | shore-normal leg |
| 1916 | 5380 | 45 | 0.21 | 16 | 0.93 | patches/dark |
| 1918 | " | " | " | ? | | - |
| 1920 | " | " | " | 20 | 0.75 | patches/dark |
| 1922 | " | " | " | - | | " |
| 1924 | 5500 | " | " | - | | light |
| 1926 | 5600 | 45 | 0.21 | - | | light |
| 1928 | " | " | " | - | | - |
| 1930 | 5640 | " | " | - | | - |
| 1932 | " | 46 | " | - | | - |
| 1934 | 5700 | " | " | - | | - |
| 1936 | " | " | " | 20 | 0.75 | patches/dark |
| 1938 | " | 47 | " | 19 | 0.79 | " |
| 1940 | " | 46 | " | 20 | 0.75 | " |
| 1942 | 5850 | " | " | - | | light |
| 1944 | 6000 | 47 | " | - | | " |
| 1946 | 6100 | " | " | - | | " |
| 1948 | 6250 | " | " | - | | " |
| 1950 | 6300 | 48 | " | - | | " |
| 1952 | 6380 | " | " | - | | " |
| 1954 | 6500 | " | " | - | | " |
| 1956 | 6510 | " | " | 20 | 0.75 | patches/dark |
| 1958 | 6500 | 47 | " | 21 | 0.71 | " |
| 2000 | " | " | " | - | | light |
| 2002 | " | " | " | - | | " |
| 2004 | " | " | " | 17 | 0.88 | patches/dark |
| 2006 | " | " | " | 17 | 0.88 | " |
| 2008 | 6410 | " | " | 18 | 0.83 | " |
| 2010 | 6340 | " | " | 19 | 0.79 | " |
| 2012 | 6280 | " | " | 19 | 0.79 | " |
| 2014 | 6250 | " | " | - | | light |
| 2016 | 6160 | " | " | - | | " |
| 2018 | 6090 | " | " | - | | " |
| 2020 | 6090 | " | " | - | | " |
| 2022 | 6020 | " | " | - | | " |

Notes:-
1. Time interval on survey line (see Figure 6.4).
2. Distance offshore (metres).
3. Approximate water depth relative to mean sea level (metres).
4. Mean grain size of the non-carbonate fraction (mm), derived from transect samples.
5. Number of ripple crests per 15 m width of seabed.
6. Mean ripple wavelength in metres (derived from 5).
7. Sedimentology of seabed, and observations of paper record tone (light - fine sediment, dark - coarse sediment).

# Appendix N

## AANDERAA CURRENT METER DEPLOYMENT, PAKIRI BAY

### Instrument Deployment

An Aanderaa RCM-4 current meter was deployed in Pakiri Bay for a period of almost six weeks. The original site was along Brown transect, 2500 m offshore in approximately 30 m water depth (Figure 7.1 a,b). Location along the pre-surveyed transect was for navigational convenience, there being no preferred site within Pakiri Bay because of the lack of alongshore variation in bathymetry. Records from an unintended deployment, in 45 m water depth, were also obtained.

The technique of measuring currents at a fixed location is described as a flow or Eulerian method. It was originally intended to deploy the instrument for a period of about six weeks. Ideally the study area would experience a wide range of sea conditions in this time, including any storm-related flows. In fact, the sea state during the deployment period was typical, with prolonged periods of calm conditions, and absence of storm waves. On all but three days winds were below 15 knots, with associated wave surge measured at the Leigh Marine laboratory below 1.0 m. The highest wave surges recorded, 2.5 m, were on the 25 April; and probably represent a maximum (swell) wave height of less than 2 m. A water level recorder was operated at the same site, in the configuration portrayed in Figure 1. This dual deployment provides a parallel record of sea level oscillation due to tidal wave progression, and the means of identifying rhythmic variations in the current meter record attributable to tidal phenomena.

The current meter used was an Aanderaa RCM-4 with a Savonius rotor. This type of rotor is sensitive to low current velocities (1.5 to 2.0 cm $s^{-1}$), but is susceptible to bio-fouling. The suppressed speeds for the period 17 to 27 April, relative to the rest of the record, suggest limited bio-fouling occurred. With this type of rotor wave-induced mooring motion and orbital water motions are recorded as a contribution to the speed, so that speed magnitudes recorded during periods of wave activity are thus overestimated (Karweit, 1974). These sources of error were most probably insignificant in Pakiri Bay, given the depths of deployment (30 and 45 m) and the marine conditions experienced. The Aanderaa meter used has a relatively large vane to keep the instrument orientated into the water flow by a gimble. A recording frequency of 10 minutes was employed. The instrument was deployed so that the rotor was approximately 1 m above the seabed.

Two records of current speed and direction resulted from the original deployment of the meter at site 1 on the 25 March, 1986. The instrument functioned normally, albeit with possible biofouling for a short period until the 27 April (33 days). In the early hours of the 27 April, despite a flashing light atop a dan buoy and public gazetting in the New Zealand Notice to Mariners, a trawler snagged the entire configuration with a net and dragged the instruments into deeper water, where they were eventually released. The current meter, but not the water level recorder, continued to function normally at site 2 (Figure 7.1 a), approximately 2.5 km north-north-east of the original site. Site 2 lies midway between Brown and Williams transects, in water depths of approximately 45 m (Figure 7.1 b). The equivalent location across Brown transect places the instrument at the base of the inner continental shelf. The current meter operated normally at this site for 6 days prior to premature battery failure, and the successful relocation and recovery of the instruments.

## Analysis of Current Meter Record

Analysis of the current meter record was undertaken by the Ministry of Works and Development, Water Quality Centre (Bell, 1986). The raw data was translated by the New Zealand Oceanographic Institute, Department of Scientific and Industrial Research, and converted to engineering units including magnetic north. The water level recorder records were translated and interpreted in the Department of Physics, University of Auckland.

The time series of current speed and direction were plotted as two rectangular velocity components - alongshore (320° to 140° true north) and onshore/offshore (050° to 230° true north). The purpose of the investigation is to determine the extent to which currents could initiate sediment transport. Hence the rectangular velocity components selected.

The edited raw data (speed, longshore and offshore/onshore velocity components) were subjected to a low-passed digital filter with a half-power cutoff period of approximately 2 hours. This removes all high frequency noise in the input data leaving components in the records which have periods greater than 2 hours. Summary statistics for the low-passed (tidal) time series were calculated. The edited raw data was also subjected to a low-passed digital filter with a half-power cutoff period of 92 hours (or 3.8 days). The diurnal and semi-diurnal tidal components are removed, leaving the low-frequency residual currents. Current roses were plotted depicting the proportion of observations for various sectors of the compass rose, 10° sectors for site one, and 20° sectors for site 2. Each sector is subdivided into speed increments of 5 $cms^{-1}$ with the length of each segment proportional to the frequency of occurrence of speeds in each group.

It has been noted that the Aanderaa RCM-4 current meter is a non-vector averaging type of meter, and susceptible to wave motion. The marine climate during the deployment was monitored at the nearby Leigh Marine Laboratory, involving daily observations of sea state, and continuous measurement of wind direction and speed, water level and atmospheric pressure. Wind speed was, in keeping with sea state, low throughout the survey period.

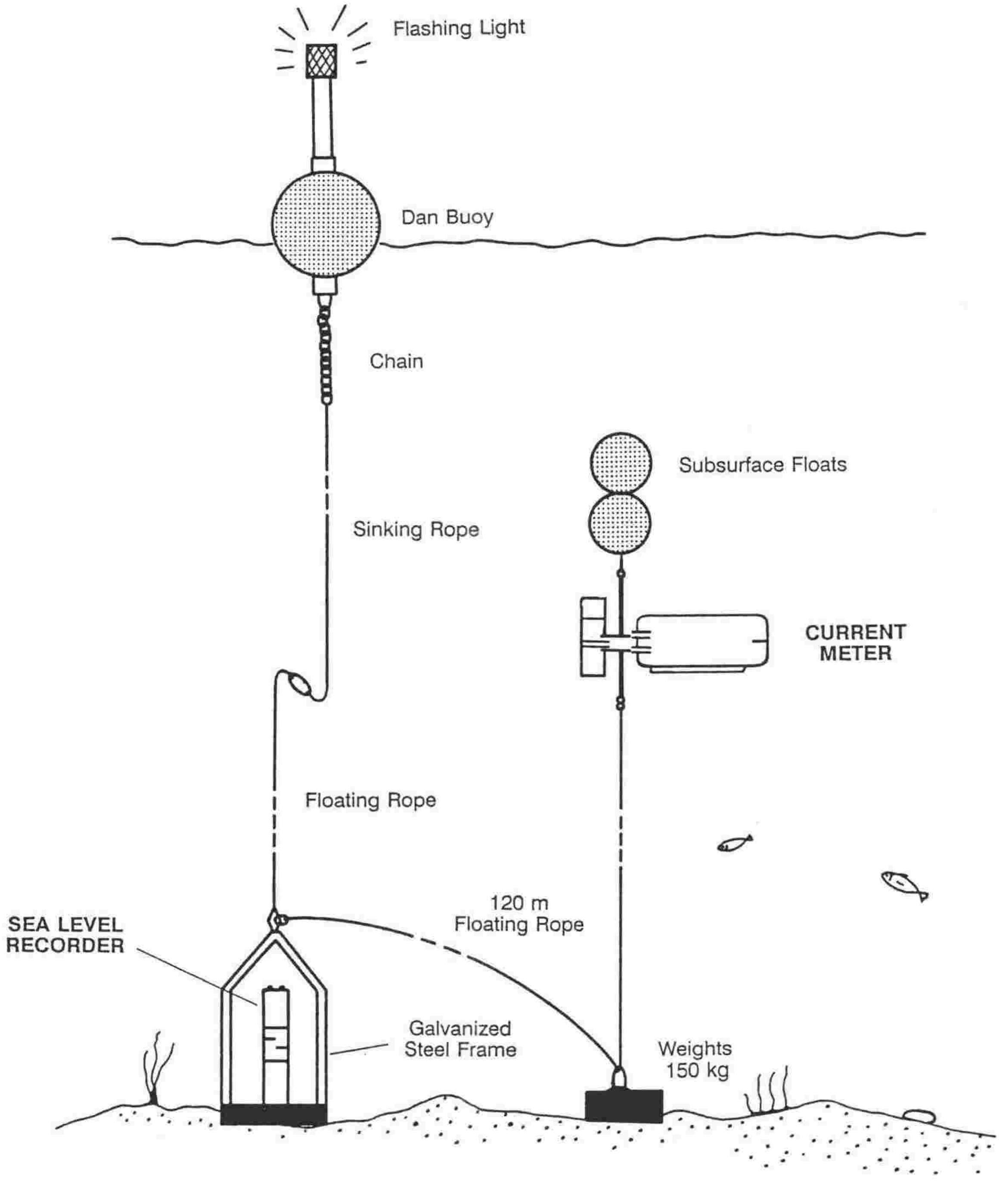



**Figure 1** Arrangement of deployed current meter and water level recorder instruments.

Appendix O

# WAVE TRANSFORMATIONS IN PAKIRI BAY DUE TO SHOALING AND REFRACTION

## Nature of Investigation

Parameters characteristic of calm and storm wave conditions are used in the computer programs of Black and Healy (1981) to predict the changes experienced due to shoaling and refraction as waves propagate across the Outer Hauraki Gulf and the shoreface and continental shelf of the Pakiri sediment body. The programmes employ the geometric optics theory utilised by Munk and Arthur (1951) and the numerical system is similar to that used by Noda (1972). The programmes also calculate the maximum orbital velocity, maximum grain size that can be moved by the wave train, and the change in wave parameters H, $\lambda$, and wave direction. In addition, depending on the selected breaking wave criterion, the programmes estimate the height and angle of waves at the breaker zone.

The bathymetry of the Outer Hauraki Gulf was digitized within a rectangular 41 x 56 km grid covering an area of 2000 $km^2$ (Figure 1). Bathymetric data was obtained from hydrographic surveys by the Royal New Zealand Navy (1974), derived from surveys between 1960 and 1970. The gross bathymetry of the Outer Hauraki Gulf and Pakiri Bay were assumed not to have changed significantly since these surveys. Following preparation of the input grid the programmes allow generation of waves of a given period, height and initial angle. Waves from two directions, easterly and northeasterly, were employed with three combinations of wave period and height:-

(a) A 1.5 m, 7 s wave, that is typical of the prevailing swell wave for most of the time.
(b) A 5.0 m, 12 s wave that might be expected to occur, on average, two or three times every 12 months.

