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Sediment Facies of an Embayed Coastal Sand Body, Pakiri, New Zealand

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ABSTRACT

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A sedimentological investigation was conducted across the Pakiri-Mangawhai sand body located on the east coast of the Northland Peninsula, New Zealand. Nearshore, inner continental shelf and mid shelf depositional environments are recognised. The sand body extends seaward as a continuous accumulation of relatively mud-free unconsolidated sand from the landward extent of the coastal dunes to the 45 m isobath, approximately 4,500 m offshore, at the base of the inner shelf.

The Pakiri-Mangawhai sand body is characterised by a regular pattern of morphological components and associated sediment types. In profile, the nearshore displays a concave geometry that extends to approximately the 22 m isobath, 1,500 m or so offshore. The inner shelf displays a convex or irregular profile and extends seaward of the nearshore to a break of slope at the 45 m isobath, approximately 4,500 m offshore, where the mid shelf commences. Nearshore gradients range between 0.4° and 1.8°, inner shelf 0.1° to 0.6° and mid shelf 0° to 0.15°

Three subtidal sediment facies are recognised. Nearshore sediments comprise fine, very well sorted sands of 2 phi (0.25 mm) mean grain size. Inner shelf sediments grade offshore from medium to coarse sands (Mz = 0.0–0.5 phi, 0.71–1.00 mm) with some very coarse sand and fine gravel present. In contrast, the sediments of the mid shelf in Pakiri Bay are very fine sands (Mz = 2.0–2.5 phi, 0.177–0.250 mm), with a relatively high mud content (5–10%). Carbonate skeletal debris, derived mostly from mollusca, comprises a significant proportion of inner and mid shelf sediments, increasing offshore from 0–5% across the nearshore to 30% at the base of the inner shelf.

The size-graded bed of the nearshore and inner shelf is consistent with diabathic sediment transport resulting in the preferential shorewards transport of the fine sand fraction of the sediments of the inner shelf. Shoaling gravity waves have the potential to disturb sediments to at least the base of the inner shelf, however, wind generated and other currents may also be significant.

Sediment exchange between the mid shelf and inner shelf is unlikely and the Pakiri-Mangawhai sand body is in effect a closed sediment system. Sand mined from the nearshore must result in a net loss of sediment from the sand body, and the sand resource should be considered finite.

ADDITIONAL INDEX WORDS: *Nearshore, shelf, sand body, Hauraki Gulf, New Zealand, sand mining.*

INTRODUCTION

Investigations of the New Zealand continental shelf have revealed distinct regional variations in shelf sedimentology and morphology (see CARTER, 1975, for a review). These variations are attributed to differences in sediment supply to the coast (CARTER, 1975; GRIFFITHS and GLASBY, 1985), tectonic stability (LEWIS, 1973a,b; NORRIS, 1978), Quaternary eustatic sea level variations (SCHOFIELD, 1978; HERZER, 1981; CARTER and CARTER, 1986) as well as local variations in geology, oceanographic and meteorologic climate and rates of carbonate sedimentation.

The shelf adjoining the east coast of the Northland Peninsula is mostly narrow and relatively steep compared with other New Zealand coasts and is not thought to receive significant quantities of sediment from fluvial sources or regional littoral drift (CARTER, 1975; RILEY *et al.*, 1985). The coast comprises stretches of rocky coast punctuated by sandy embayments. The dune and nearshore sands of many of these bays have long been mined to provide aggregate for construction purposes, although historically little has been known of the nature of the subtidal deposits or the effect of mining on coastal stability (HILTON, 1989). Recent legislation, primarily the Conservation Act (1987) and the Resource Management Act (1991), demand of consent-granting authorities much greater cognizance of the impact of mining on coastal systems. Attention is presently focused on the impact of nearshore sand mining on the Pakiri-Mangawhai coast. Of particular interest is the question of the areal and stratigraphic extent of the sedimentary deposits presently mined and the

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likelihood of natural replenishment and hence the sustainability of the mining operations.

The objectives of the present study are to (1) describe and offer an initial interpretation of the sediments of the subtidal environments of the Pakiri-Mangawhai embayment, and (2) examine the findings in terms of the likely sustainability of nearshore coastal sand mining in the study area. Characteristics of this coast make it a useful location to investigate the nature and development of shallow marine facies, and specifically the offshore extent of modern sedimentation. While a substantial body of sediment has apparently accumulated in the embayment, the modern supply of sediment to the coast from other than offshore sources and *in situ* biogenic production is likely insignificant (HILTON, 1990). There is thus a reasonable expectation that the sedimentology of the seabed represents a response to the hydraulic regime in Pakiri Bay.

COASTAL SETTING

The study area covers the southern half of the Pakiri-Mangawhai embayment located in the outer Hauraki Gulf on the east coast of the Northland Peninsula, New Zealand (Figure 1). The outer Hauraki Gulf coast of the lower Northland Peninsula comprises a series of sandy embayments separated by rocky headlands. The Pakiri-Mangawhai embayment is separated from adjacent embayments, Bream and Omaha Bays, by Bream Tail to the north and Cape Rodney to the south (Figure 1).

Coastal Morphology

The Pakiri-Mangawhai coast is backed by a dune field that extends up to 3 km inland, increasing in width and overall elevation to the north (Figure 2). Dune topography is hummocky and irregular with numerous active and stabilised parabolic blowouts. Foreshore/inshore morphologies are characteristic of WRIGHT and SHORT's (1984) 'intermediate' beach states; the inshore zone characterised by a simple trough/alongshore bar complex, extending as a subtidal ledge approximately 250 m seaward of the foredune (HILTON, 1990). The morphology of the offshore has not previously been described in detail. Existing bathymetric surveys indicate the presence of a broad surface offshore of the sandy coast, narrowing towards Cape Rodney and Bream Tail, sloping seawards to the mid shelf which commences in water depths of between 40 and 50 m. In profile, the seafloor of the Pakiri-Mangawhai embayment comprises a relatively steeply-sloping segment of the Hauraki Gulf profile. THOMPSON (1975) interpreted the base of this slope as the seaward limit of the inner shelf.

Geology and Sediments

Pakiri Bay adjoins the aseismic Northland land mass, thought to be tectonically stable since the upper Miocene (LENSEN, 1977). The rocks of the headlands, Bream Tail, Te Arai Point and Cape Rodney are Mesozoic greywacke or Tertiary sandstone. The intervening coasts of Mangawhai and Pakiri Bays are comprised of unconsolidated sand dunes, mostly of Holocene age, overlying consolidated sands possibly of last interglacial age (SCHOFIELD, 1970).

The sedimentology of coastal and shelf environments in Pakiri Bay is known from surveys of Hauraki Gulf coastal and shelf sediments. SCHOFIELD (1970) labels the sediments of the mid shelf and those of the coast (incorporating dune, nearshore and inner shelf environments) as the Hauraki A and B Sand Facies, respectively. The Hauraki B Sand Facies is considered a coastal derivative of the sediments that blanket the sea floor of the outer Hauraki Gulf, and to have been worked shoreward and onshore during successive late-Quaternary sea level transgressions (THOMPSON, 1975; SCHOFIELD, 1978).

The Pakiri-Mangawhai coasts are not thought to receive significant quantities of new sediment from fluvial sources (HILTON, 1990), or as a result of regional alongshore littoral transport (RILEY *et al.*, 1985). LEES (1982) estimates the rates of erosion of rocky coast in the embayment in historic times as 5.7×10^2 m^3/yr, which is low in comparison with the potential volume of Hauraki B Facies sediments between Bream Tail and Cape Rodney (1.26×10^8 m^3 assuming these sediments are only 1 m thick). Biogenic production of carbonates—as the tests of mollusca—is likely of far greater significance (HILTON, 1990). The mineralogy of the quartz-feldspathic sands of the Mangawhai (MCCABE, 1985) and Omaha (SCHOFIELD, 1970, 1978) coasts, to the north and south of the study area, are consistent with an offshore provenance and are considered to have been worked onshore during late Quaternary (THOMPSON, 1975).

