Nearshore-Surfzone System Limits and the Impacts of Sand Extraction*

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ABSTRACT

Nearshore coastal sand mining may adversely affect coastal development where extractions occur within the active beach-nearshore sand system. In this paper the outer limits of the beach-nearshore system are reviewed, with the inclusion of new data from Pakiri, New Zealand. These include interpretation of nearshore sedimentology, morphology, bedforms and benthic fauna, theoretical estimates of sediment movement, historic evidence of beach-nearshore morphodynamics, measurement of the seaward extent of ripplike plumes during or following storm wave conditions, and stratigraphic indications of seabed erosion and deposition. There is convergent data that for east coast Australian and New Zealand moderate to high energy beaches, including Pakiri, the maximum limit of the modern beach-nearshore sand system occurs around the 25 m isobath.

Recent interpretations of the geomorphology of the Pakiri-Mangawhai sand system, within which shallow marine mining takes place, are re-examined in light of the results of this review. The conclusion that substantial onshore sediment exchange occurs between inner shelf and nearshore environments, and that the Pakiri-Mangawhai sand system is therefore open to sediment inputs, is not sustained. The results of investigations of bedforms, subtidal facies, historic morphodynamics and theoretical estimates of sediment transport thresholds, indicates that the nearshore-inner shelf boundary approximates the 25 m isobath at Pakiri. Significant sediment transport does not occur beyond this depth over the relevant time scales. A re-analysis of the beach profile records, as well as interpretation of barrier morphostratigraphy, indicates that, contrary to most previous interpretations, the Pakiri-Mangawhai coast shows no strong accretory trend, is at best stable and possibly erosional. We hypothesize that the weak recovery of the Pakiri-Mangawhai coast following severe erosion in 1978 may be a consequence of sand mining.

In the Pakiri-Mangawhai context nearshore coastal sand mining entails a high risk of adversely affecting coastal processes and landforms.

ADDITIONAL INDEX WORDS: nearshore-surfzone system limits, Hallermeier closure, beach profiles, shoreface, inner continental shelf, sustainability, bedforms.

INTRODUCTION

Mining of nearshore sediments may cause or exacerbate erosion of exposed beaches by beach drawdown, intercepting sediments during transportation, removal of shelter afforded by offshore bars and banks and by modifying patterns of wave refraction (BRAMPTON, 1987; MOTYKA and WILLIS, 1975; ANCTIL and OUELLET, 1990; Kojima et al., 1987; Uda et al., 1986; NIELSEN et al., 1991). In order to assess the potential or actual impacts of surfzone and nearshore mining, it is necessary to determine the magnitude and frequency of sediment transport, deposition and erosion in these zones and the outer limits of these processes. This is so the kinds of negative impacts described above do not occur or occur so little as to be negligible.

Many countries have sought to limit the impact of open coast mining by allocating relict or palimpsest sediments that lie in water depths in excess of 18–20 m (e.g. VAN ALPHEN et al., 1990; Tsurusaki et al., 1988). This approach has not emerged in New Zealand. Applications to mine sand are evaluated on a case by case basis and mining currently takes place within surfzones in water depths of less than 8 m along the Pakiri-Mangawhai coast.

In this paper we examine two issues. The first is a review and analysis of the spatial extent of nearshore limits inside of which mining may impact coastal processes and landforms. In this section we include new data from Pakiri, New Zealand. The second aim is to present a detailed examination of the case of Pakiri, New Zealand, where sand extraction takes place within a surfzone, and where the nature of sediment supply and beach dynamics is in dispute. We attempt a critical re-evaluation of the impact of mining at Pakiri in the light of the results of our first aim, and the specific morphodynamic processes operating at Pakiri.

The Pakiri Coastal Setting

The Pakiri-Mangawhai embayment is located on the headland-bay coast of northeast North Island, New Zealand. Com-
pared with other locations around New Zealand the northeast shelf is starved of modern terrigenous sediments—rivers are small, rainfall moderate and estuaries are thought to trap much of the fluvial sediment delivered to the coast (Carter, 1975).

The study area lies adjacent to a lee shelf in a mid latitude zone of prevailing westerly winds. These winds are infrequently displaced by the dominant east and northeastward winds associated with the passage of subtropical low pressure systems, occluded fronts and slow moving anticyclones lying east of New Zealand (Harris, 1985). The wave climate along the northeast coast is one of mixed storm and swell waves, and is both lower and more variable 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 in the outer Hauraki Gulf is 1.4 m and rarely exceeds 3.0 m (Ewans and Kibblewhite, 1986). Periods are mainly in the range 6 to 9 sec (average 6.55 sec). The most extreme storm of recent times occurred in 1978 when a subtropical cyclone generated near hurricane force easterly onshore winds, and waves in the outer Hauraki Gulf of 8 m maximum height and 12 sec period (Peek, 1979f). The onshore wind-generated waves associated with this event were estimated to have a return period of between 10 and 30 years (Reid, 1979).