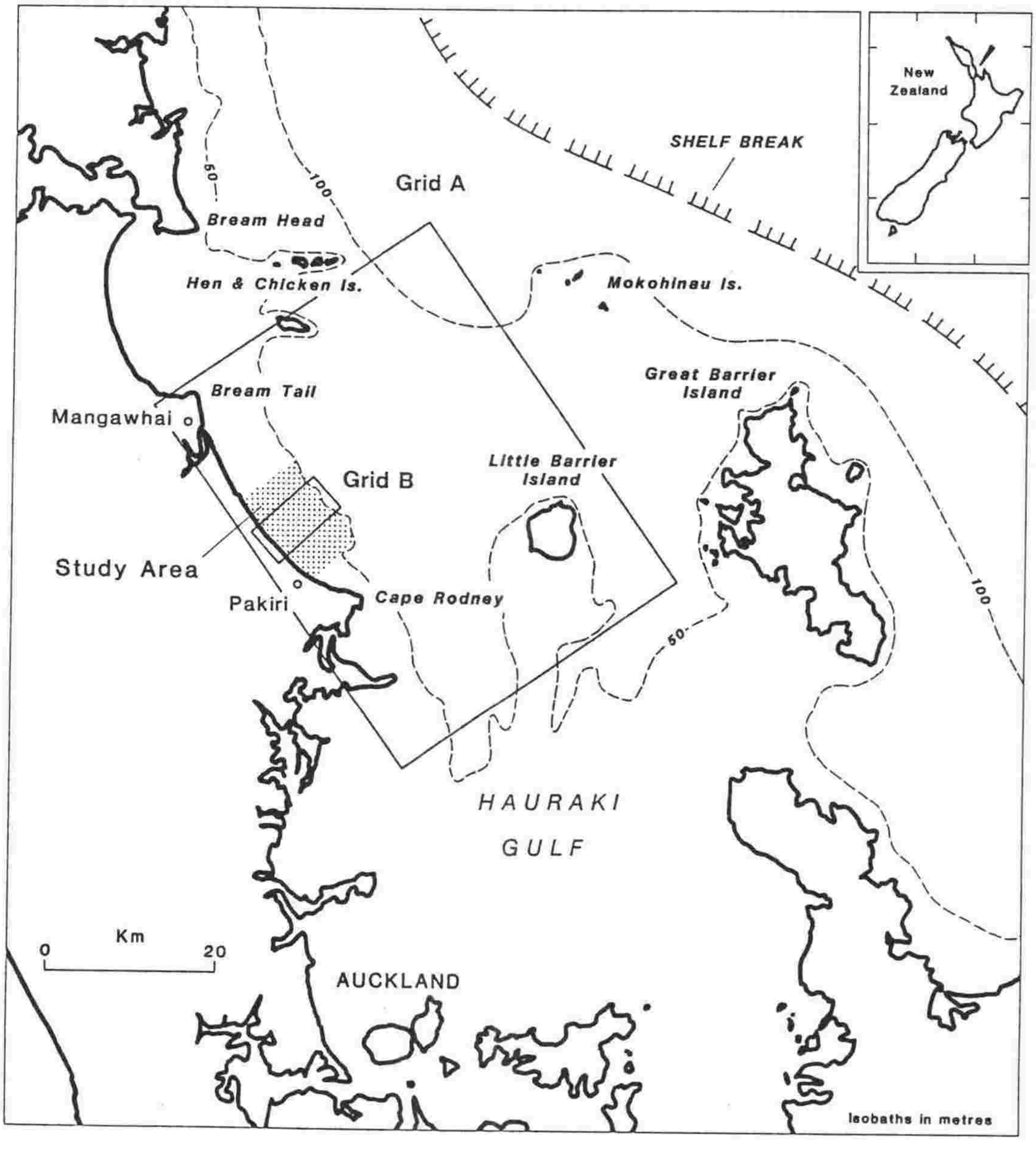



Figure 1  Location of wave refraction grids

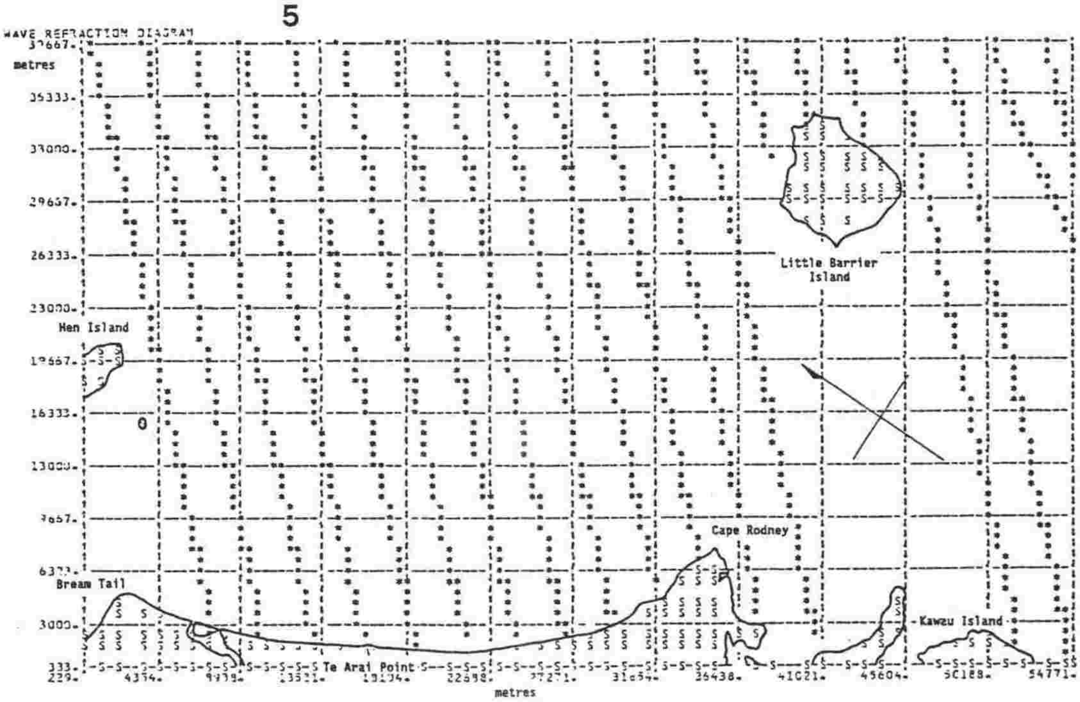
(c) An 8.0 m, 15 s wave that represents extreme storm conditions in the Outer Hauraki Gulf, that probably occur every 10 to 30 years.

The larger grid commences inside the Mokohinau Islands, approximately 50 km from the Pakiri coast. These islands create two windows through which swell waves propagate into the Outer Hauraki Gulf. To the south the Gulf is relatively sheltered by Little and Great Barrier Islands, and Bream Bay to the north is afforded some protection by Bream Head and the Hen and Chicken Islands. Otherwise the study area is directly exposed, in the absence of refraction, to waves from the northeast and east. These directions are employed in the programmes. Waves from an easterly direction are generated inside and outside Little Barrier Island, to examine the significance of the wave shadow effect.

Waves of 1.5 m height and 7 s period from either an easterly or northeasterly direction are little affected by shoaling or refraction transformations (Figure 2 a,b). Wave orthogonals show little convergence and there is no pronounced focusing of wave energy on the coast. Table 1 shows the variation in wave height and angle at regular intervals along a representative orthogonal for 1.5 m waves from northeasterly (orthogonal 5) and easterly (orthogonal 14, Figure 2) directions.

The larger 5 and 8 m waves are more affected by the bathymetry of the Outer Hauraki Gulf. However, waves entering Pakiri Bay from the northeast are little refracted, and tend to intercept the coast at approximately 90° (Figure 3 a,b). Within the bay very little converging of wave orthogonals occurs, and wave energy appears evenly distributed along the Mangawhai-Pakiri sandy coastline. In contrast orthogonals converge along the rocky Cape Rodney coast with high energy focusing around the headland. Waves refracting to the south of Cape Rodney and Little Barrier Island experience severe height and direction transformations. This is not surprizing given the relative shallowness of the Hauraki Gulf south of Little Barrier Island compared with the wavelength of these large waves.

a.




b.

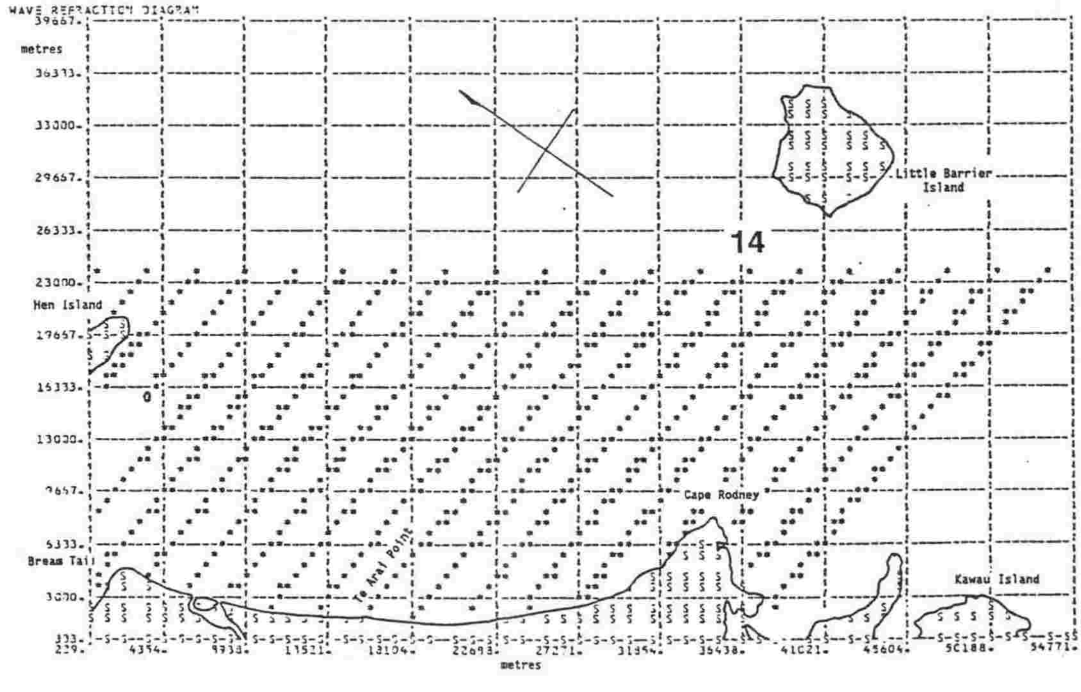
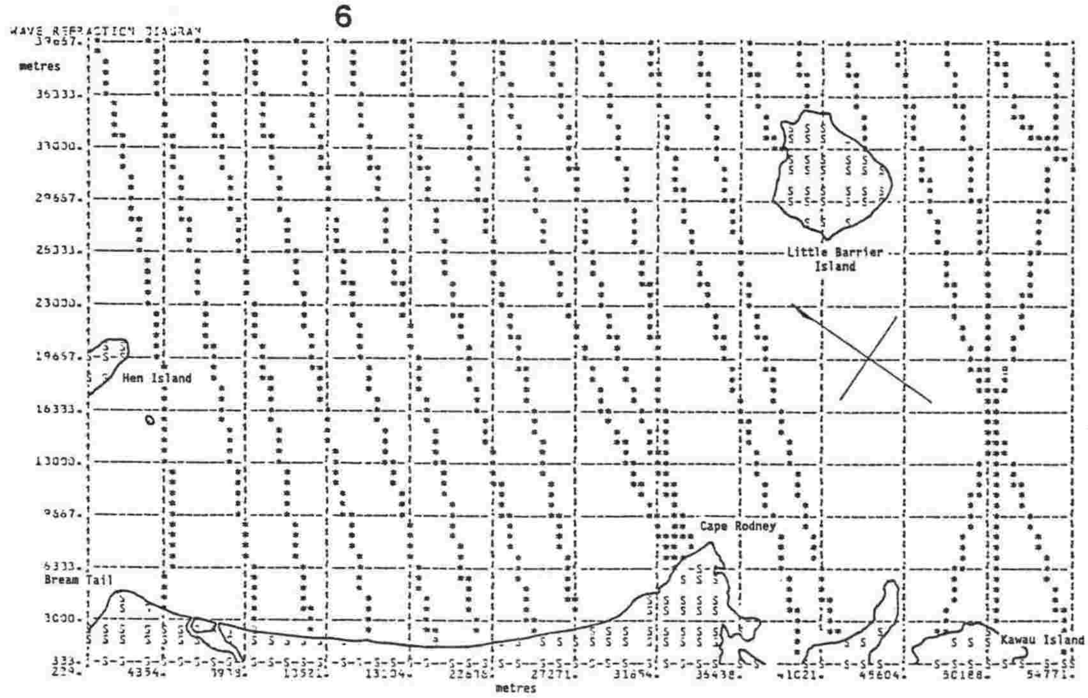



**Figure 2** Refraction of (a) a 1.5 m 7 s northeasterly and (b) 1.5 m 7 s easterly wave.

a.




b.