Dune sands from the Pakiri and Mangawhai coasts are described as having median grain sizes of 2–2.5 phi (0.23–0.27 mm) (SCHOFIELD, 1970)

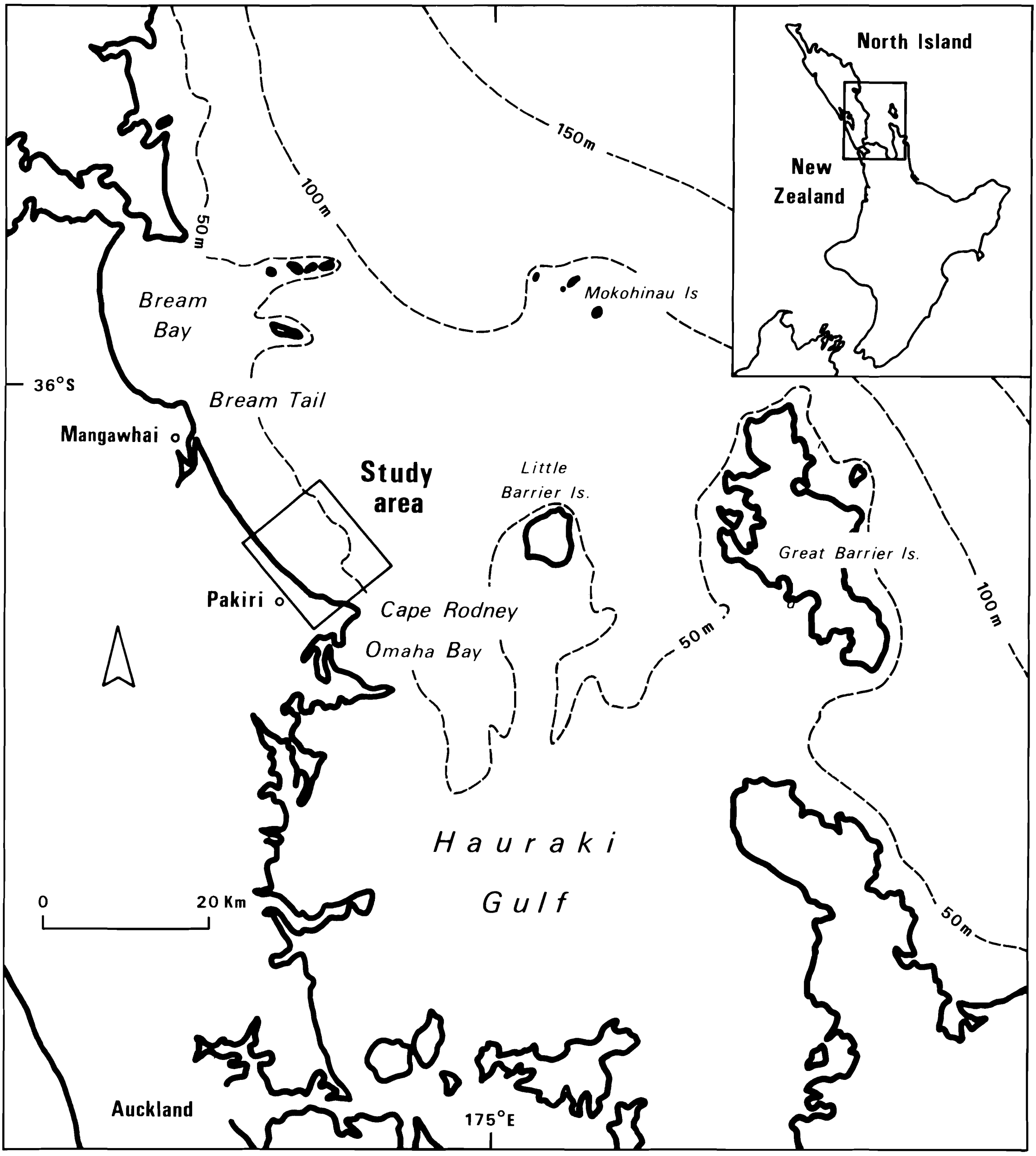

Figure 1. Location map of the Pakiri-Mangawhai sand body, outer Hauraki Gulf, North Island, New Zealand.

and 1.5–2.5 phi (0.35–0.18 mm) (McCabe, 1985), respectively. The mean grain size of 44 intertidal samples analyzed by Hilton (1990) from Pakiri Bay ranged from 1.17 phi (0.47 mm) to 1.83 phi (0.28 mm), although all but three of the samples were contained in the range 1.60–1.83 phi (0.34–0.28 mm). The foreshore sands of the Mangawhai coast are also medium sands (McCabe, 1985). The presence of modern autochthonous carbonate facies offshore of Bream Tail and Cape Rodney,

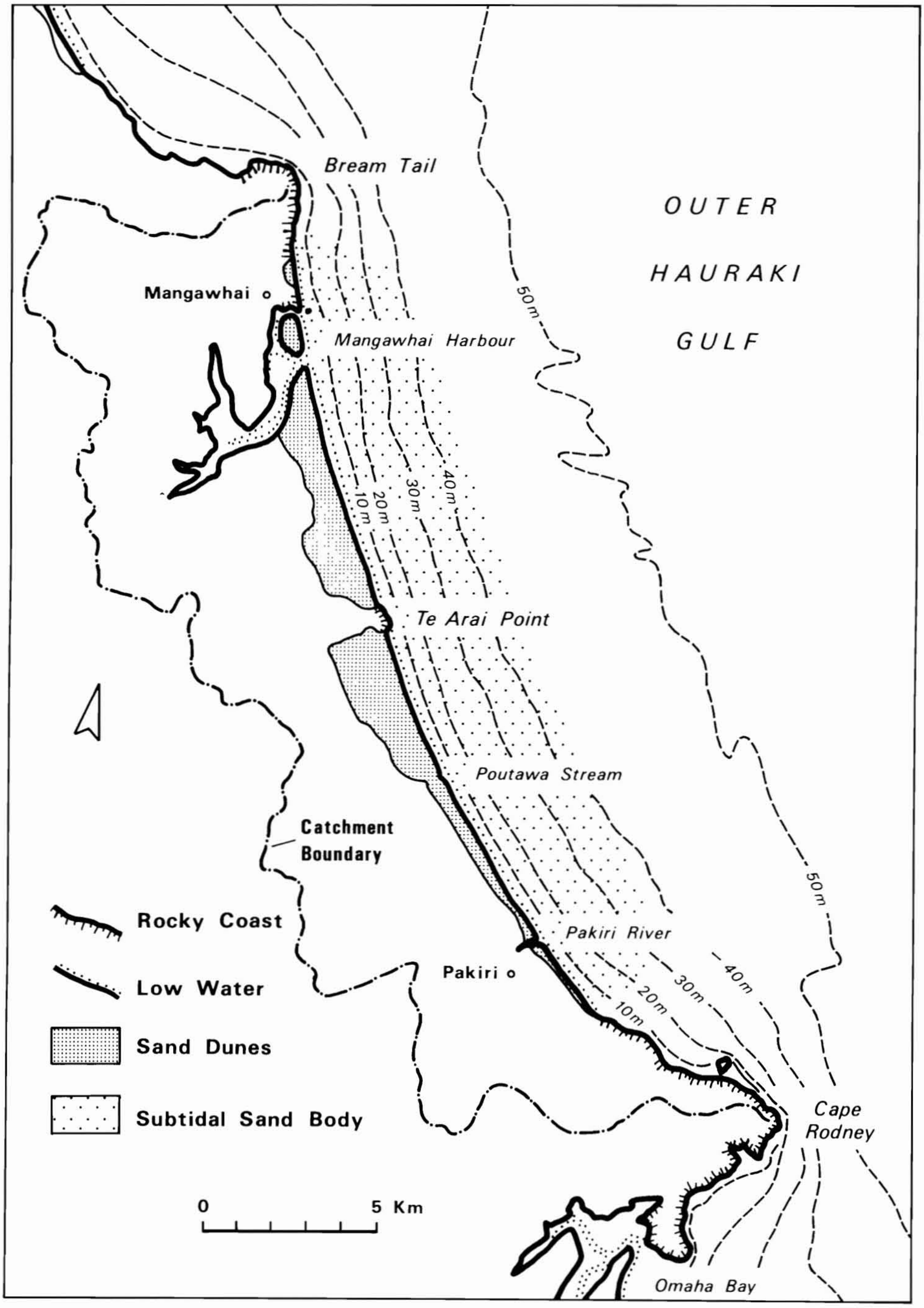

Figure 2. Bathymetry and coastal physiography of the Pakiri-Mangawhai embayment showing approximate limits of the sand body and boundary of catchments feeding the Pakiri-Mangawhai embayment.

described by McCabe (1985) and Hilton (1990), further suggests sediment exchange between the Pakiri-Mangawhai embayment and Omaha and Bream Bays is unlikely.