Tides are semi-diurnal and meso-tidal, with a maximum range of 3.0 m at springs and 1.5 m at neaps. Tidal currents are weak; maximum speeds do not exceed 0.19 m/sec. However, these values are exceptional; speeds greater than 0.10 m/sec were exceeded only 4.7 per cent of the record (Bell, 1986). Currents are dominated by bidirectional tidal flows, primarily oriented alongshore. Local (storm) wind-generated bottom currents of up to 4.0 m/sec are reported by Braudshaw et al., (1991) from the nearby east Coromandel Peninsula coast in water depths of 27 m and it is possible such currents also occur in the study area during periods of strong onshore winds. Regional scale parabathic currents such as the East Auckland Current are not thought to impinge into the Hauraki Gulf and significantly affect the study area (Harris, 1985).

THE SEAWARD LIMIT OF COASTAL NEARSHORE SYSTEMS

Hallermeier (1981), Nielsen et al. (1991, 1992a) and Nielsen and Lord (1993) review empirical and qualitative techniques and data which can be used to define the seaward limit of the subaqueous beach. These include (1) field surveys and interpretation of surfzone/nearshore/shelf morphology and sedimentology, (2) surveys of surfzone and nearshore bed movement data, (3) theoretical calculation of the maximum limit of bed disturbance by shoaling waves, (4) measurement of the seaward extent of rip-head plumes, (5) examination of bedform types and their indications for sediment movement, (6) the presence and stratigraphic interpretation of erosion surfaces in seabed cores and (7) variation in the distribution of benthic fauna diagnostic of specific depositional environments. In the following we examine these and related data in order to define the limits of the active beach-nearshore system.

Nearshore-Shelf Facies

Carter (1988) stated that the boundary between wave-worked and non-wave-worked sediment may be apparent from the sediment size, grain preservation or faunal community structure. In eastern Australia, many beaches display typical nearshore-offshore sediment patterns such that an inner nearshore zone 0 to 12 m depth comprising medium to coarse sands, an outer nearshore zone from 12 to 22 m depth comprising finer sand, an inner shelf sand from 22 to 45 m depth comprising course grained sediments and a mid-shelf fine sand and mud zone deeper than 45 m have been identified (Roy and Stephens, 1980; Chapman et al., 1982). Surficial sediments of the nearshore and inner shelf are oxidised while mid shelf sediments are not. Nearshore and inner shelf sediments are typically iron stained.

A review of data from many east coast Australian beaches indicates that the seaward limit of the inner and outer nearshore fine sand zone typically occurs in water depths of 15–30 m (Nielsen et al., 1991, 1992a; Nielsen and Lord, 1993). This range of water depths is partly a function of the range of modal wave energy received by any particular embayment and beach-surfzone type. Low energy reflective beaches display a narrow, more compressed sedimentary sequence and zonation while high energy dissipative beaches characteristically have wide, extensive sediment sequences (e.g. Clifton, 1976; Short, 1986).

A feature of many New Zealand east coast beaches is the juxtaposition of fine, well-sorted, nearshore sands and medium to coarse inner shelf sands (e.g. Dell et al., 1985; Bradshaw, 1991). The contact between these sediments usually occurs at depths of 20 to 30 m, and is generally interpreted to correspond to the limit at which wave-induced sediment movement most frequently occurs (e.g. Carter and Carter, 1986; Hume and Hicks, 1993). Further offshore, the inner shelf boundary has been interpreted to coincide with an increasing proportion of clay and silt around depths of 45 to 50 m (e.g. Dell et al., 1985; Riley et al., 1985).

Hilton (in press, a) interprets the unconsolidated marine sands of the Pakiri-Mangawhai embayment as a discrete 'sand body', and recognises coastal-nearshore, inner continental shelf and mid shelf facies (Figure 1). The former facies comprises fine, very well sorted sands of 2 phi (0.25 mm) mean grain size. The finest sands occur approximately 1500 m offshore in water depths of around 15 m (Figure 2a), a pattern which has been generally interpreted to indicate the seaward limit of rip transported sediment. At water depths of about 22 m (below m.s.l.) these fine (nearshore) sands grade into a medium to coarse (inner shelf) sand facies (M, = 0.0–0.5 phi, 0.71–1.00 mm). An interesting feature of this facies is the trend of increasing coarseness with distance offshore (Figure 2a,b); mean grain sizes may range from 1.5 to 0.0 phi across the inner shelf. An abrupt change in sediment texture occurs at the base of the inner shelf, notably a sharp increase in mud content (from 1 to 10 per cent) and fining of the sand fraction (Figure 2a–c). The sediments of the mid
Nearshore-Shelf Morphology