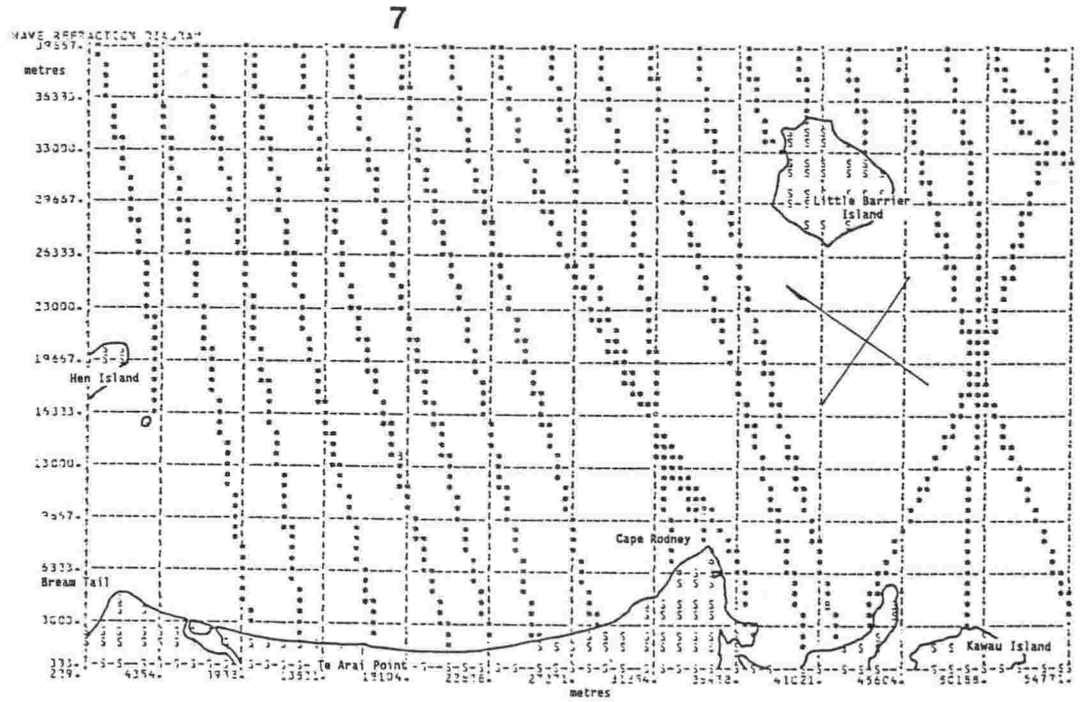



**Figure 3** Refraction of (a) a 5 m 12 s northeasterly and (b) 8 m 15 s northeasterly wave.

Large waves from the northeast in the Outer Gulf maintain their direction and height as they propagate towards the coast (Table 2). For representative wave rays (#6 and #7, Figure 7.3) wave heights increase abruptly in water depths close to the coast, but over much of the width of the Pakiri inner shelf approximate the initial wave heights of 5 and 8 m.

**Table 1** Transformations of Easterly and Northeasterly, 1.5 m 7 s Waves

| Northeasterly | Distance Offshore (km) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 5 | 10 | 15 | 20 | 40 |
| Depth (m) | 4.5 | 21.3 | 30.0 | 41.1 | 51.9 | 54.1 | 66.0 | 101.8 |
| Angle | 174.6 | 170.6 | 170.1 | 170.0 | 169.9 | 169.9 | 169.9 | 170.0 |
| Height (m) | 1.48 | 1.41 | 1.46 | 1.48 | 1.49 | 1.49 | 1.50 | 1.50 |

| Easterly | Distance Offshore (km) | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2 | 3 | 5 | 7 | 10 | 15 | 20 |
| Depth (m) | 21.4 | 28.5 | 38.1 | 45.6 | 49.8 | 55.4 | 53.1 |
| Angle | -147.0 | -145.1 | -144.1 | -144.0 | -144.0 | -144.0 | -144.0 |
| Height (m) | 1.32 | 1.45 | 1.49 | 1.50 | 1.50 | 1.50 | 1.50 |

Large easterly waves generated within Little Barrier Island undergo more pronounced transformations, especially as they are influenced by the steeply sloping seabed near Cape Rodney (Figure 4 a,b). The wave orthogonals indicate conspicuous refraction close to the Pakiri coast, in water depths of less than 45 m, corresponding to the commencement of the Pakiri inner continental shelf. Angle determinations along representative orthogonals (5 m, #14; 8 m, #12;

Table 2 Transformations of 5 m 12 s and 8 m 15 s Northeasterly Waves

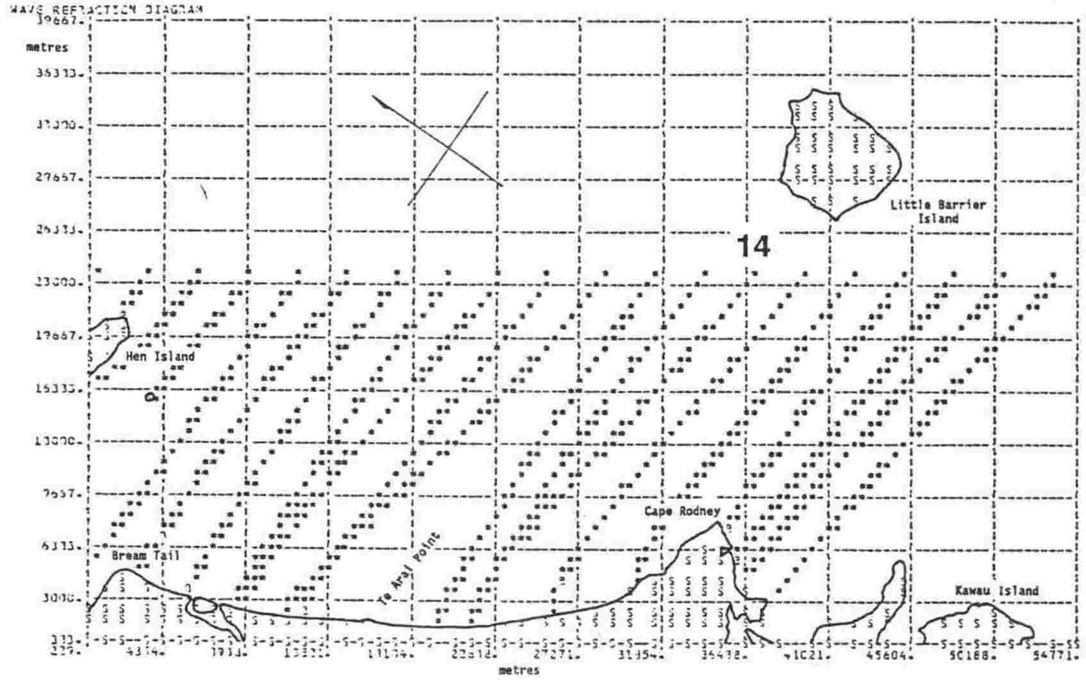
| 5 m wave | Distance Offshore (km) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 5 | 10 | 15 | 20 | 30 | 40 |
| Depth (m) | 20.3 | 29.5 | 38.7 | 52.0 | 56.1 | 62.1 | 84.4 | 101.5 |
| Angle | 170.0 | 169.8 | 169.7 | 169.4 | 168.4 | 168.2 | 169.8 | 170.0 |
| Height (m) | 5.4 | 5.2 | 5.0 | 4.9 | 4.9 | 4.8 | 4.9 | 5.0 |

| 8 m wave | Distance Offshore (km) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 3 | 5 | 10 | 15 | 20 | 30 | 40 |
| Depth (m) | 17.2 | 28.3 | 39.3 | 52.0 | 56.9 | 62.1 | 84.3 | 101.5 |
| Angle | 168.0 | 168.0 | 167.9 | 166.9 | 166.2 | 166.1 | 169.2 | 170.0 |
| Height (m) | 8.1 | 7.7 | 7.6 | 7.7 | 7.9 | 7.8 | 7.8 | 8.0 |

Figure 4 a,b, respectively) indicate refraction of easterly waves occurs over the Cape Rodney inner and middle shelves, but that waves are still incident on the coast with a northerly component (Table 3).

Little Barrier Island, and the shallows to the south, disrupt the progress of 5 and 8 m waves from the east, creating a wave-shadow (Figure 5 a,b). The coast south of Te Arai Point is sheltered, although 8 m waves are refracted onto the coast south of Te Arai. Such waves experience substantial transformation. Ray 15 (Figure 5 b) breaks on the coast with a predicted wave height of 3.8 m. In comparison predicted heights close to shore for shoaling waves from the northeast approximate the initial wave heights. Easterly waves

a.




b.

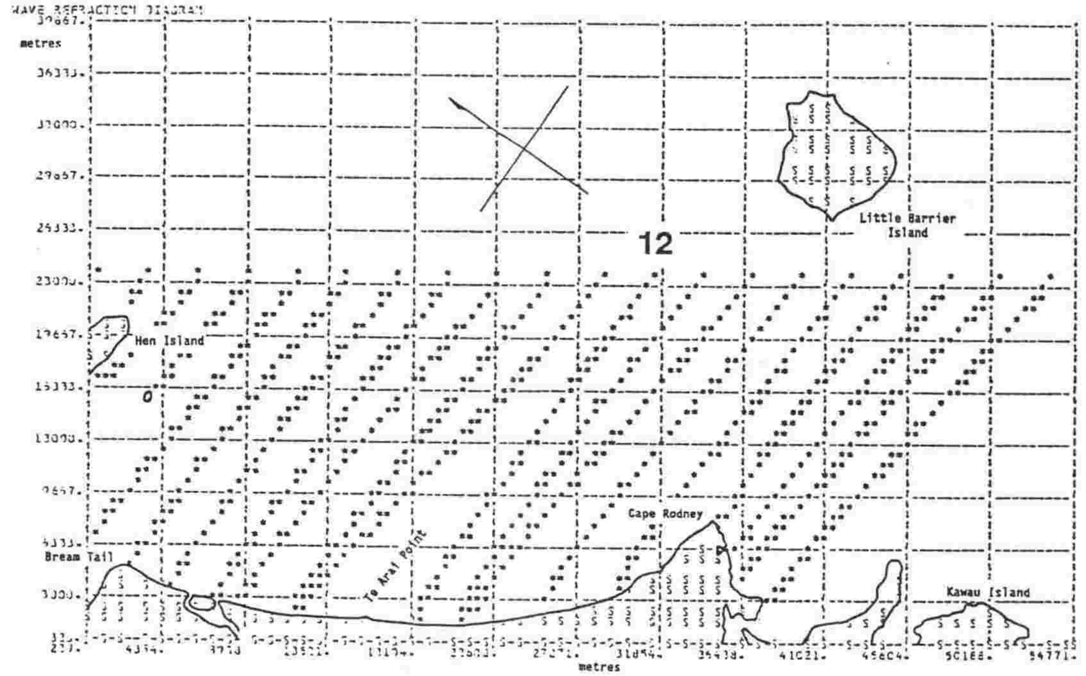



**Figure 4** Refraction of (a) 5 m 12 s and (b) 8 m 15 s waves from an easterly direction generated inside Little Barrier Island.

a.

b.