Waves and Currents

Observations of the northeast New Zealand wave climate have shown that wave energy is both lower and more variable along the East Coast than other exposed coasts around New Zealand with local storm events the primary influence (Harris *et al.*, 1983). The dominant swell wave arrives from a northeast direction. The mean deep water wave height is 1.4 m and rarely exceeds 3.0 m (Ewans and Kibblewhite, 1986). Periods are mainly in the range 6 to 9 sec, with 6.55 sec the average. Episodes of high wave activity in the study area result from onshore winds associated with intense sub-tropical cyclones that originate to the northwest of New Zealand. The most extreme storm of recent times occurred in 1978 when a sub-tropical cyclone generated near hurricane force easterly (onshore) winds and waves in the outer Hauraki Gulf of 9 m maximum height and 12 sec period (Peek, 1979). Periods of moderate and high wave energy along the east coast of the North Island do not, however, persist for long. Harris *et al.* (1983) reported 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, periods of low wave activity, less than 1.5 m, could persist for as long as 300 hours.

Knowledge of wind- and tide-generated currents in the Pakiri-Mangawhai embayment is poor. Tides in the study area are semi-diurnal and mesotidal with a maximum range of 3.0 m at springs and 1.5 m at neaps. An Aanderaa RCM-4 Eulerian continuous recording current meter has been operated in water depths of 30 (site 1) and 45 m (site 2) in Pakiri Bay for a 6 week period (Bell, 1986). Maximum speeds do not exceed 0.19 m sec^{-1} at site 1 and 0.15 m sec^{-1} at site 2. However, these speeds are exceptional: at site 1, speeds greater than 0.10 m sec^{-1} were exceeded only 4.7 percent of the record. The current meter record is dominated by bidirectional tidal flows, primarily oriented alongshore. Offshore winds of unexceptional velocity and near calm seas occurred throughout this meter deployment; hence, there is no likelihood of the local (storm) wind-generated bottom currents reported by Bradshaw *et al.* (1991) from a comparable east coast location. The East Auckland Current is not thought to impinge into the Hauraki Gulf and have any significant effect on the coast (Harris, 1985); however, a persistent, mostly southeasterly current of maximum speed 0.06 m sec^{-1} is superimposed over the bidirectional tidal flows.

METHODS

The investigations reported, with the exception of some alongshore side-scan sonar surveys, were conducted across a series of eight, regularly spaced, shore-normal transects, originally established by the Auckland Regional Council in 1978 (Figure 3). Transect lines were relocated using shore markers and the position of the research vessel along the transect by radar rangefinder.

Sediment sampling involved two components. Samples were initially obtained across all transects during June and August 1986. A 20–25 litre sample of the top 10–20 cm of the bed was obtained at regular intervals using a pipe dredge. Sampling commenced about the crest of the alongshore bar and was discontinued approximately 8 km offshore. Samples were obtained at 90 m intervals across the relatively steeply sloping seabed seaward of the alongshore bar, and every 260 m thereafter. A total of 175 samples were obtained across the seven transects. In addition, 46 foreshore samples were collected from low and high water levels at regular intervals between Okakari Point and Te Arai Point.

The second sampling component entailed the extraction and analysis of multiple samples from a selection of stations across a single transect. A total of 59 samples were dredged from 10 stations at water depths of 4, 10, 15, 20, 25, 30, 35, 40, 45 and 47 m across Williams transect over a 3 day period (Figure 3). The aim was to determine whether the results of the one-off sampling programme, in which a single sample was obtained at each station, accurately represents the range of bed sediments present, and to assess the natural variability of the bed sedimentology. 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 sedimentological trends it is transitional between the three transects to the north (Couldrey, Walkway, Gravel) and south (Brown, Matheson, Okakari). In several respects, the results from Williams transect represent the typical condition.

Laboratory analysis of sediments involved de-

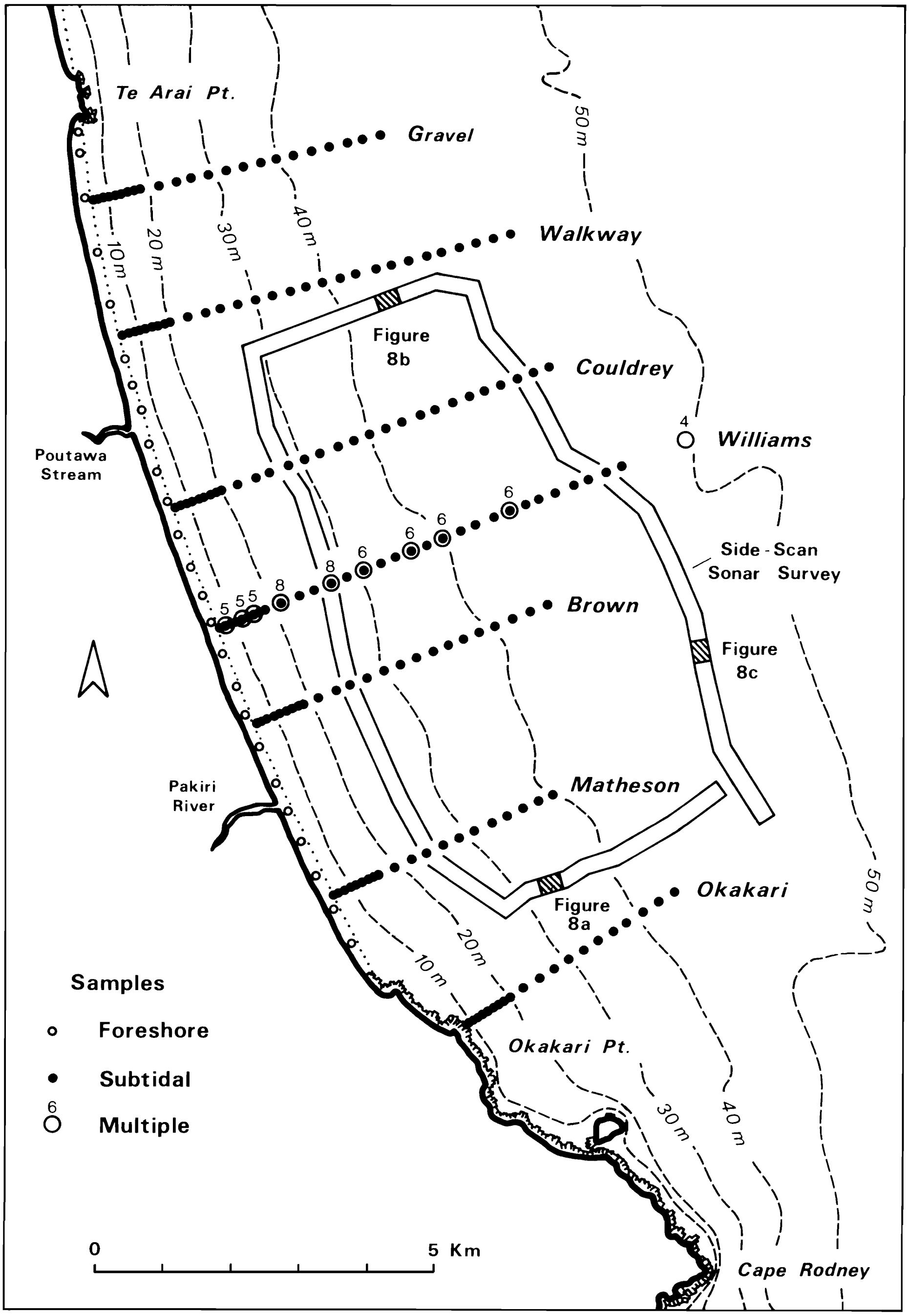

Figure 3. Location of Pakiri Bay beach and offshore samples and side scan sonargraph survey.

termining settling velocities and grain size distributions (excluding particles <4 phi, 0.0625 mm) by automated settling tube (including and excluding the carbonate fraction), the proportion of mud (sediment finer than 4 phi) and the proportion of carbonate material, using the standard methods of CARVER (1971) and FOLK (1974). Percentage fines and carbonates refer to the proportion of the dry weight of the original untreated sample.

Additional information on the spatial distribution of sediments, and in particular variations associated with small- and large-scale bedforms, was provided by SCUBA diving and side-scan sonar, respectively. Side-scan data was obtained in March 1987 to investigate sediment variations associated with large scale bedforms on the inner and middle continental shelf. A total of 3.3 km^2 of seabed was surveyed using a Klein side-scan sonar operating at a range of 100 m and 375 Khz frequency.

RESULTS

Morphologic Features of Pakiri Bay

A typical shore-normal echosound survey in Pakiri Bay indicates the presence of three major subtidal features—nearshore, inner shelf and mid shelf (for example, Gravel profile, Figure 4a). In profile, the nearshore consists of a relatively steeply-sloping concave-out component between the alongshore bar and the inner shelf. Superimposition of Pakiri Bay shore-normal echograms shows the cross-sectional geometry of the nearshore to be consistent with a width of about 1,700 m and depth range of 3 to 20–25 m below mean sea level. Characteristic gradients are of the order of 0.4 to 1.8°, lower and higher gradients being associated with the lower and upper nearshore, respectively.

Relative to the nearshore, the inner shelf slopes more gradually, with gradients ranging between 0.2 and 0.5°. The geometry of inner shelf profiles varies within Pakiri Bay, from irregular in the south near Okakari Point to convex offshore of Te Arai Point. Inner shelf profiles towards the centre of the Mangawhai-Pakiri embayment; Gravel and Walkway display a convex-out geometry. While the inner shelf can be recognised across most profiles as a single convexity, across Walkway transect two additional (secondary) convexities are also present (Figure 4b). In profile, the transition from the nearshore to the inner shelf forms a near level surface. Across the northern transects (Couldrey, Walkway, Gravel and Te Arai), this juncture occurs as the meeting of concave nearshore and convex inner shelf slope components (Figure 4a and b).

The transition from the inner shelf to the mid shelf occurs more or less uniformly alongshore, 4,200 to 4,500 m offshore, in water depths of 42–45 m. Characteristic slope angles on the lower inner shelf are 0.4 to 0.5°, while slope angles on the middle continental shelf are usually less than 0.1°. Seaward of Pakiri Bay, the mid shelf extends as a broad, undulating, relatively gently-sloping surface to the shelf break, approximately 60 km offshore (THOMPSON, 1975).

Nearshore, inner and mid shelf profile components are more readily recognised from echogram surveys north of the Pakiri River. South of the river, the profile geometry of these features is much less regular; in particular, the abrupt change in slope marking the juncture between nearshore and inner shelf profile components is absent (for example, Brown transect, Figure 4c). This is possibly because the morphology of the profiles south of the Pakiri River is increasingly influenced by the underlying bedrock as the Cape Rodney coast is approached.

Shore-Normal Variation in Grain Size and Sorting

Unconsolidated sediments are continuous between the coastal dunes and the seaward limit of sampling, 8 km offshore. The sediments are predominantly moderately to very well-sorted sands with mean grain sizes varying between 0 phi (1 mm), coarse sand, and 3 phi (0.125 mm), very fine sand. The mud and carbonate content of the samples varies from 0 to 15 and 1 to 30 percent of total sample weight, respectively. Within these ranges, the sedimentology of the bed in Pakiri Bay shows a systematic, primarily onshore-offshore variation in texture and composition. This variation is exemplified by the results obtained across Walkway transect (Figure 5). The sands of the inshore are marginally (but consistently) coarser (mean, Mz = 1.7 phi) than the medium to fine sands (Wentworth size grades) of the mid nearshore (Mz = 2 phi), so there is a trend of seaward fining offshore from the alongshore bar, ending 800 to 1,000 m offshore in water depths of about 15 m. Thereafter, the sediments become progressively coarser with increasing distance offshore (Figure 5a and b). This trend culminates at the base of the inner shelf, 3,500 to 4,000 m

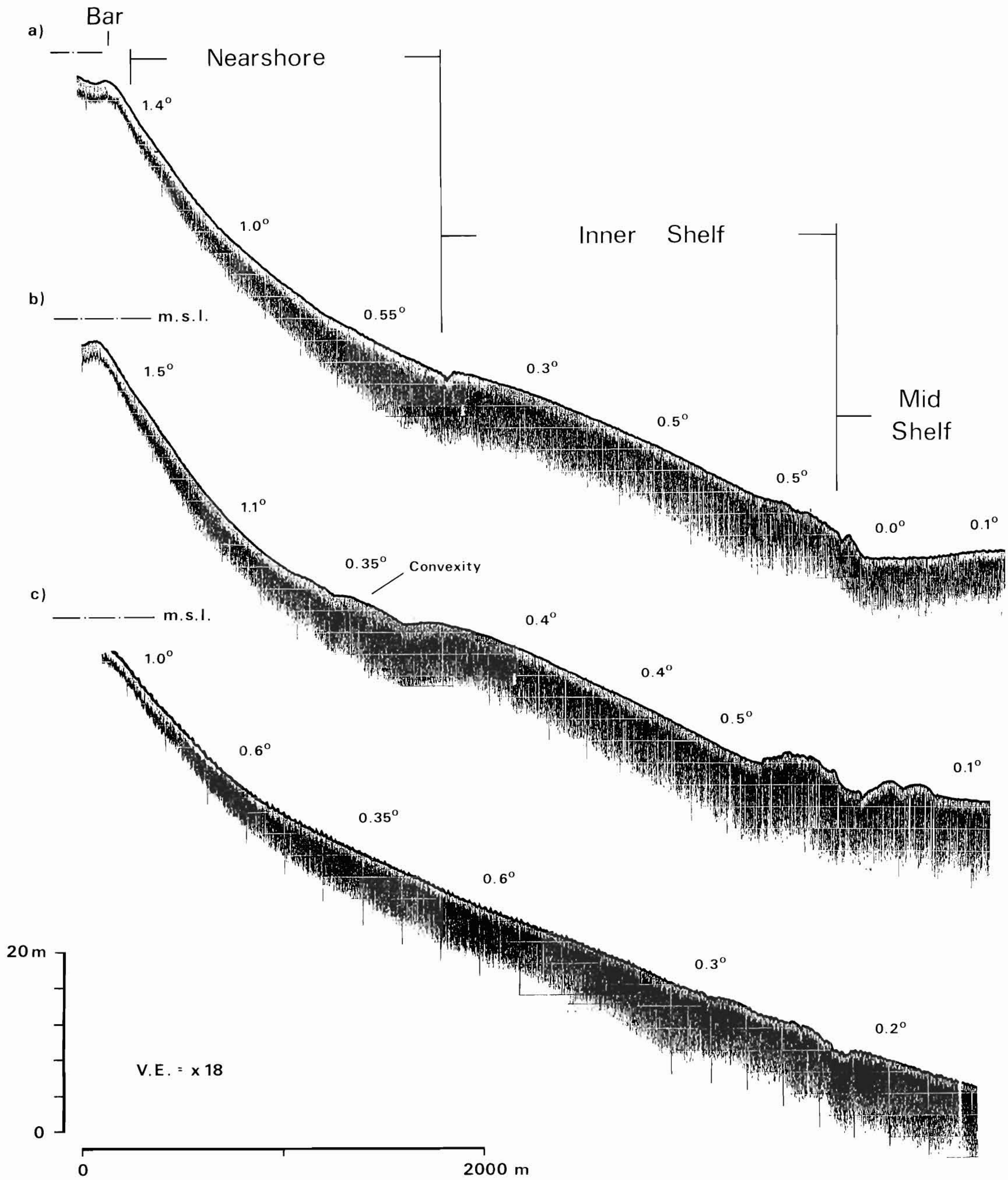

Figure 4. Shore-normal nearshore/shelf echosound records, Pakiri Bay: (a) Gravel transect, showing well defined morphological break between the nearshore, inner shelf and mid shelf features; (b) Walkway transect, showing second order convexities at the base of the nearshore; and (c) Brown transect, showing the characteristic irregularity of the southern shore-normal profiles.

offshore, in water depths of 40 to 45 m. These sediments are comprised mostly of very coarse sand, with some granules and pebbles (Mz = 0.0–0.8 phi). Immediately seaward of the inner shelf, there is an abrupt change in the sedimentology of the bed (Figure 5a and b). The non-mud fraction of mid shelf sediments comprise very fine sands. These sands are the finest in the study area with mean grain sizes of about 2.5 phi (0.177 mm).

As the sediments of the mid to lower nearshore and inner shelf become coarser they become progressively less well sorted. The best sorted sediments (SD = 0.35 phi) are the fine sands (Mz = 2 phi, 0.25 mm) of the shallow nearshore, 200 to 1,000 m offshore (Figure 5a). The degree of sorting decreases offshore, with the least well sorted sediments (SD = 0.5 phi) the coarse sands and fine gravels at the base of the inner shelf. Seaward of this coarse material sorting improves, although samples from the mid shelf are much less well sorted than the sands of the nearshore. Foreshore sands are coarser (Mz = 1.2–1.9 phi) and less well sorted (SD = 0.36–0.61 phi) than the medium to fine, well-sorted sands of either the upper nearshore or the coastal dunes. Aeolian dune sands are well to very well sorted, medium to fine sands and have typical mean grain sizes of 1.7 phi and a standard deviation of 0.34 phi.

With one exception, the grain size frequency distributions of all beach and subtidal samples analyzed are unimodal. 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). Samples from near the base of the inner shelf tend to be negatively skewed, reflecting the predominance of coarse sands in these samples. Sediment distributions from the middle continental shelf are weakly negatively skewed and near-symmetrical. In general, the distributions tend to become more symmetrical across the inner shelf and nearshore with sample distributions from the alongshore bar being essentially symmetrical.