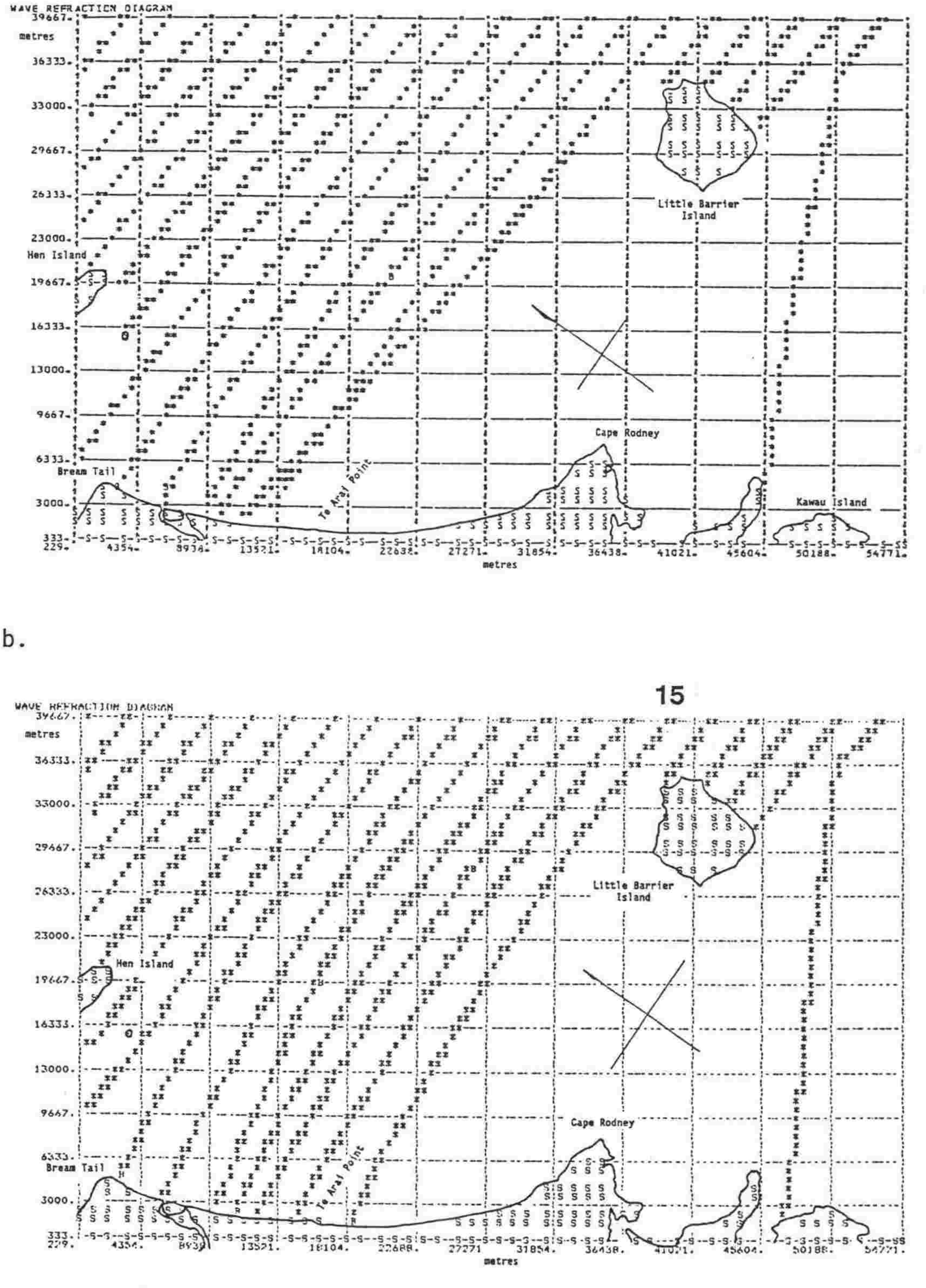



Figure 5 Refraction of (a) 5 m 12 s and (b) 8 m 15 s waves from an easterly direction generated outside Little Barrier Island.

Table 3 Transformations of 5 m 12 s and 8 m 15 s Easterly Waves

| 5 m wave | Distance Offshore (km) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 2 | 3 | 4 | 6 | 8 | 10 | 15 | 23 |
| Depth (m) | 19.0 | 28.4 | 34.5 | 42.2 | 48.2 | 50.3 | 55.5 | 51.0 |
| Angle | 144.0 | 152.2 | 148.6 | 145.1 | 143.3 | 143.3 | 142.9 | 144.0 |
| Height (m) | 5.8 | 5.9 | 6.1 | 6.3 | 6.3 | 6.1 | 5.5 | 5.0 |
| 8 m waves | Distance Offshore (km) | | | | | | | |
| | 1 | 2 | 4 | 6 | 8 | 10 | 20 | 23 |
| Depth (m) | 8.0 | 20.4 | 36.8 | 43.0 | 48.2 | 50.5 | 52.8 | 52.0 |
| Angle | 168.6 | 161.3 | 155.0 | 152.2 | 151.2 | 151.3 | 149.9 | 144.0 |
| Height (m) | 6.5 | 6.3 | 6.5 | 6.8 | 7.2 | 7.5 | 7.8 | 8.0 |

of initial height of 1.5 m and period 7 s are refracted around Little Barrier Island such as being able to affect the coast north of the Pakiri River Mouth. However, whereas unrefracted waves experience little or no height transformation, the predicted height of waves near the coast that experience refraction is only 0.15 m.

## Wave Transformations Across the Shoreface and Continental Shelf

The Black and Healey (1981) programmes are used to generate waves over a surface characteristic of the morphological components of the Pakiri inner shelf. The bathymetric data input is based on the shore-normal variation across Couldrey transect, a configuration representative of much of Pakiri Bay. The Couldrey transect data was taken as representative of the morphology of the shoreface and continental shelf, and there is assumed to be no major alongshore variations in bathymetry. This three-dimensional surface allows the generation of easterly waves at angles acute to the isobaths.

The bathymetric grid created covers an area of 6000 x 5000 m, and extends well beyond the inner shelf-mid shelf boundary (see Figure 1). Nodes were input at 50 x 50 m intervals. Waves of height 1.5, 2.5, 5.0 and 8.0 m height and 7, 9, 12 and 15 s respectively were generated across the middle and inner shelves, from easterly (216°) and northeasterly (175°) directions. Northeasterly waves approach most of the coast at Pakiri at slightly less than 90°.

In addition to wave transformations options in the programs are employed that calculate the maximum bottom orbital velocity ($U_m$) using linear wave theory, as well as deriving grain thresholds. The programmes use threshold velocities by Komar and Miller (1973, 1975) for quartz particles of diameter less than 0.5 mm in sea water and formulae by Rance and Warren (1968) for particles greater than 0.5 mm diameter. Critical velocities and the grain size capable of being disturbed are calculated for each wave at 25 m increments offshore.

Height transformations for 1.5 and 5.0 m waves across the inner shelf are not pronounced for waves either approaching shore-normal (Table 4) or from the east or northeast (Table 5). Initial wave heights are essentially maintained across the inner shelf to the break point. However, the heights of large waves are affected by the relatively abrupt increase in slope at the point of inflection between the shoreface and the inner continental shelf slopes. At this point, in about 30 m water depth, wave heights begin to increase.

**Wave-induced Sediment Movement**

Using the Black and Healy programmes the maximum bottom orbital velocity was calculated at regular distance intervals across the

Table 4 Height Transformations of Shore-Normal 1.5 and 5.0 metre Waves Across the Pakiri Shoreface and Continental Shelf

| Distance Offshore (m) | Water Depth (m) | Wave Height (m) 1.50 | 5.00 |
|---|---|---|---|
| 5900 | 46.6 | 1.50 | 5.00 |
| 5500 | 45.8 | 1.50 | 4.99 |
| 5000 | 45.0 | 1.50 | 4.99 |
| 4500 | 44.2 | 1.50 | 4.99 |
| 4000 | 43.0 | 1.50 | 4.98 |
| 3500 | 40.9 | 1.49 | 4.97 |
| 3000 | 36.4 | 1.49 | 4.96 |
| 2500 | 31.4 | 1.47 | 4.97 |
| 2000 | 28.0 | 1.46 | 4.99 |
| 1500 | 25.3 | 1.44 | 5.02 |
| 1000 | 19.9 | 1.41 | 5.13 |
| 500 | 8.1 | 1.40 | 5.90 |
| 100 | 2.3 | 1.70 | Wave Breaks |

Table 5 Height Transformations of Easterly and Northeasterly Waves Across the Pakiri Shoreface and Continental Shelf

| Distance Offshore (m) | Water Depth (m) | Wave Heights (m) Easterly 1.5 | 5.0 | 8.0 | Northeasterly 1.5 | 5.0 | 8.0 |
|---|---|---|---|---|---|---|---|
| 5900 | 46.6 | 1.50 | 5.00 | 8.00 | 1.50 | 5.00 | 8.00 |
| 5500 | 48.8 | 1.50 | 4.99 | 7.99 | 1.50 | 4.99 | 8.00 |
| 5000 | 45.0 | 1.50 | 4.99 | 7.98 | 1.50 | 4.99 | 8.01 |
| 4500 | 44.2 | 1.50 | 4.98 | 7.97 | 1.50 | 4.99 | 8.02 |
| 4000 | 43.0 | 1.50 | 4.98 | 7.96 | 1.50 | 4.98 | 8.03 |
| 3500 | 41.0 | 1.49 | 4.97 | 7.91 | 1.50 | 4.97 | 8.05 |
| 3000 | 36.6 | 1.49 | 4.96 | 7.82 | 1.49 | 4.96 | 8.12 |
| 2500 | 31.4 | 1.47 | 4.96 | 7.75 | 1.47 | 4.97 | 8.23 |
| 2000 | 27.9 | 1.46 | 4.98 | 7.67 | 1.46 | 4.99 | 8.34 |
| 1500 | 25.4 | 1.44 | 5.01 | 7.55 | 1.44 | 5.02 | 8.44 |
| 1000 | 19.9 | 1.41 | 5.11 | 7.58 | 1.41 | 5.12 | 8.73 |
| 500 | 8.2 | 1.39 | 5.88 | breaks | 1.40 | 5.92 | breaks |
| 100 | 2.4 | 1.67 | breaks | breaks | 1.69 | breaks | breaks |

representative bathymetric surface. The programs employ linear wave theory to determine the maximum bottom orbital velocity ($U_m$) where

$$U_m = \frac{\pi H}{T\sinh(2\pi d/L)}$$

where H is the wave height, T is the wave period and d is the depth. Komar and Miller (1973, 1975) show that for grain diameters less than about 0.5 mm the threshold velocity to move sediments of diameter D is given by

$$\frac{\rho U_m{}^2}{(\rho_s-\rho)gD} = 0.21\left(\frac{d_o}{D}\right)^{1/2}$$

where g is the gravitational acceleration, $\rho$ is the seawater density, $\rho_s$ is sediment density and

$$d_o = \frac{U_m T}{\rho}$$

where $U_m$ is the maximum bottom orbital velocity, and $d_o$ is the orbital diameter of the wave motion obtained from linear Airy wave theory. For grain diameters greater than 0.5 mm the threshold is predicted with an empirical curve presented by Rance and Warren (1968), where

$$\frac{\rho U_m{}^2}{(\rho_s-\rho)gD} = 0.46\pi\left(\frac{d_o}{D}\right)^{1/4}$$

where the sand density $\rho_s$ is taken as 2.65 in both cases.

The threshold analysis was conducted on waves of 1.5 and 5.0 m and 7 and 12 s period respectively. Waves of these dimensions were initiated 6000 m offshore in water depths of 45 m. A 2 m depth of water was added to create a sea level that approximates the mean high tide level in normal atmospheric pressure conditions. That is,

# Management of the New Zealand Coastal Sand Mining Industry: Some Implications of a Geomorphic Study of the Pakiri Coastal Sand Body

*M. J. HILTON*

Commercial coastal sand mining has traditionally been an important source of aggregate for the New Zealand construction industry. This paper is concerned with the development of a management strategy that ensures coastal mining is located and regulated so as to maximise the sustainability of the resource, and the stability of the industry, while minimising adverse environmental impacts. The stimulus for this discussion arose from a geomorphic and sedimentological investigation of the coast and seabed in Pakiri Bay in the Outer Hauraki Gulf. The upper slopes of the Pakiri inner continental shelf are presently mined for sand by two extraction companies, and is the only major aggregate mining operation on the East Coast of the Auckland Region.

Past decisions concerning coastal sand and shingle extractions at many locations on the New Zealand coast and continental shelf have not been made with regard to an orchestrated management strategy. Directives by consent-granting authorities as to where, how and the volume of sand or shingle to be mined were made in ignorance of the market requirements, resource and manufacturing options, and the environmental context and consequences of the extractions. The need for a national management strategy is timely, particularly in the Auckland Region. Suburban growth and redevelopment of the central business district has ensured a demand for aggregate for concrete manufacture and other construction purposes. Coastal sands from Pakiri are recognised as superior to sands from other sources, and the coastal mining companies are keen to increase their market share (BERL, 1988, 60). While it has been involved in a review of licensing procedures, and in the absence of comprehensive environmental impact information, the Department of Conservation has resisted annual applications to increase production at Pakiri. Should extractions on the Waikato River cease, however, a scenario considered inevitable in the early 1980s (Applied Geology Associates, 1982), the Department may relent to the ensuing pressure and allow the expansion of coastal mining. If future coastal mining activities are to be consistent with environmental legislation such as the *Water and Soil Conservation Act 1967*, the *Town and Country Planning Act 1977* and the *Conservation Act 1987*, there is an urgent need to establish the sustainability of presently mined deposits, the environmental consequences of particular extractions and the range of extraction options.

The transfer of licensing responsibility for coastal extractions from the Ministry of Transport to the Department of Conservation allowed new licence criteria and procedures to be implemented. Regulation of the coastal sand and gravel industry is now under new jurisdiction in accordance with the *Conservation Act 1987*, that binds the Department to conservation principles while administering the requirements of the *Harbours Act 1950*. This new brief is reflected in interim DOC policy which establishes, for the first time, stringent criteria to be considered during the licence application procedure. In all probability some of the existing mining operations, such as those in the Outer Hauraki Gulf, will not satisfy these criteria. If alternative sources of aggregate are required, whether from the seabed or on land, forward planning is required to identify resource options with the greatest possible benefit to society.

Concern for the environmental consequences of mining at Pakiri and other places has grown. Government Departments and territorial authorities that have a statutory responsibility to regulate coastal mining, however, have lacked both specific information and an overall strategy with which to assess applications to mine Crown-owned seabed. Nor has the situation encouraged a coordinated or consistent response to monitoring the environmental impacts of licensed operations. The formation of a management strategy is now being made possible by an expanding knowledge of coastal and continental shelf sediments and geomorphic processes. Recent research of the sedimentology of the Pakiri inner continental shelf (Hilton, 1988) for example, has provided environmental information on which to assess licence applications and alternative research options. Mining operations at Pakiri and elsewhere have, in the past, been justified by the companies and permitted by authorities on superficial information.

## DEVELOPMENT OF THE COASTAL SAND MINING INDUSTRY: THE HAURAKI GULF CASE STUDY

The coasts of the Hauraki Gulf, Kaipara Harbour and Firth of Thames have been a major source of sand and gravel for construction purposes since European colonisation. The beaches provided accessible sediments, of the appropriate size and cleanliness, for a wide range of construction purposes. As demand increased, exploitation of beaches farther afield was made possible by the use of flat bottomed coastal scows. Commercial extractions were undertaken on behalf of sand and gravel merchants who paid a small royalty to the (then) Marine Department. Records and controls were limited, and Ashby (1975) notes that poaching of beaches was a common practice. Figure 1 records the method of loading shingle by the scow *Thistle* on Pakihi Island (ca. 1900-1930), and was typical of the method employed. The vessels were beached on the falling tide and the aggregate shovelled or barrowed aboard during the low tide.

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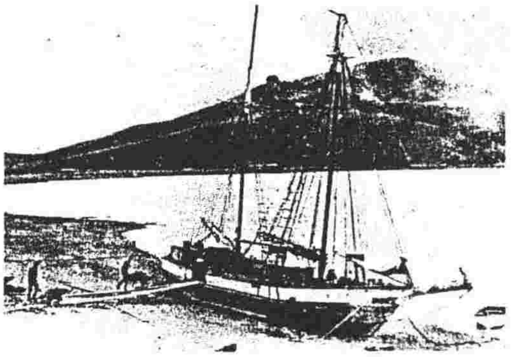

*Fig. 1.* The scow *Thistle* loading shingle on Pahiki Island, Hauraki Gulf, ca. 1900. *Source:* Ashby (1975).

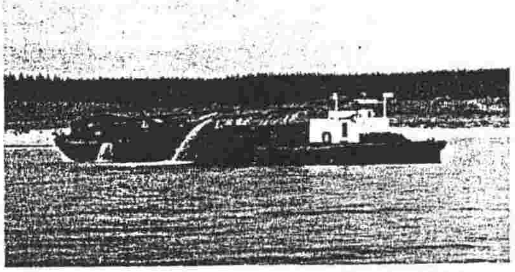

*Fig. 2.* Modern suction dredge, Pakiri Beach, 1987.

Following the Second World War the Harbours and Foreshores Division of the Ministry of Transport was given statutory responsibility for granting annual mining licences under Section 146A of the *Harbours Act 1950.* This legislation provided procedures for declining licences at the discretion of the Minister (of Transport) and regulating the location and quantity of sand or gravel mined. In practice, at least until the early 1970s, this amounted to little more than the inclusion of questions in the mining application on how mining might affect the surrounding environment. Introduction of the *Harbours Act 1950* corresponded with a fundamental change in the nature of the industry with the mechanisation of the extraction process, and the advent of grabs and suction dredges (Figure 2). The largest modern dredges are capable of mining and transporting 1,200 cubic metres of sand over a period of hours, in contrast with the tens of metres of aggregate shifted over a period of days by the scows. That the mechanised operations were efficient is evidenced by the estimates of material extracted from some areas of the coast. Schofield (1985) estimates that 376,000 cubic metres of sand were extracted from Omaha Bay between 1942 and 1963, and Ministry of Transport licence records (now with the Department of Conservation) show that at least 1.5 million cubic metres of sand have been extracted from Pakiri Bay alone since 1966. Figure 3 shows some of the beaches and amounts licensed for mining between 1966 and 1979. Virtually every beach on the East Coast of the Auckland Region has been mined, although production has centred on the mainland and island beaches of the Outer Hauraki Gulf.

The actual quantity and location of aggregate mined from the beaches, and the adjacent shallow nearshore, are poorly documented. There is no independent assessment of the amounts extracted, since all statistics are derived from data forwarded by the companies themselves. Because the volume of aggregate removed attracted both a royalty and a port handling charge, the total volumes reportedly mined are, at best, a conservative estimate. Figure 4 records the volume of aggregate reported to have been landed at the Port of Auckland from all East Coast locations, including silica sand from Parengarenga Harbour, between 1900 and 1987. These data presently provide the best indication of trends in coastal mining production this century. The amount of aggregate extracted from the Hauraki Gulf can be seen to constitute a major proportion of the total volume, and accounts for most of the fluctuation over the last 15 years. The graph of total aggregate indicates a general growth in production, with temporary declines accompanying the two World Wars and the depression of the early 1930s. That these patterns are real, and not some artifact of changing administrative procedures, is suggested by comparable trends in the production of cement over the same period. Production of both products peaked in 1974, declined until 1980, then continued to rise until 1986. The marked decline in production of both products after 1974 coincided with the completion of major public works in the North Island, including hydroelectric schemes.

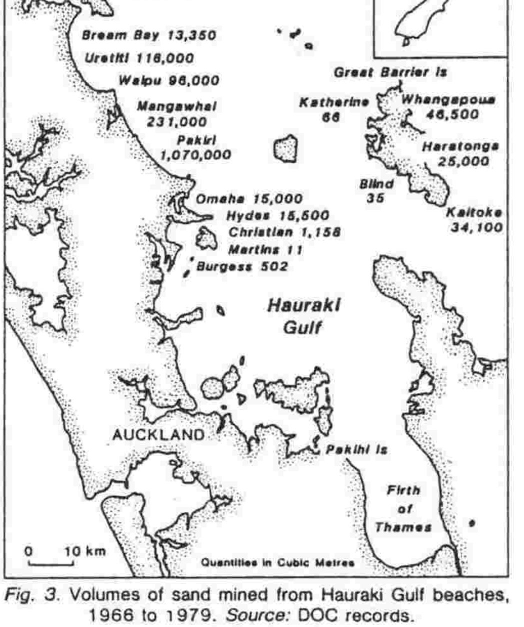


*Fig. 3.* Volumes of sand mined from Hauraki Gulf beaches, 1966 to 1979. *Source:* DOC records.

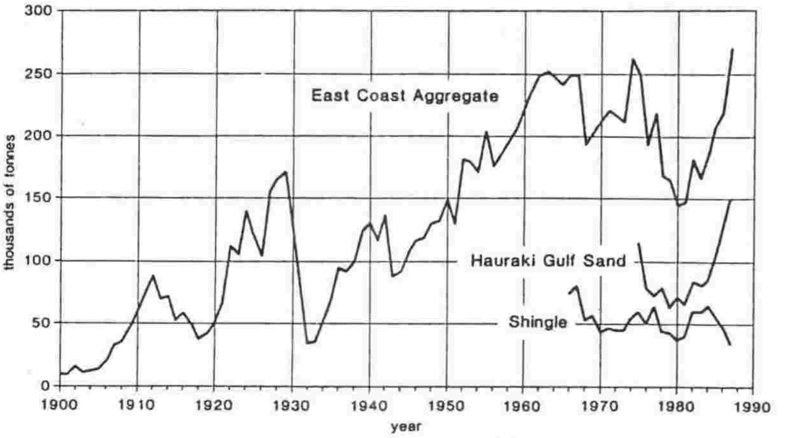


*Fig. 4.* Coastal aggregate landed at the Port of Auckland, 1900 to 1987. *Source:* Auckland Harbour Board.

The clean, well sorted, quartz-feldspathic sands of the Outer Hauraki Gulf are ideal for construction purposes and have become the standard against which other sand occurrences are compared (Applied Geology Associates, 1982). The composition and textural characteristics required of sands for concrete manufacture are described in New Zealand Standard Specifications 3111 and 3121 (1986). These specifications allow a wide range of sediment textures to be utilised, so long as the salt concentration and proportion of mud remain low. Blending of aggregates from different sources to achieve an ideal mix is common. The only coastal sands presently being mined in the Hauraki Gulf are those along the Pakiri coast. These sands are barged directly to Auckland where they are mixed with dune sands from Woodhill and crushed Auckland basalt in the manufacture of concrete, or used directly for a range of construction purposes. The Woodhill sands are by themselves too fine to be used in the production of concrete, while the composition of Waikato sands makes them more suitable for concrete block and related products.

Since the devastating East Coast storms of July 1978, which caused severe beach erosion, there has been increasing awareness of both natural and human-induced causes of erosion. Consent-granting authorities have become increasingly reluctant to issue licences near areas of coastal development. For example, at Pakiri mining was eventually restricted to the isolated northern third of the bay, primarily as a result of lobbying from local residents. Coastal mining steadily decreased in the late 1970s, while production from the Waikato River has been allowed to increase. Examination of Ministry of Transport files indicates that little scientific justification for either denying or reducing licences has so far been offered, and there has apparently been scant consideration of production trends in the aggregate industry generally when assessing coastal mining-licence applications.

## LEGISLATIVE CONTROLS ON COASTAL SAND MINING

In 1987 statutory responsibility for annual licensing of mining operations passed from the Harbours and Foreshores Division of the Ministry of Transport to the newly created Department of Conservation (DOC). Licences are still issued under Section 146(A) of the *Harbours Act 1950,* although in accordance with its conservation role DOC now places much greater emphasis on the provision in the Act for environmental protection. Section 6 of the *Conservation Act 1987* outlines some of the functions of the Department, including the responsibility to 'Manage for conservation purposes, all land, and all other natural and historic resources for the time being under this Act', and to 'Advocate the conservation of natural and historic resources generally'. Hence, for the first time, legislation specifically requires a licensing authority to manage coastal aggregate resources.

DOC interim policy (1987) distinguishes between sediments that are renewable and non-renewable, and those that are part of dynamic beach-nearshore sediment systems. The potential for exchange between nearshore, beach and dune sediments is appreciated, and there is a requirement that the general environmental and particular geomorphic context of a prospective mining site be understood, prior to licensing. The DOC guidelines are non-specific, however, as regards the type and quality of information required, only that 'Should the impacts be significant a more detailed environmental impact assessment may be required and applicants may need to obtain specialist advice or employ a consultant' (DOC, 1987, 5). What constitutes a 'significant' impact, and over what time scale, is unclear. A more fundamental problem may be assembling (by whoever) sufficient data on which to assess the exact impacts of a particular seabed extraction.

The procedure by which consent is obtained to mine the coast or seabed allows for the participation of local, regional and national Government agencies. Licence applications are forwarded to the Ministry of Transport, Ministry of Works and Development, Ministry of Agriculture and Fisheries (Fisheries Management Division), Maritime Planning Authorities, Catchment Boards and Territorial Local Authorities for approval. A key step in the procedure is the assessment of information pertaining to the environmental impacts of the proposed mining operation. Applicants are required to establish that the extraction will result in no long-term harmful environmental effects, and that no alternative extraction site is available. These requirements represent a fundamental change in policy since, for the first time, onus is placed on the mining companies to support their applications with substantive environmental evidence that their operations have no adverse effects. Given the present lack of understanding of coastal sediment systems, and alternative coastal sources, however, it is most unlikely that these requirements can be completely satisfied. In all likelihood long term environmental impacts are presently beyond human prediction anyway. To expect the mining companies to undertake impartial research required to identify effectively their impact on a complex, imperfectly understood, natural system, in the absence of coordinated governmental research and an effective management strategy, is impractical. Nor would *ad hoc* decisions by DOC, based on environmental impact assessments alone, provide the benefits of a comprehensive management strategy.

Local and regional government authorities have statutory responsibilities concerning activity that might affect the quality of the coastal environment. In the Auckland Region, for example, the Auckland Regional Water Board exercises influence and responsibilities under the *Soil Conservation and Rivers Control Act 1941* and the *Water and Soil Conservation Act 1967*. Both Acts require the Board to prevent unwarranted erosion of the coast and seabed, that might result from activities such as sand mining. The Auckland Regional Authority is required by the *Town and Country Planning Act 1977*, First and Second schedules, to consider and plan for those activities that might have a detrimental effect on the coast. In the Auckland Region the Planning Scheme is operative and has specific policy concerning coastal sand mining . Policy 5.73 (Auckland Regional Authority, 1988. p60) states that

> Mining, drilling or dredging in marine areas which have high ecological, fishery, recreational or amenity values will be opposed, unless such values are outweighed by the economic advantages of extraction to the regional community.