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 an abrupt increase in the proportion of mud in the samples (Figure 5c). Mud content is 0–2 percent across the nearshore, and low (2–5 percent) across the inner shelf between water depths of 25 and 42 m. However, immediately seaward of the inner shelf the proportion of mud in samples increases to between 10 and 15 percent.

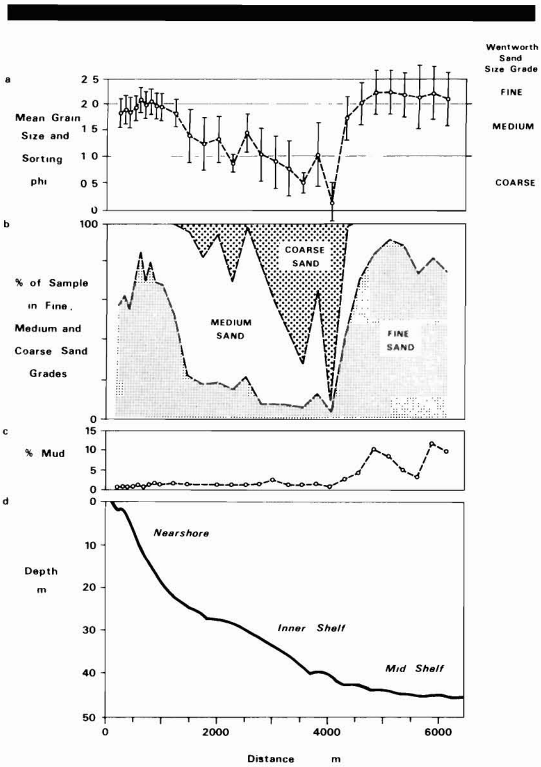

Figure 5. Variation in (a) mean grain size and sorting (bars indicate standard deviations), (b) proportion of total sample in different sand size grades (Wentworth classification) and (c) percent mud across (d) Walkway transect.

The pattern of offshore coarsening of bed sediments across the nearshore and inner shelf is consistent across all Pakiri transects. However, trends are most strongly indicated over the northern transects in terms of both the range of grain sizes present and the consistency of the station to station trends. The range of mean grain sizes present across the transects decreases from north (Gravel) to south (Matheson), although there is no comparable trend in sorting. These differences are unlikely to result solely from sampling error such as there appears to be a systematic alongshore variation in grain size. In general, such alongshore variations in bed texture are minor compared with shore-normal variations.

Carbonate Content

The carbonate fraction of the sediments analyzed is largely comprised of fragments of benthic molluscan macrofauna. Carbonate content in-

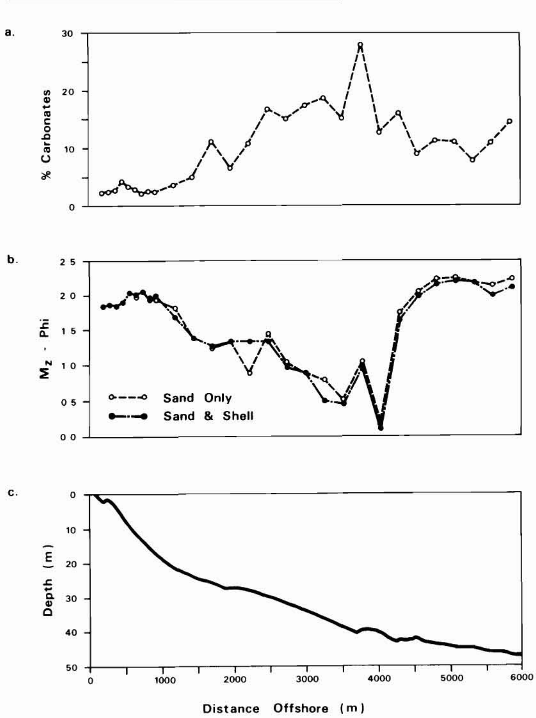

Figure 6. Variation in (a) percent carbonates and (b) mean grain size for carbonate-digested and undigested samples across Walkway transect.

creases, more or less uniformly across each transect in an offshore direction. For example, across Walkway transect (Figure 6a) the carbonate content of the fine, well-sorted sands of the shallow nearshore is relatively low, generally between 2 and 5 percent. The carbonate content steadily increases offshore across the nearshore and inner shelf, attaining maximum concentrations of 20 to 30 percent at the base of the inner shelf. The coarsest (non-carbonate) sediments are thus also those that contain the most carbonate material. Seaward of the inner shelf there is an abrupt reduction in carbonate content, although concentrations in the mid shelf sediments are moderately high at around 10 percent.

The grain-size distribution of samples obtained across two transects was determined prior to and following carbonate digestion. Living mollusca were removed prior to analysis. The retention of the carbonate fraction in the samples does not greatly affect the sample means, despite carbonates comprising up to 30 percent of total sample weight (Figure 6b). Microscopic examination of samples confirms that the size distribution of the carbonate fraction at any site is virtually the same as the size distribution of the non-carbonate grains. Hence, carbonate fragments associated with the sediments of the lower inner shelf are commonly of granule size, whereas the carbonates associated with the very fine sands of the middle continental shelf are highly comminuted.

South of Pakiri Beach shelf sediments contain increasingly greater quantities of shell. Maximum concentrations range from about 20 percent across Matheson transect to nearly 100 percent offshore from the rocky coast south of Okakari Point. Where the carbonate content is less than 100 percent, the balance often comprises locally derived rock fragments. Analysis of the species composition of these carbonate sediments indicates they are derived from mollusca and echinoderms that inhabit the rocky intertidal and subtidal habitats in this area. A similar carbonate-rich facies is described by McCabe (1985) offshore from the rocky coast between Mangawhai estuary and Bream Tail at the northern limit of the Pakiri-Mangawhai sand body.

Interpretation of Replicate Samples, Williams Transect

The second component of the sampling program entailed the extraction and analysis of multiple samples from 10 stations across Williams transect. The results support and refine the results of the one-off sampling programme. Intra-station variation, indicated by the length of the standard error bars about the mean of the sample means at each station, is low relative to the inter-station variation across the transect, with a clear trend of offshore coarsening across the lower nearshore and the inner shelf (Figure 7a). The standard error (indicated by vertical bars) is small, with the exception of samples from a station at the base of the inner shelf. Consistent results are also obtained for mud and carbonate concentrations, although there is somewhat greater variability at each station in the case of the latter. This variability is partly due to the occasional presence in samples of large bivalves which tend to result in the overestimation of the carbonate content.

The analysis of multiple samples from Williams transect suggests that the overall shore-normal grain size trends are more uniform than the results of the one-off sampling suggest. The transition from coarse inner shelf to very fine mid shelf sands usually occurs abruptly as portrayed in Figure 5a; however, at times it may occur somewhat landward of this position especially across the southern Pakiri Bay transects.

The available side-scan sonar data is limited (Figure 3) and unverified, but does suggest something of the nature of the transition from inner shelf to mid shelf sediments. The sonargraphs indicate a fine sand present as patches (Figure 8a) or as a continuous sheet (Figure 8b) overlying a coarser sediment at the location of the inner shelf–mid shelf juncture. This interpretation is consistent with the side-scan results of BLACK and HEALY (1988) from Bream Bay, and DELL *et al.* (1985) and BRADSHAW *et al.* (1991) from the Coromandel inner shelf who describe comparable instances of juxtaposed coarse and fine sands.

A second source of textural variation may result from the presence of large-scale dune-type bedforms located on the mid shelf in Pakiri Bay. The plan configuration of these dune-type bedforms is variable, but most examples are elongated with the long axis oriented approximately normal to the Pakiri coast. The landward margin is relatively broad and crenated with the seaward end being more acute (as shown in Figure 8c). These features are interpreted as accumulations of relatively fine sediment separated by bands of coarser sediment (Figure 8c). The former is probably the very fine sand type characteristic of the mid shelf in Pakiri Bay, and the latter medium to fine sands, samples of which were, on occasion, dredged from the mid shelf. That the darker toned sediments are in fact coarser is also suggested by their occasional association with large, linear-crested ripples. Such ripples are correlated with the coarse sands of the inner shelf in Pakiri Bay (HILTON, 1990) and commonly associated with the coarse sands described by BLACK and HEALY (1988) in neighbouring Bream Bay and BRADSHAW *et al.* (1991) on the Coromandel east coast shelf.