The present Government favours the concept of 'Devolution of decision making to that Authority which is nearest the community of interest most affected . . .' (Ministry for the Environment, 1988, 46). As a result of the Resource Management Law Reform process the Catchment, Regional and Local Authorities may well be required or invited to undertake a more active role in coastal management generally. If these agencies become the consent-granting authority, overall management of coastal aggregate resources should still be vested in a Central Government authority, such as DOC, that would retain a national perspective and have ultimate responsibility for the management of coastal aggregate resources.

## A CASE STUDY: THE PAKIRI-MANGAWHAI COASTAL SEDIMENT BODY

The environmental context of offshore sand mining at Pakiri is probably similar to many operations around the East Coast of the Bay of Plenty, Coromandel, the Hauraki Gulf and Northland. Between Auckland and Whangarei the coastal embayments of the Hauraki Gulf were the sites of extensive marine deposition of late-Quaternary marine sediments. In many instances the dune and beach-ridge sands of the Holocene barriers are contiguous with beach and extensive subtidal sediments of the inner continental shelf. These accumulations of marine sediments, particularly in the Outer Hauraki Gulf, appear to be discrete sediment bodies, isolated from adjacent compartments. They are composed primarily of quartz-feldspathic fine to medium sands, which are thought to have been worked onshore during the late-Quaternary sea level transgressions (Schofield, 1970). Contributions of terrestrial sediments to the coast are not thought to be significant (Carter, 1975). The catchments draining to the East Coast are small, and sediment that does reach the coast is trapped behind coastal barriers in lagoons and estuaries. As a result biogenic production is an important contemporary influence on the sedimentology of the inner continental shelf.

The Pakiri-Mangawhai coastal sediment body extends from Bream Tail to Cape Rodney in the south, and is the largest of the Hauraki Gulf sediment bodies. The quintessence of this feature is the continuity of unconsolidated sediments between the coastal dunes and the base of the inner continental shelf. This accumulation of marine sediment extends alongshore, within the Mangawhai-Pakiri embayment, 23 kilometres, and offshore a maximum of 5,000 metres to depths of 45 to 50 metres. The rocky headland of Te Arai Point separates the coasts of Mangawhai and Pakiri Bays, but exerts only a local influence on the sedimentology and morphology of the sediment body. The sedimentology of the seabed around the major headlands, however, indicates sediment exchange with Omaha Bay to the south, and Bream Bay to the north, does not occur. The catchments draining into Pakiri and Mangawhai Bays are small, and unable to supply significant amounts of sand-sized sediment to the sediment body. New sediment may thus enter the subtidal sediment system from offshore, erosion of the foreshore or as a result of *insitu* biogenic production.

The unconsolidated sediments of the Pakiri-Mangawhai sediment body extend across the width of the inner continental shelf. This feature is a broad, gradually-sloping surface that culminates relatively abruptly, 6,000 metres offshore, in water depths of approximately 45 metres. At this point there is a change in slope marking the juncture between the inner and relatively flat middle continental shelf of the Outer Hauraki Gulf. Across the inner shelf itself there is a systematic variation in morphology, with five subtidal components consistently present (Figure 5a). A beach, inshore trough/nearshore bar association, an upper concave and lower convex shoreface, an area of hummocky topography at the base of the inner shelf, and the relatively flat middle continental shelf. This pattern is persistent between Mangawhai and the Pakiri River, but is modified as the sediment body is attenuated towards the headlands of Bream Tail and Cape Rodney and the inner shelf narrows and steepens. The modal beach state according to Short and Wrights' (1981) classification is of the intermediate longshore bar-trough type, tending towards a dissipative morphology. Repeated echosound surveys since 1978 indicate the nearshore bar is a persistent feature of the Pakiri coast, over which waves break in high energy conditions. During low-wave activity the beach state tends more towards a reflective (intermediate) state, with the development of transverse bars and rips.

The sedimentology of the Pakiri inner continental shelf shows marked textural and composition variations across the inner shelf. Seven sediment facies are identified (Figure 5b):

1) Fine, well-sorted eolian sands of the coastal dunes.
2) Medium, moderately-well sorted beach sands with a high carbonate content.
3) Fine, very-well sorted sands of the inshore-nearshore.
4) A medium to coarse sand facies that extends across the inner shelf, becoming increasingly coarse and muddy with distance offshore.
5) A poorly-sorted sediment, comprising very coarse sands and fine gravels, with a high carbonate content.
6) Fine, muddy sands, with a moderate shell content, seaward of the inner-middle continental shelf break.
7) Sediments of the rocky coasts dominated by high proportions of carbonate fragments and fine gravels.

The boundaries of some of these facies are not as abrupt as portrayed, but rather tend to grade into adjacent facies. The exception is the abrupt change in sedimentology between the inner shelf and the middle continental shelf. This is evident in the variation of mean grain size (non-carbonate fraction), proportion of mud (sediment less than four phi units) and carbonates across a representative transect (Figure 6). The sands of the beach and inshore (surf) zone are coarser and less well sorted, and contain a higher proportion of carbonate material, than either the eolian sands of the adjacent coastal dunes, or the fine nearshore sands. Seaward of the nearshore bar the very well sorted sands become initially finer, but then progressively coarser, and with an increasing shell content, across the inner shelf. At the base of the inner shelf, associated with the hummocks, the sediments are very coarse sands and fine gravels and contain up to 30 percent shell material. Seaward of the mounds the sediments become abruptly finer, and contain much less shell. The proportion of mud in the samples, which remains less than three percent across the inner shelf, increases rapidly as the sands become abruptly finer, to between ten and 15 percent of total sample weight. An extensive and intensive sampling programme of the surficial sediments (Hilton, 1988), and the work of McCabe (1986), have shown this sequence of facies to extend alongshore between Mangawhai and the Pakiri River (Figure 7). The sediments near Cape Rodney and Bream Tail are primarily locally-derived shell gravels, dominated by rocky shore mollusca and rock fragments.

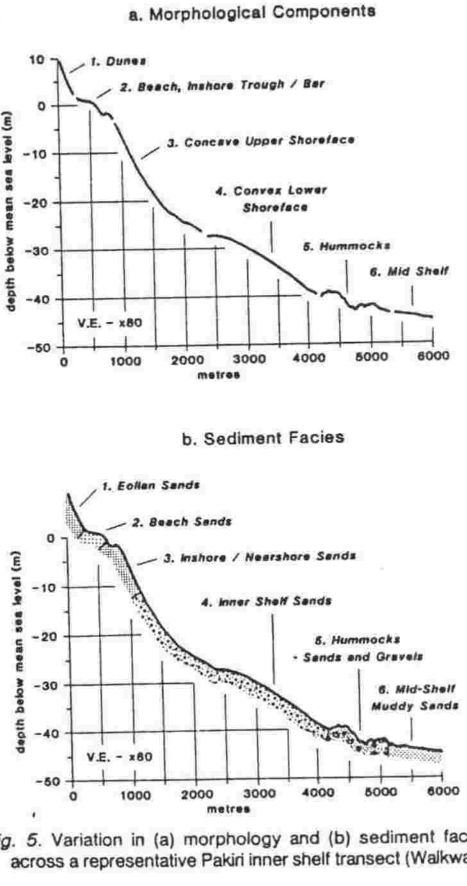


*Fig. 5.* Variation in (a) morphology and (b) sediment facies across a representative Pakiri inner shelf transect (Walkway).

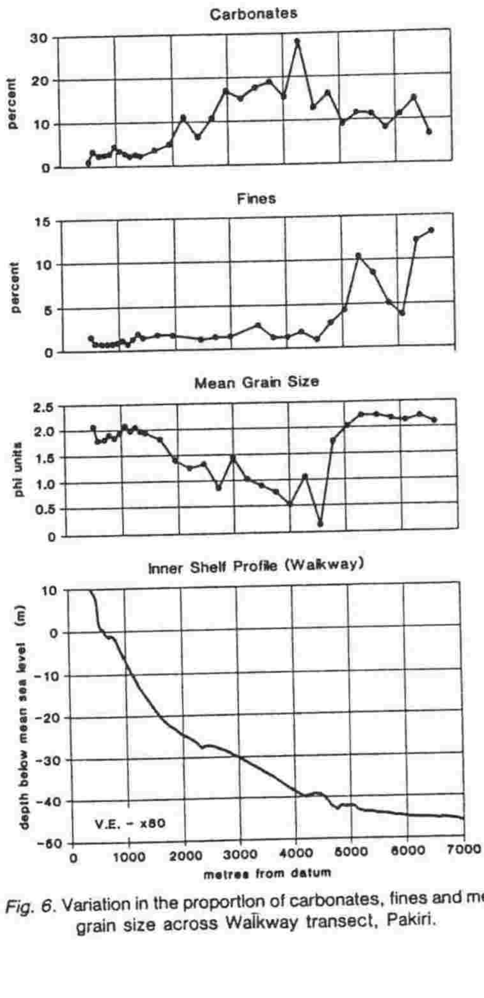


*Fig. 6.* Variation in the proportion of carbonates, fines and mean grain size across Walkway transect, Pakiri.

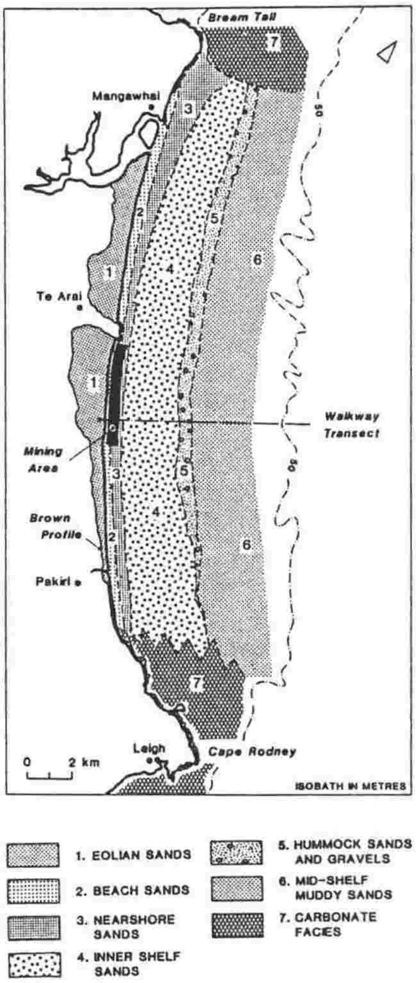


*Fig. 7.* Sediment facies of the Pakiri-Mangawhai sediment body.

The paucity of sand in these sediments suggests alongshore sediment transport around these headlands does not occur. Replicate sampling over a four year period has indicated the persistence and stability of these facies patterns (Hilton, 1988).

The East Coast of the Northland Peninsula is a lee coast, sheltered from the prevailing westerly winds, but exposed to the dominant easterly and northeasterly winds. The latter are associated with subtropical cyclones, or the remnants of tropical cyclones, which track in a southeast direction to the east of New Zealand. Winds associated with these cyclones may reach hurricane force, and produce long-period waves associated with onshore storm surges. During the storm of 19 to 21 July 1978, a waverider buoy moored in Bream Bay recorded waves of nine metres' height and 12 seconds' period (Peek, 1979). McCabe (1985) calculated that the Pakiri-Mangawhai coast experienced a storm surge of 2.24 metres above predicted water levels during this event, which caused foreshore erosion of tens of metres at Pakiri and Omaha and other coasts exposed to the northeast. For prolonged periods, however, mean wave height is less than 1.5 metres with periods of six to eight seconds. The high frequency and persistence of such conditions allows sand to be mined from the nearshore bar, with regard to other operating constraints, about 120 days on average each year (BERL, 1988). The geomorphic environment at Pakiri in which sand extractions are made is thus one of considerable dynamism, an intrinsic characteristic of exposed sandy beaches.

The mining companies presently extract the fine, very well sorted, sands of the seabed around the nearshore bar. The cleanliness of these sands almost certainly results from the constant wave motion in this area. The origin of the facies is, however, less equivocal. They may result from the erosion of coastal dunes during storms, as occurred during the 1978 events, and commonly occur on a much lesser scale. Or fine sediments may be transported shorewards preferentially, by the action of orbital currents caused by shoaling waves. The coarsening of sediments offshore across the shelf may be the result of the preferential transport of fine sediments shorewards. Calculation of maximum (bottom) orbital velocities using linear wave theory, and the sediment threshold velocity formulae of Komar and Miller (1973, 1975), indicate the potential for waves to transport sediments across Walkway transect. Waves of 1.5 metres height have the potential to disturb sediment 2,250 metres offshore, to water depths of 28 metres below mean sea level, while storm waves of five metres may disturb sediments of greater than granule size over the width of the inner shelf, and fine sands across parts of the middle continental shelf.