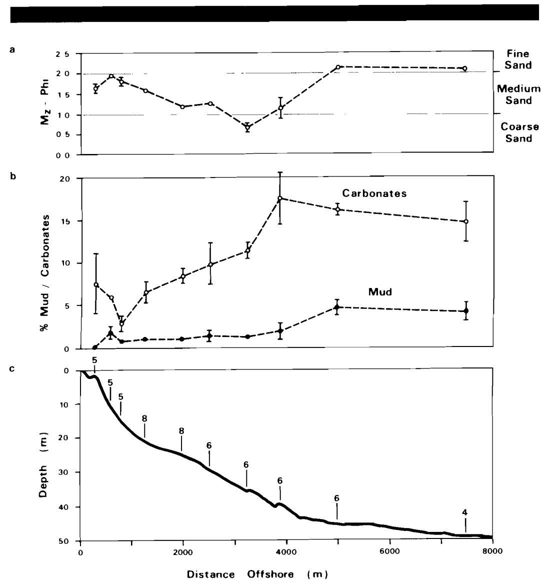

Figure 7. Variation in (a) mean grain size, (b) percent mud and carbonates (variance about means indicated by standard error bars) across (c) Williams transect.

Analysis of Raw Grain Size Data

The pattern of shore-normal grain size variation described does not simply reflect variations in the relative proportion of sediment present in each size fraction, but rather the virtual absence/presence of whole phi fractions. For example, the analysis of samples across Williams transect (Figure 9) indicates that 0.0 (1 mm) and 0.5 phi (0.71 mm) sand only occurs on the inner continental shelf, and 3 to 4 phi (0.125–0.0625 mm) sand only on the mid shelf. The size-graded bed of the inner continental shelf results from the decrease onshore of the proportion of coarse sand and granules in the samples and a commensurate increase in the proportion of fine sands.

DISCUSSION

Previous interpretations of the sedimentology of the Pakiri-Mangawhai embayment by SCHOFIELD (1970), THOMPSON (1975) and CARTER and EADE (1980) were based on a small number of samples collected during synoptic investigations of the sedimentology of the Hauraki Gulf coast and shelf. Intensive offshore sediment sampling in Pakiri Bay has shown the (coastal) Hauraki B Facies of SCHOFIELD (1970) to comprise a well defined body of unconsolidated, fine to coarse, relatively mud free sands, incorporating backshore dune, foreshore, inshore, nearshore and inner shelf sediments. The sedimentology of this sand body is both more complex and regular than previously appreciated, a feature being the offshore gradation in sample grain size and sorting. Three new facies are proposed (Table 1); (1) the mid shelf muddy, fine sand facies; (2) an inner shelf medium to coarse sand facies; and (3) a coastal medium to fine sand facies (incorporating foreshore, inshore and nearshore sediment types).

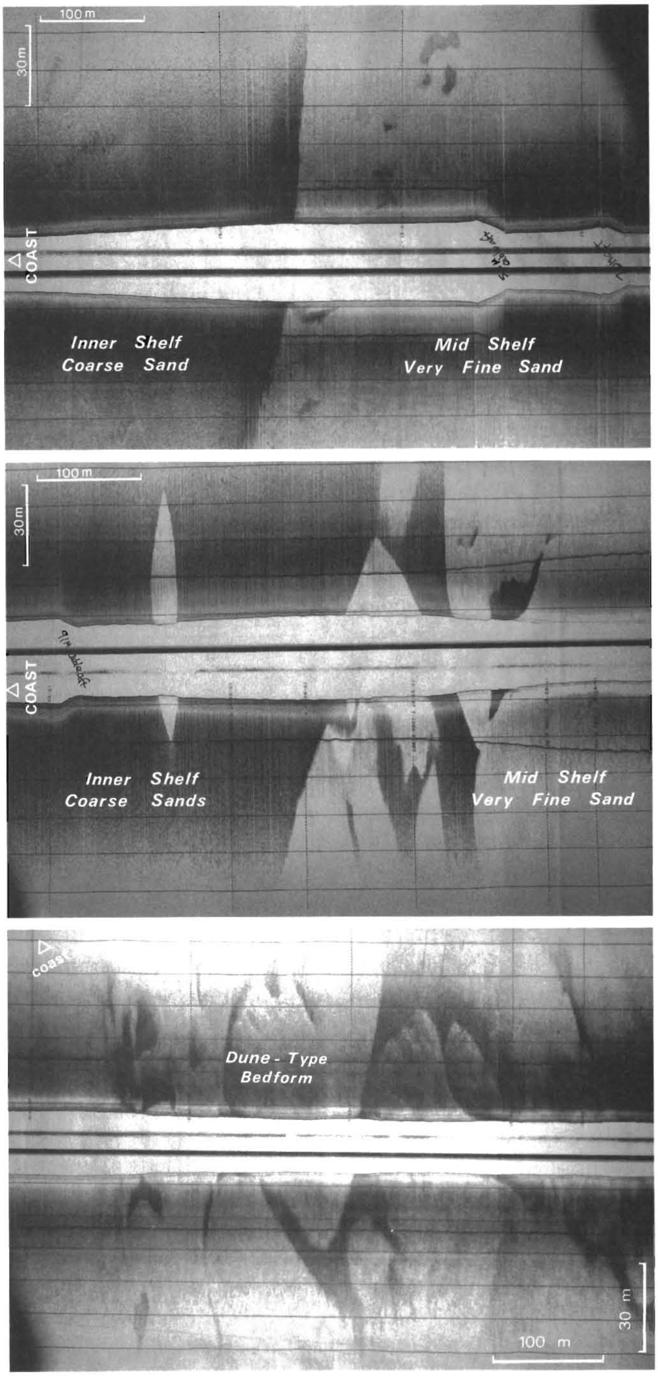

Figure 8. Side-scan sonargraphs of the contact between the inner shelf (dark) and mid shelf (light) sediment types, (a) in the presence of large scale bedforms and (b) in the absence of large scale bedforms; and (c) sonagraph of a large-scale dune-type bedform located on the mid shelf. Scenes located in Figure 3.

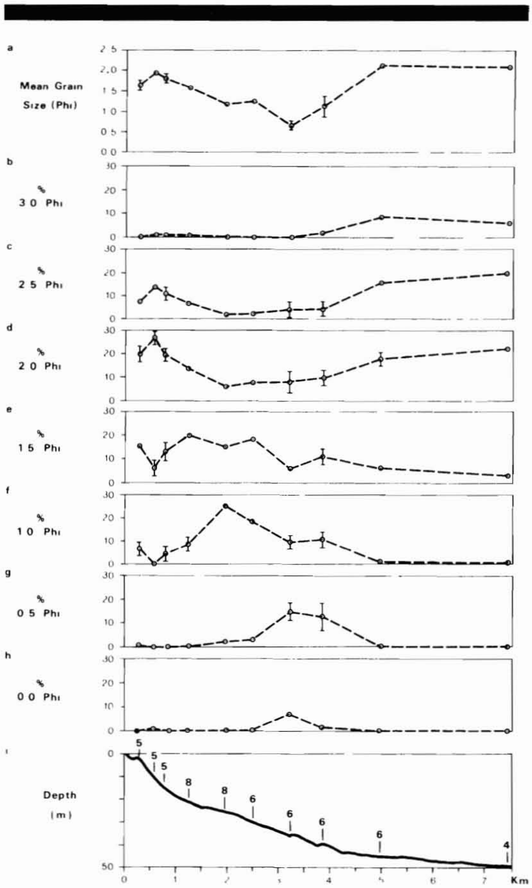

Figure 9. Variation in (a) mean grain size and sorting and percent weight of sample present in (b) 0.0, (c) 0.5, (d) 1.0, (e) 1.5, (f) 2.0, (g) 2.5 and (h) 3.0 phi size fractions across (i) Williams transect. Variance about means indicated by standard error bars.

In plan view, the sand body comprises two shore-parallel facies, bounded to seaward by the mid shelf facies (Figure 10).