The precise mechanisms by which waves and currents influence the morphology and sedimentology of the Pakiri-Mangawhai sediment body are as yet unresolved. A few tentative conclusions, however, are justified. Field studies of tidal and other currents, and theoretical and field investigations of wave-sediment interactions, indicate the disturbance and transport of sediments are largely due to currents associated with shoaling waves. Oscillatory currents at the seabed result from wave progression through the water body, and unidirectional currents result from the interaction of storm waves with the seabed and coast. The former is probably responsible for the shoreward movement of sediment during a range of wave energy conditions. This might account for the transgressive-like morphology of the convex component of the lower inner shelf, the presence of wave-formed ripples and megaripples, the formation of the coarse sand and shell deposits of the hummocks as lag deposits, as well as the textural gradients that imply shoreward transport of sediment. The upper concave section of the inner shelf is envisaged as dominated by rare storm events, during which sediment is circulated within the concave component of the inner shelf, primarily in an onshore-offshore direction. These processes are envisaged as occurring over thousands of years, and in terms of net transport of sediment may involve relatively small volumes over human time spans. Perhaps the most important implication of the work to date is that the fine nearshore sands presently mined are probably not being renewed by either onshore or alongshore sediment movement. Compared with other coastal and shelf environments which receive copious fluvial supplies of sediment, such as the South Otago Shelf (Carter, 1986; Griffiths and Glasby, 1985), the Pakiri, sediment body is a closed system with finite amounts of sediment.

## THE ENVIRONMENTAL CONSEQUENES OF COASTAL SAND MINING: THE PAKIRI CASE STUDY

The Pakiri-Mangawhai coastal sediment body is more complex, dynamic and expansive than was previously envisaged. DOC guidelines (1987) propose that the seaward limit of sediment exchange within the beach system is between water depths of six and twelve metres. At sites like Pakiri, sediment disturbance and transport may occur over the entire sediment body, from coastal dunes to deep shelf depositional environments. The sediment facies described at Pakiri are not relict, but rather a response to modern processes of marine sedimentation. Determining the environmental impacts of offshore coastal mining in this context is a complex problem.

The potential impacts of coastal sand mining in New Zealand have been discussed by Anon (1974), Gillie and Kirk (1980) and van Roon (1981). Mining can result in physical, biological and chemical modifications of the coastal environment. Although to date attention has focused on physical disturbance of coastal and shelf sediment systems, in particular the potential for accelerated erosion of sandy foreshores. For example, foreshore erosion and property loss at Omaha following the 1978 storms were attributed in part to offshore sand mining. Schofield (1985) concluded that nearshore sand mining and the lowering of the frontal dunes along the Omaha foreshore, had exacerbated a situation which tended naturally towards one of coastal erosion. In a review of coastal zone erosion problems, Kirk (1977) states that coastal sand mining is probably the most damaging human impact on beach sediment budgets throughout New Zealand. This connection between coastal mining and erosion is often cited, yet the causal relationships between accelerated erosion and mining have not been well documented.

Gillie and Kirk (1980) identify four main classes of physical impacts that may result from mining, namely, bathymetric changes, changes in sediment particle size , increased turbidity and coastal erosion. At Pakiri the sand is suction dredged from water depths of between four and eight metres on, or seaward of, the nearshore bar, about 200 metres offshore. The result is a borrow pit or trench two to three metres deep, covering an area of between 15 and 20 square metres. These depressions may persist for several days during periods of prolonged low wave energy, but are usually smoothed over several hours. Extraction sites are sufficiently dispersed within the licence area for there to be no apparent localised short-term effects of the extractions. Focusing of wave energy on the beach, as waves are refracted over the borrow pit, is thus unlikely to be of serious import. The textural characteristics of the nearshore sediments are not drastically modified by the mining operations, although persistent screening of molluscs at the moment of extraction must increase the proportion of shell material in the nearshore sediments; and because of the absence of muds in the nearshore surface sediments water turbidity is not normally influenced.

The area of greatest concern at Pakiri is the longterm, persistent removal of sand from the nearshore bar. Established models of beach change and sedimentation (see Komar, 1976) predict the dynamism of exposed sandy beaches. Sand is commonly eroded from the berm and upper beach by storm waves and transported offshore, to accumulate in relatively calm water as a nearshore bar. During subsequent calm swell wave conditions this sediment may be transported back onshore to form a berm and contribute to foreshore accretion. For example, the July 1978 storms resulted in erosion of the foreshore and the deposition of vast quantities of sand on the nearshore seabed to water depths of between 15 and 20 metres below mean sea level. Figure 8 presents the results of an analysis of a time series of beach-nearshore profiles (located in Figure 7), surveyed along Brown transect between 1978 and 1987. Given that the profiles were surveyed by different organisations, using different techniques to varying degrees of accuracy, trends should be interpreted with caution. Even allowing for substantial vertical and horizontal error margins, however, the isoline analysis indicates bathymetric fluctuations. Over the ten year survey period the morphology of the nearshore has varied between two forms. Following the 1978 storms a convex bulge extended to water depths of 15 to 20 metres. Since then the nearshore shore-normal profile has attained a concave form, presumably as sand eroded from the foreshore in 1978 has been redistributed within the beach-nearshore circulatory system. These results indicate that mining of sand from the nearshore bar must result in a loss of sand from this system. This activity is potentially detrimental, even though the amounts extracted are orders of magnitude below the quantities regularly eroded during storm events. The location of the mining may be more important than the quantities mined, particularly if sand extracted from the nearshore bar is replaced during storms from erosion of the beach and foreshore, rather than from sources offshore or alongshore. That this is not the case has yet to be established.

Coastal mining may also have serious consequences for biological systems in the shallow marine environment. At Pakiri the mining operations have the potential to influence greatly the distribution and abundance of various marine macrofauna that inhabit the nearshore bar. The sand dollar *Arachnoides zelandiae* may be present in concentrations of over 100 per square metre, and another echinoderm, the heart urchin *Echinocardium australe,* is also common. The small gastropod *Unbonium zelandicum* is commonly present along the crest of the nearshore bar in densities of thousands per square metre. The effect of the mining extractions on these animals has not been investigated, although the echinoderms are exceedingly brittle and would almost certainly be crushed by the suction apparatus. They form an intrinsic part of the ecology of nearshore sand bodies and may also be important in maintaining bed stability by armouring the seabed.

Mining has not been the only anthropogenic disturbance of the Pakiri coast. Prehistoric Maori occupation (Pritchard, 1983) afforestation and foredune disturbance, grazing, subdivision, non-commercial beach mining and recreational activities have resulted in either direct or indirect losses of sediment from the foreshore and dunes. Many of these impacts have disturbed the distribution of sand-binding plants, resulting in the formation of blowouts and landward migration of dunes. This process reduces the volume of sand in the foredune

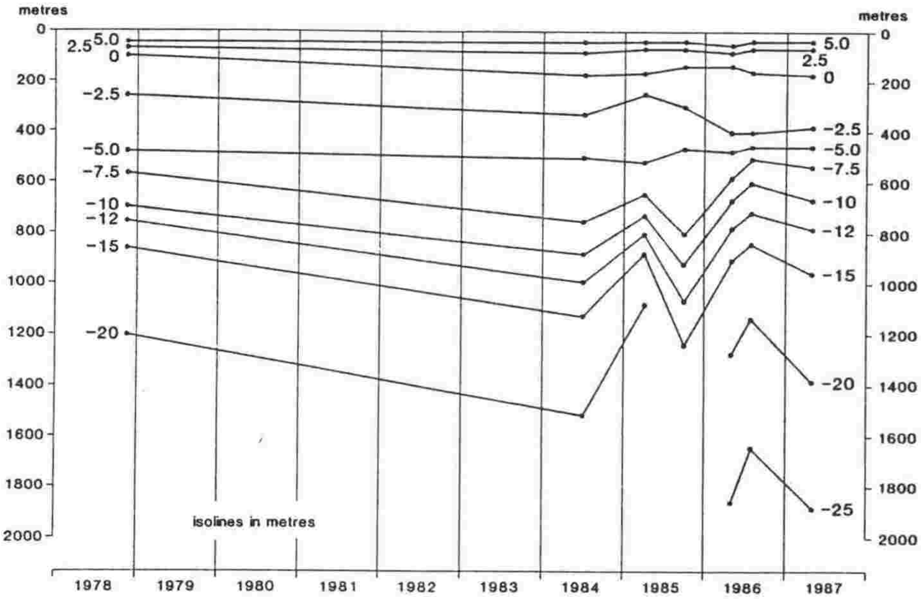


*Fig. 8.* Analysis of a time series beach-nearshore profiles, 1978 (post-storm) to 1987 (Brown transect). Each isoline connects points of equal elevation. Mean sea level approximately 1.7 metres above chart datum (0 metres). *Source:* Auckland Regional Authority, Field Survey.

complex and hence the volume of sand in the beach-nearshore circulatory system. The possible result is accelerated foreshore erosion during storms. Whether erosion is due mainly to storm events, or is a function of longterm fluctuations of global sea levels, exhaustion of offshore coastal sediment supplies following a prolonged sea level stillstand, the activities of people, or a combination of all of these factors, is as yet unresolved. It is important to appreciate, however, that at sites like Pakiri, with a history of anthropogenic disturbance, mining is but one of a number of factors contributing to coastal change. It is not surprising then, that in an atmosphere of ignorance and often indifference, consent-granting authorities in the past have failed to consider adequately the longer term consequences of coastal sand mining. This has occurred within an administrative system that has historically placed the onus on licensing authorities to establish that a particular mining activity is detrimental, rather than the converse.

Consent-granting authorities have permitted and regulated coastal mining operations on the basis of the most superficial environmental information. The present extraction levels at Pakiri are based on a brief study of historic coastal change by Lees (1982). A beach sediment budget for the Pakiri-Mangawhai Coast is calculated by Lees in which onshore-offshore sediment transport, in addition to fluvial inputs, accounts for the transfer of 180,000 cubic metres of sand per year into the beach sediment system. However, the use of inadequate data derived over differing time periods renders the results meaningless. The sediment budget is intended to apply to the period of photographic analysis, 1942 to 1981. The factor 'change in storage', however, is derived from two series of beach surveys over a six month period in 1989 by the Auckland Regional Water Board. These extend between the crest of the foredune and the approximate position of mean low water, and represent only a minor portion of the beach-inshore-nearshore sediment circulatory system that extends hundreds of metres offshore. Further, the deflation factor applies to a two year period (1979 to 1981) during which artificial foredune construction occurred, while the basis for assuming significant alongshore transport is to the north, and that estuary infilling is 10 percent of this value, is not stated. Despite Lees' primary conclusion that the 'hazy data, and the lack of rigorous data, means data interpretation and conclusions are not definitive' (in Applied Geology Associates, 1982, Appendix 2, 54) the results have been used to determine the volume of sand mined since 1982. There is thus no basis for the present licence conditions at Pakiri that state the amount of sand to be mined and that mining should be constrained between the Poutawa Stream and Te Arai Point.

It must be acknowledged that there are no obvious localised impacts of the sand mining activity, particularly as the operations have been largely confined to the area between Poutawa Stream and Te Arai Point since 1980 (see Figure 6). This may simply reflect the moderately high energy regime of this coast, where wave action rapidly removes any local signs of the mining, and impacts are averaged over the entire sediment system by internal circulation. Or it may be that the amounts mined to date are insignificant compared to the dimensions of the natural system. The Pakiri shore apparently responds in a similar direction, and with a comparable magnitude to storm events that affect the entire Northland East Coast, suggesting that mining is of secondary or lesser importance in explaining coastal development. Clearly,

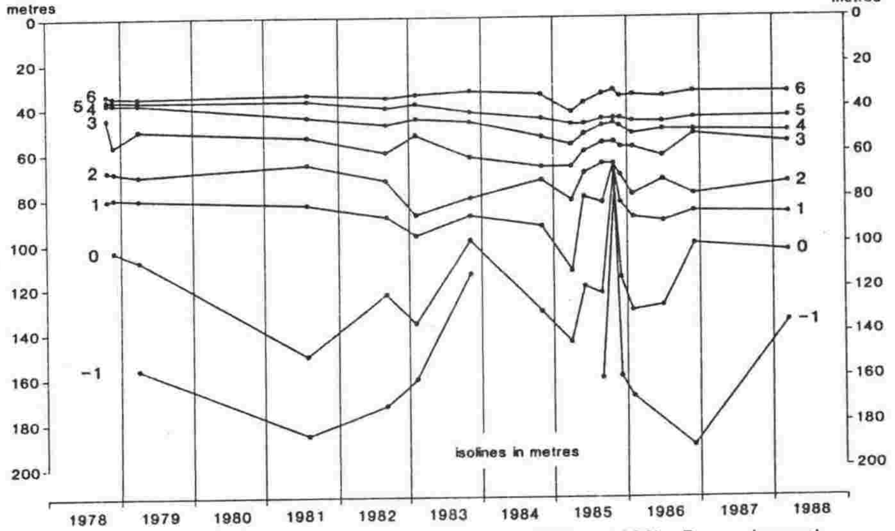


*Fig. 9.* Analysis of a time series of beach surveys (1978 to 1988), Brown transect. *Source:* Auckland Regional Authority, Field Survey.

storm events of the severity of the July 1978 storms overwhelm local circumstances and are the primary factor in explaining foreshore erosion. Nor is there evidence that the Pakiri coast has eroded in an exceptional manner in historic times, although at isolated sandy coasts like Pakiri the historic data are notoriously inadequate. In a review of historic shoreline changes, Lees (1982) compared aerial photographs of the Pakiri-Mangawhai Coast covering the period 1942 to 1981. The photographic record is unsatisfactory, with infrequent coverage at varying photo scales. Further, the results reported do not seem consistent with the conclusion that 'The long-term change at Pakiri-Mangawhai Beach is towards progradation' (Lees, 1982, 29). Accretion reported by Lees between Te Arai Point and the Poutawa Stream in the periods 1976/77 to 1980/81 is not natural, rather the result of foredune reconstruction by the New Zealand Forest Service, following the storms of July/August 1978 (Wishnowsky, 1981). Most seriously, calculation of the net rates of change between the Poutawa Stream and the Pakiri River do not incorporate the effects of the 1978 storms, and are locally biased by fluctuations in foreshore position around the Pakiri River mouth and Mangawhai Harbour entrance. Exclusion of these data and the incorporation of beach survey data indicate that the net change in position of the Pakiri foreshore since 1942 has been landward tens of metres. The most significant conclusion, however, is not that a particular trend is evident, but that the Pakiri coast is dynamic, and responsive to marine conditions.

The most reliable historic evidence of the direction and magnitude of coastal development at Pakiri is a time series of beach and nearshore echosound surveys commenced in 1978. Figure 9 presents the results of an analysis of beach surveys across a representative Pakiri Beach transect (Brown). These were surveyed by the Auckland Regional Water Board between 1978 and 1983, and by the author from 1984 to 1988. Fluctuations in beach width and volume are at least partly explicable in terms of the variations in incident wave height and period. Since a persistent period of easterly winds in September 1985, periodic scarping of the foredune during storms has translated the beach profile to about its position when the surveys began, immediately following the 1978 storms. The net change in shoreline position over the ten year period (1978 to 1988) has thus been negligible. Whether erosion since 1985 is a short, medium or long term trend, and is exacerbated by the mining operations, is presently beyond confirmation. Given the apparent global trend towards erosion of sandy coasts, however, there should be concern for the recreational and ecological values of beaches, and intense scrutiny of those activities, including sand mining and foredune disturbance, that may disrupt the natural development of sandy coasts.

The major reason nearshore coastal mining has continued, despite occasional protestations (for example, Anon, 1974; Kirk, 1977) has been the difficulty determining the extent to which observed coastal change can be attributed to mining activities, rather than natural processes of coastal development. While at least 1.5 million cubic metres of sand have been mined from the Pakiri nearshore, there is no unequivocal evidence that mining has accelerated natural processes of coastal erosion. This is not to imply there have been no detrimental impacts: rather they are, given our present understanding of coastal development, inseparable from natural processes. While the immediate impacts of the mining at Pakiri may be obscured by water, and rapidly obliterated by wave action, the long-term consequences may be no different than if direct mining of the beach had continued. Consent-granting authorities must appreciate that such long-term impacts are gradual, probably irreversible and difficult to predict with precision. In all probability, mining of the nearshore bar at Pakiri and elsewhere entails the greatest risk of accelerating or exacerbating natural occurrences of erosion.

The sands presently mined at Pakiri are part of an extensive subtidal sediment body (Hilton, 1988). In terms of the potential of these sediments to be mined for construction purposes, it is significant that the proportion of fines in seabed samples remains low to water depths of 40 metres, attained some four kilometres offshore, and the percent weight of carbonate material is generally less than 10 percent. Much of this carbonate material occurs as whole molluscs which may be separated at the time of dredging, as occurs during the present mining operation. Mean grain sizes fluctuate only within the Wentworth sand size grades, such that the offshore sands are comparable to those sands presently mined. These grades appear consistent with the textural requirements of the New Zealand Standards Association Specifications for concrete manufacture. Assuming an average sediment thickness over the Pakiri inner continental shelf of only two metres, the total volume of recoverable sand in water depths between 20 and 40 metres is approximately 120 million cubic metres. Given that existing extraction rates are 65,000 cubic metres annually, this represents a resource of potential significance.

## THE NEED FOR A MANAGEMENT STRATEGY FOR THE COASTAL SAND MINING INDUSTRY

Little attempt to date has been made to develop or implement a management strategy for the coastal mining industry. The existing legislation has allowed the industry in the Auckland Region and elsewhere to evolve in the absence of an overall strategy that would either facilitate development of the industry, or protect the resource from unwarranted exploitation or the environment from unnecessary damage. Decisions of when, how and where to mine have been based primarily on entrepreneurial enterprise. Sand is presently mined from beach sediment systems because that is the cheapest place to obtain the raw material. In the absence of an overall management strategy, *ad hoc* decisions have been forced on district, regional and central government authorities. These decisions are frequently retrospective and negative, following occasions of coastal erosion or expressions of public concern. Ideally a consent-granting authority would not simply react to entreprenurial initiatives, or to other external pressures, but work from a position that enabled it to recommend mining sites, methods and rates of extraction to those who perceive a commercial advantage from this activity.

This process would be based on calculated decisions towards well-defined objectives by consent-granting authorities, including a justification of the real need to extract coastal sands. This process is anticipated in the operative Auckland Regional Planning Scheme. To date the need for coastal sediments, however, has not been demonstrated with respect to the 'wider public benefit'. If there is a demonstrable need for coastal sands then alternative, more environmentally sensible options should be explored. The discussion of the Pakiri coast, as an example of just one of the areas of New Zealand's coast presently mined, has argued both that the present mining activity of the beach-nearshore bar is potentially damaging, and that alternative sources of sand are available nearby. While mining of any part of the seabed will result in some environmental damage, enough is now known about the Pakiri inner continental shelf to predict that mining here will result in far less impact. It is beyond the scope of this paper to assess the viability of the various options, in terms of the technologies required, socioeconomic or environmental implications. Rather, it is argued that technology and resource options do exist, and have not yet been considered.

In accordance with the *Conservation Act 1987*, DOC has the responsibility to manage coastal aggregate mining. It is thus ideally situated to provide, for the first time, an overview of both the resource base and mining activities. With regard to the former, management has been frustrated in the past by a lack of knowledge of coastal and inner shelf sediment deposits. A vital first step towards an enlightened management strategy would be a detailed survey of the sand and gravel deposits of the New Zealand coast. In the first instance this survey should be targeted towards areas where mining is likely to be both environmentally and commercially acceptable. Such a survey is presently being undertaken around the coast of England by the British Geological Survey (Milne, 1987), with the aim of identifying the potential sand and gravel resource. While the sedimentology of the New Zealand continental shelf has been surveyed by the New Zealand Oceanographic Institute (for example, Eade, 1974), investigations of the more accessible inner continental shelf have been attempted at comparatively few locations. For this reason past attempts to evaluate future resource options (for example, Applied Geology Associates, 1982) have been hindered by insufficient knowledge of specific coastal deposits. A knowledge of the potential recoverable resource is essential, and would place DOC in the ideal situation of being able to promote certain areas where mining is most environmentally acceptable.

Research in recent years has developed an understanding, albeit incomplete, of coastal sedimentation. Processes of sedimentation affecting the inner continental shelf, however, are still poorly described, and from relatively few shelf environments. Questions concerning the potential for onshore/offshore movement of sediment across the inner continental shelf sediment bodies, and the response of the shoreface to rising sea levels remain to be answered. Hence, it will not always be possible to predict the actual consequences of sand mining, even at well researched locations. Monitoring should thus form an important part of a management strategy with continuous assessment of any activity. Bishop (1984) describes the approach to environmental monitoring developed for the Deep Ocean Mining Environmental Study (DOMES). This approach allows continual adjustment of the mining operation following the results of monitoring investigations, and in response to increased knowledge of a particular system. Such an approach is both efficient and viable, particularly if overall control is retained by a central agency that has the resources and the authority to maintain an ongoing monitoring program, in cooperation with other organisations, such as local or regional government authorities.

## ELEMENTS OF A PROPOSED MANAGEMENT STRATEGY

This paper has discussed inadequacies in the way in which coastal sand mining has been regulated in the past.

At no time has such a strategy, with clearly defined objectives, been applied. Decisions on where and how much of the seabed's aggregate resources should be mined have rested on market forces, the entrepreneurial initiatives of individuals and companies, and the *ad hoc* decisions of consent-granting authorities. In recent years this situation has become increasingly inconsistent with widely-held aspirations for the coastal environment. This is in no way a criticism of the companies concerned. The coastal sand mining industry in the Auckland Region has developed a high level of efficiency, in the absence of a management strategy that has provided an acceptable level of commercial security. This situation has encouraged an atmosphere of confrontation rather than cooperation, and should be rectified as soon as possible.

The adoption of improved administrative and consultative procedures should be given high priority. It has been argued in this paper that in the past the situation has served neither the Departments involved, the environment, the industry nor the wider community. Every effort should be made to involve the mining industry as closely as possible, such that future options are explored jointly with a share purpose and understanding. This will be particularly important if the development of the industry necessitates adopting modified or completely new technologies to allow exploitation of alternative sources of aggregate. The new administrative structure should provide for liaison with regional and local government, so that monitoring, research and other activities can be coordinated so as to maximise effectiveness. The present review of coastal legislation as part of the RMLR will hopefully both empower and simplify the consent-granting process.

Steps in a proposed management strategy for coastal aggregate mining are listed in Figure 10. The basis of the strategy is an understanding of the aggregate requirements of communities, most logically assessed within regional boundaries. The second step entails investigation of all potential sources of aggregate, involving field studies of both coastal and non-coastal aggregate sources. At this stage it should be possible to determine the actual need for sediment mined from the coast. The contribution of coastal sands to the construction industry needs to be identified, with consideration of trends in production from other sources, product specification requirements and the relative value of the aggregate. The mining of new reserves, in deeper water, for example, would require new or modified technologies, and potentially greater production costs. A consideration of the technological options that do exist should be made in respect to the projected value of the resource.

The fourth step entails an assessment of the potential aggregate resource around the New Zealand coast, and the environmental consequences of extraction at any particular site. To facilitate forward planning it is essential the nature of the resource be understood. This should involve a targeted survey of the coastal and shelf deposits of New Zealand with regard to the specifications for manufacture of the various construction products. Areas that would involve a minimum of environmental disturbance could then be identified and promoted by government in their system of licensing and royalties.

If coastal or continental shelf options involve mining costs that are commercially unacceptable, then market forces must dictate that alternative non-coastal sources are available that are cheaper to mine or market. Where

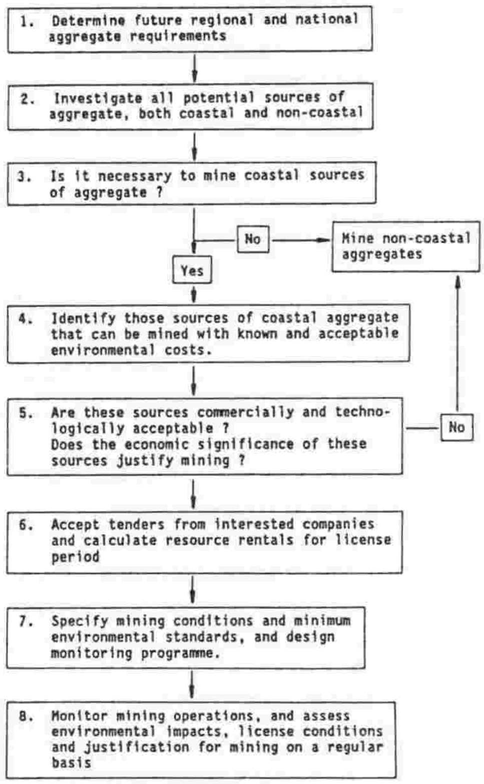


*Fig. 10.* A proposed management strategy for coastal sand mining.

coastal or shelf sands are the only option, consent to mine should be granted reluctantly by the Authority, and only after full consideration of the available coastal options. International experience suggests shallow water extractions along sandy coasts should be avoided.

Competition among mining companies for the right to extract aggregate from the coast and seabed should occur, so as to maximise the return to the wider community through resource rentals and royalties. The licence terms should impose precise conditions and restrictions and minimum environmental standards to be maintained. Operations should be constantly monitored by Local or Regional Authorities, or their representatives or consultants. If the impacts observed are different from those predicted in step 4, the licence may be revoked or modified. The mining companies themselves should not have to indulge in protracted annual negotiations to ensure a licence is renewed, nor prepare an environmental impact statement prior to mining. As argued previously, such an approach is less effective than contracting such works to an independent and impartial authority. The final step entails a periodic review of the effectiveness of the management strategy.

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