Further work is required to define the outer limits of the mid shelf facies of the type described; the sediments of the Hauraki Gulf mid shelf, as described by THOMPSON (1975), are texturally more variable than those samples analyzed from the mid shelf bordering the Pakiri-Mangawhai sand body. With one exception, all the samples obtained during the present study are unimodal. This contrasts with the polymodal sediments of the middle continental shelf beyond the 70 m isobath. The unimodal nature and high degree of sorting of nearshore and inner shelf sediments in

Table 1. *Textural characteristics of Pakiri Bay sediments.*

Feature	Distance from Foredune (m)	Water Depth (m)	Dominant (Wentworth) Sand Grade	Mean Grain Size (phi)	Sorting (phi)	Gravel (%)	Carbonates (%)	Mud (%)
Coastal-Nearshore Facies								
Coastal Dunes	—	—	Fine	2.00–2.25	—	—	—	—
Foreshore	0–30	—	Medium	1.60–1.83	0.34–0.48	0	1–11[1]	0
Inshore	100–350	0–4	Fine–Medium	1.82–2.13	0.35–0.37	0	2.3–6.9	0.0–2.1
Nearshore	350–1,700	4–22	Fine–Medium	1.26–2.09	0.32–0.56	0	1.7–12.9	0.0–3.0
Inner Shelf Facies								
Inner Shelf	1,700–4,200	22–42	Medium–Coarse	0.13–1.65	0.30–0.72	0–5	5.4–28.0	0.6–2.9
Mid Shelf Facies								
Mid Shelf	4,200–6,300+	42–51+	Fine	2.03–2.66	0.31–0.59	0	6.5–19.6	3.8–14.7

[1] From Schofield (1970).

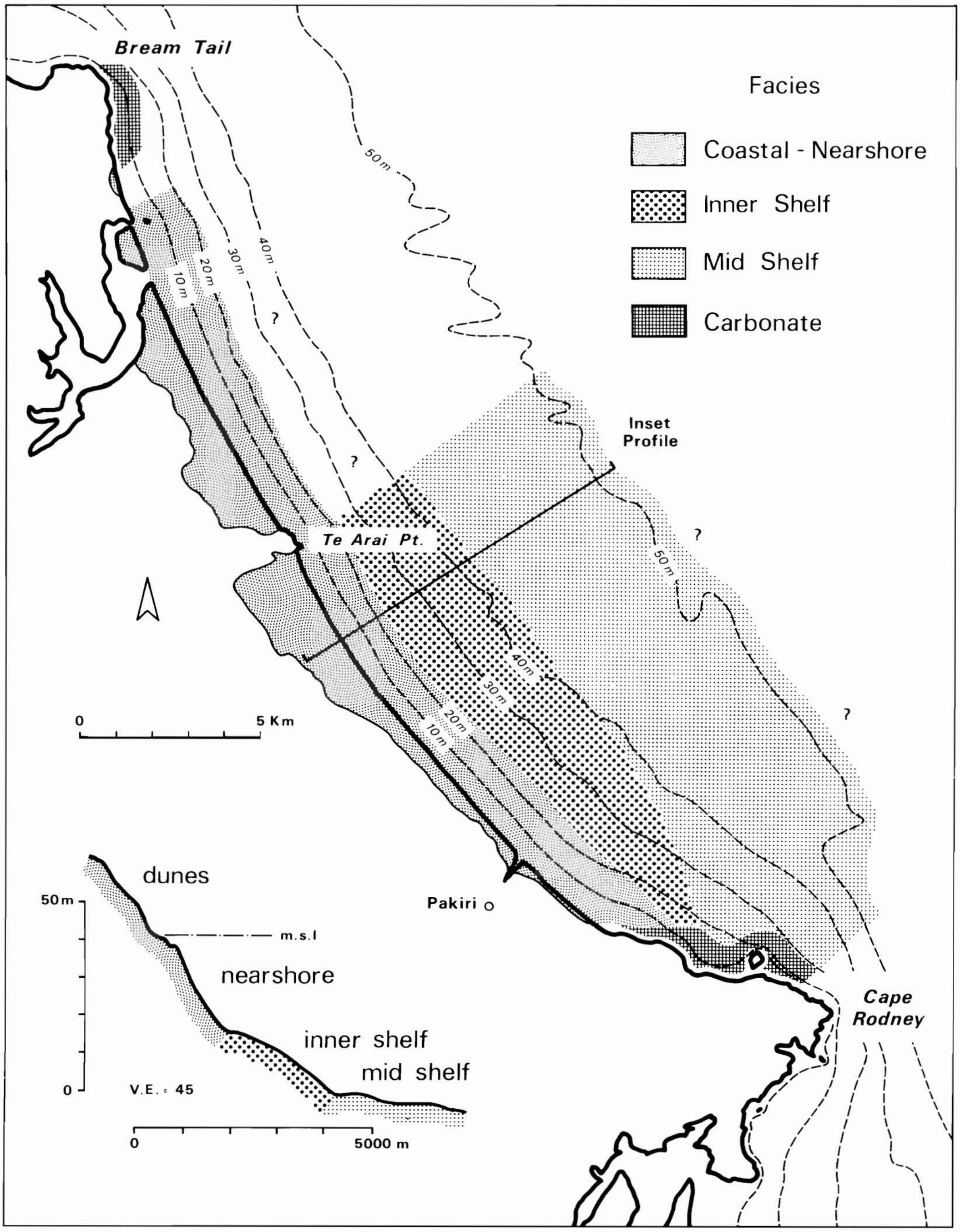

Figure 10. Map showing the approximate distribution of the coastal-nearshore, inner shelf, mid shelf (Pakiri Bay variation) and carbonate facies recognised in Pakiri Bay, and (inset) the approximate morphologic-facies relationships across the sand body. Delineation of Mangawhai Bay facies after McCabe (1985).

the study area supports the interpretation of SCHOFIELD (1970) that the coastal sediments of the Hauraki Gulf are derived from the Hauraki A Facies.

The shore-normal morphological and sedimentological phenomena described are continuous alongshore in Pakiri Bay, although the trends described are best expressed north of the Pakiri River. At the southern end of Pakiri Bay, nearshore and inner shelf sands grade into a locally derived carbonate and gravel/sand facies offshore from the rocky Cape Rodney to Okakari Point coast (portrayed approximately in Figure 10). A similar rocky shore facies is described between Mangawhai and Bream Tail by MCCABE (1985). The textural characteristics of foreshore and nearshore samples described by MCCABE (1985) are comparable to those of Pakiri Bay, and it is likely that the sedimentology and morphology of the seabed in Pakiri Bay is representative of the overall Pakiri-Mangawhai sand body.

The shore-normal pattern of grain size variation across that section of the Pakiri-Mangawhai sand body examined does not accord with the classic 'equilibrium' model of offshore sediment fining of JOHNSON (1919). However, the results do indicate an offshore gradation in the grain size distribution of the sand fraction. The mean grain size fraction of these sediments steadily increases from the shallow nearshore to the base of the inner continental shelf. At the same time, the proportion of mud increases across the inner shelf, although in all samples from this environment the total proportion of mud is low. Further seawards of the inner shelf, the sediments of the middle shelf (in Pakiri Bay) are very fine, muddy, sands.

The juxtaposition of a fine, well-sorted, sand and a coarser, less well-sorted, sediment further offshore is comparable with results obtained from the Atlantic coast of North America (STETSON, 1938; GORSLINE, 1963; PILKNEY and FRANKENBERG, 1964), the east coast of New Zealand (SCHOFIELD, 1978; DELL *et al.*, 1985; BRADSHAW *et al.*, 1991), the California shelf (CACCHIONE *et al.*, 1984; HUNTER *et al.*, 1988) and from the New South Wales coast (ROY and CRAWFORD, 1980). The seaward limit of the fine sands has generally been interpreted as indicating the limit of modern sedimentation (BIGHAM, 1973; ROY and STEPHENS, 1980). Further seaward, the sediments of the inner shelf are usually interpreted as palimpsest and are not considered a component of the modern coastal sediment system.

The sediments of the Pakiri nearshore and inner continental shelf can be generally characterised as well sorted fine sands and less well sorted, medium to coarse sands, respectively. However, the transition from nearshore to inner shelf sediments is not abrupt; rather there exists a gradation in the grain size of bed sediments from the base of the inner shelf, approximately 4,500 m offshore where the water depth is around 45 m, to near the top of the nearshore. This gradation invites consideration of the extent to which: (1) the graded surface of the subtidal sand body evidences the preferential onshore transport of fine sands originally contained in the heterogeneous sand body; (2) this process is ongoing and (3) the differentiation of nearshore and inner shelf facies as proposed is justified.

It is problematic to determine to what extent the fine to medium nearshore sands are the result of former or ongoing shoreward transport of the fine sand fraction of heterogeneous offshore sediments, since the culmination of the last sea level transgression, or result from the reworking of eolian and other barrier sediments of potentially greater age, as envisaged by ROY and CRAWFORD (1980) for the New South Wales coast. Both mechanisms may be important in the study area. Comparison of a 10 year time series of inshore-nearshore profiles (HILTON, 1990) indicated that during the 1978 storms large volumes of backshore dune sand was eroded and subsequently deposited on the mid to upper nearshore. SCHOFIELD (1978) interprets the coarse sand facies of neighbouring Omaha Bay as a modern lag deposit that results from the preferential shorewards transport of the fine sand fraction of an originally heterogeneous sediment; the development of fine and coarse sand deposits is considered to be related to late Holocene second order sea level transgressions and regressions, respectively. The development of fine sand coastal (nearshore, inshore, foreshore and backshore) and medium to coarse inner shelf sand facies in Pakiri Bay may thus be closely interrelated and ongoing.

Evidence supporting the interpretation of the fine and coarse sand deposits as modern includes:

(1) all samples obtained from Pakiri Bay are unconsolidated, with no evidence of aggregation or any form of *in situ* cementation;
(2) all samples obtained are moderately well to very well sorted;
(3) low mud content of samples from these en-

vironments compared with the adjacent mid shelf;
(4) the consistency of the shore-normal grain size trends;
(5) the carbonate fraction of the sediments exhibits the same size gradation as that described for the bulk sample—a survey of the macrobenthos by HILTON (1990) showed that such a pattern is unlikely to result from authocthonous biogenic production of carbonates and is more likely a consequence of sediment transport and resulting sorting;
(6) presence of sharply defined textural boundaries associated with large-scale bedforms at the base of the inner shelf; and
(7) the predictable geometry of nearshore and inner shelf profiles (particularly north of the Pakiri River mouth).

Differentiation of nearshore and inner shelf facies is not justified on the basis of comparison of the mean grain size of one-off samples since there is overlap (Table 1). Greater confidence in the distinction is gained from comparison of the average of the multiple samples from across Williams transect and consideration of the raw phi data from the same transect. When multiple samples from the same transect station are averaged, there is no overlap between nearshore and inner shelf sediments. The inner shelf samples contain a significant proportion (8–25%) of sediment in the 0.0, 0.5 and 1.0 phi sand fractions whereas such fractions are virtually absent from nearshore sediments.

Diabathic sediment transport offshore of exposed coasts may result from a wide range of currents, including those induced by shoaling gravity waves, rip currents, wind- and tide-driven currents, and combinations of these currents (WRIGHT, 1987). The potential significance of combined oscillatory wave- and wind shear-generated currents to the present study is suggested by the results of BRADSHAW *et al.* (1991) which identify a north flowing current generated during episodes of strong onshore easterly winds. Probably a component of a more complex three-dimensional current system, this current is able to transport inner shelf sands to water depths of at least 30 m. Waves formed by the same onshore easterly winds are likely to intensify rates of transport. Investigations of dredge spoil dispersal on the inner shelf off Tauranga Beach by HARMS (1989), HEALY *et al.* (1991) and others suggest diabathic sediment transport to water depths of at least 25 m. These results accord with those of BLACK and HEALY (1988) for Bream Bay and GILLIE (1979) for stretches of the Northland inner shelf. The inner shelf at Pakiri occurs in somewhat deeper water (24–45 m) and is bounded by a greater width of continental shelf. Shoaling gravity waves of 2.5 m height have the potential to disturb fine to medium sands to the base of the inner shelf (HILTON, 1990); however, there has as yet been no attempt to determine rates of sediment transport.

Implications for Coastal Mining

Sand is currently mined from Pakiri Bay by suction dredges at the rate of approximately 170,000 m^3/yr. Since the 1950's, extractions have concentrated on the seabed a little seaward of the alongshore bar in water depths of 4–8 m (HILTON, 1989). With the passing of the Resource Management Act (1991), local authorities and central government departments have sought an understanding of the sustainability of the extractions and specifically the potential for the operations to affect natural coastal development. Recent environmental impact assessments recognise the Pakiri-Mangawhai sand body does not receive significant modern inputs of sand from either alongshore littoral or parabathic offshore sediment, fluvial sources or from the erosion of local rocky coasts (O'BRIEN and ASSOCIATES, 1992; BECA CARTER HOLLINGS AND FERNER, LTD., 1992). Instead, sands mined from the nearshore are thought to be replenished by shorewards movement of inner shelf sediments.

The results of the present study show that inner shelf sediments are mostly comprised of sediment in the medium to coarse sand grades, whereas the sediments mined from the shallow nearshore are predominantly fine sands. Consequently, it is unlikely that sands mined from the nearshore would be replenished by onshore transport of inner shelf sediments. Similarly, the juxtaposition of very fine mid shelf and coarse lower inner shelf sediments indicates sediment exchange between the two environments is unlikely. Replenishment of sands mined from the nearshore is more likely to occur as a result of either diabathic or parabathic transport of nearshore sands or erosion during storms of foreshore/backshore sands.

The results of the present study also show that collectively the sediments of the coastal dunes, foreshore, inshore, nearshore and inner shelf environments in Pakiri Bay comprise a discrete sand body, bounded to landward by fluvial sediments and basement rocks, to seaward by muddy sediments, and alongshore by the coarse carbonate facies described from offshore of the rocky headlands by McCabe (1985) and Hilton (1990). Management of the sand mining operations should be based on the understanding that the sand body comprises a finite resource and, with the exception of autochthonous biogenic sedimentation, a closed sediment system. The sands mined from the nearshore constitute a net loss of sediment from the sand body such that mining cannot be considered a sustainable activity.

CONCLUSIONS

This study has presented the results of a sedimentological survey of an embayed sand body on the east coast of the Northland Peninsula. Environmental factors that distinguish this coast include the episodic exposure of the study area to easterly storm winds and waves, the dearth of fluvial sediment delivered to the coast, the embayed, isolated, nature of the sand body and the Recent tectonic stability of the area.

Bathymetric surveys conducted during the present study show the subtidal Pakiri-Mangawhai sand body to comprise a regular arrangement of morphologic features. In profile, the nearshore consists of a relatively steeply-sloping concave-out component between the alongshore bar and the inner shelf with a width of about 1,700 m, depth range of 3 to 20–25 m below mean sea level and characteristic gradients of 0.4 to 1.8°. The inner shelf profiles north of the Pakiri River display a convex-out geometry and slope more gradually, with gradients ranging between 0.2 and 0.5°. The transition from the inner shelf to the mid shelf occurs more or less uniformly alongshore, 4,200 to 4,500 m offshore, in water depths of 42–45 m. Characteristic slope angles on the lower inner shelf are 0.4 to 0.5°, while slope angles on the middle continental shelf are usually less than 0.1°.

The southern half of the Pakiri-Mangawhai sand body comprises an accumulation of relatively mud-free, unconsolidated sand, that is continuous between the coastal dunes and the base of the inner shelf. Seaward of the inner shelf there is an abrupt change in the characteristics of the bed—the sediments of the middle continental shelf in Pakiri Bay comprise very fine, muddy sands. The sedimentology of the sand body comprises a regular sequence of juxtaposed, shore-parallel, sediment types. The sediments of the nearshore are fine, very well sorted sands, while samples from the inner shelf are typically medium to coarse sands. Sediments of the backshore, foreshore and inshore, are comparable with those of the nearshore, foreshore and inshore sands being marginally coarser and less well sorted. The carbonate component of the sediments increases in an offshore direction, the highest concentrations being associated with the coarse sands and granules at the base of the inner shelf. The shell component of bed sediments shows the same size grading across the sand body as the non-carbonate fraction. It is proposed that the sediments of the nearshore-inshore-foreshore-backshore, inner shelf and mid shelf be recognised as distinct facies.

The juxtaposition of fine nearshore sands and medium to coarse sands to seaward characterises the southern half of the Pakiri-Mangawhai sand body offshore of the sandy coast. This pattern is reported from nearby exposed east coast North Island locations, including Omaha Bay (Schofield, 1978), Tauranga Beach (Harms, 1989), east Coromandel Peninsula (Dell *et al.*, 1985; Bradshaw *et al.*, 1991). However, in the Pakiri case there exists a systematic shore-normal gradation in grain size across the nearshore and inner shelf. As a working hypothesis, it is proposed that this gradation results from diabathic sediment transport resulting in the preferential shorewards transport of the fine sand fraction of the sediments of the inner shelf. The relatively low mud content of inner shelf sediments implies frequent disturbance of the bed by currents, however, the relatively low fine sand content of inner shelf sands suggests significant onshore transport of sediments may no longer be occurring. Further work is required to characterise the nature of the current regime, especially during episodic easterly storms.

The offshore boundary of the Pakiri-Mangawhai sand body occurs along a well-defined sedimentological boundary between the inner and mid shelf sediment types. In terms of the potential sustainability of sand mining in Pakiri Bay, it is unlikely that the sand body is receiving significant inputs of sediment and therefore comprises a finite resource. The relationship between inner shelf and nearshore sediments is less equivocal. There remains the potential for sands mined from the shallow nearshore to be replenished as a result of the onshore transport of inner shelf sediments, however; the sedimentology of the inner shelf makes this environment an unlikely source.

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