The term ‘nearshore’ in the present paper is used to define the bottom slope lying between the outer reaches of the surf zone and modal wave base, which equates to the ‘shoreface’ of Swift (1976) and ‘nearshore’ of Short (1984a) and is a zone of active bedload sediment transport (Niedoroda et al., 1984). This feature is widely recognised as a concave-upward bottom slope, with the steepest slopes nearer to shore (Niedoroda and Swift, 1991), and generally interpreted as an equilibrium response of an unconsolidated coast to the typical local wave and current regime (Niedoroda and Swift, 1981). For open ocean beaches the depths of the upper and lower boundaries of the nearshore are primarily controlled by the net local wave and current environment and are variable. Estimates of the latter for moderate energy beaches include 25 m along the sandy coasts of the New York bights (Niedoroda et al., 1984), 15 m at Duck, North Carolina (Wright, 1987), between 10 and 25 m for Southeast Australian beaches (Short, 1986), and 20 to 30 m for beaches of northeast North Island, New Zealand (e.g. Dell et al., 1985; Bradaslaw et al., 1991; Hume and Hicks, 1993). Following a review of nearshore studies Wright (1987, p.28) concluded that the ‘sea-ward limit of bidirectional sediment exchange or “depth of closure” is between the depths of 20 and 30 m’.

In profile, the Pakiri nearshore displays a concave geometry that extends to approximately the 22 m isobath, 1500 m or so offshore, with gradients ranging between 0.4° and 1.8° (Figure 2d). The inner shelf displays a convex or irregular profile, with slopes of 0.1° to 0.6°, and extends seaward of the nearshore to a break of slope at the 45 m isobath, approximately 4500 m offshore. The mid shelf slopes gently seaward with gradients of 0° to 0.15°. The overall morphology of most Pakiri-Mangawhai shore normal profiles accords with the ‘depressed’ shoreface type of Everts (1978), with a terrace between nearshore and inner shelf environments.

Nearshore-Inner Shelf Bedforms

Wave formed sedimentary structures can be used to characterise 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 (Clifton and Dingler, 1984). The phase models of stress-related bed deformatons of Clifton et al. (1971), Davidson-Arnott and Greenwood (1974, 1976) and Clifton (1976) predict a transition from flat bed (no movement) to ripple marks (symmetric forms), small sand waves and dunes (asymmetric) and plane beds (sheet flow) as stress increases. The progression from one phase to another is controlled by variations in water depth, grain size, velocity, wave period and wave asymmetry (Clifton, 1976).

Modal wave base is generally interpreted to occur at the transition from asymmetric to symmetric ripples, although in most cases this juncture corresponds with a transition from fine to medium or coarse sands and can not simply be related to flow regime. Short’s (1984a) systematic study of beach and nearshore sediments, structures and bedforms from a range of Southeast Australia beaches exposed to modally low, moderate and high wave activity indicates that the results are consistent with the gradation in shoreface facies between low- and high-energy systems predicted by the phase models. For Seven Mile beach, an exposed beach (Hₚ = 1.6 m) of the bar-trough type (Short and Wright, 1983), modal wave base occurs at 25 m, with sinuous-crested wave ripples to landward (L = 20–50 cm, H = 5–10 cm), and large, well-developed, parallel sharp-crested, ripples (L = 100 cm, H = 25 cm) to seaward.

Comparable bedform sequences are reported from moderate energy beaches of northeast New Zealand (e.g. Dell et al., 1985; Hume and Hicks, 1993), with the juncture between rippled fine and very fine sands and megarippled coarse sands, and interpreted modal wave base, occurring at depths of about 20 m. Hilton (1990) identified five bed configurations offshore of Pakiri Beach (Table 1). Small asymmetric, discontinuous, ripples (L = 10–15 cm, H = 5–8 cm) occur between the alongshore bar and the 10 m isobath. Regular, periodic bedforms are not present on the shoreface between water depths of 10 and 25 m, the bed being essentially flat or irregular with relative relief less than 12 cm. In marked contrast, broad areas of the inner shelf are characterised by
Nearshore Sand Systems

Figure 2. Shore normal variation in (a) mean grain size (with standard deviations portrayed as error bars), (b) proportion of each sample in coarse, medium and fine sand grades, (c) per cent mud, across (d) Walkway transect showing interpretation of nearshore and shelf environments (after HILTON, in press a, b).
Table 1. Bedform configurations and characteristics, Pakiri Bay.

<table>
<thead>
<tr>
<th>Environment</th>
<th>Depth Range (m)</th>
<th>Configuration</th>
<th>Ripple Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nearshore</td>
<td>4–10</td>
<td>Asymmetric, discontinuous ripples</td>
<td>λ (m) 0.1–0.15</td>
</tr>
<tr>
<td></td>
<td>10–22</td>
<td>Irregular</td>
<td>η (m) 0.05–0.08</td>
</tr>
<tr>
<td>Inner shelf</td>
<td>22–42</td>
<td>Symmetric, linear-crested, continuous ripples</td>
<td>D (mm) 0.25–0.28</td>
</tr>
<tr>
<td>Mid shelf</td>
<td>42–48+</td>
<td>a. Featureless</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>b. Linear-crested ripples</td>
<td></td>
</tr>
</tbody>
</table>

λ—mean ripple wavelength (m); η—ripple amplitude (m); D—mean grain size of non-carbonate fraction (mm); from surveys September–October, 1987

continuous, linear-crested, symmetrical ripples and megaripples ($L = 83–136$ cm, $H = 20$ cm). Apart from rare continuous, linear-crested, ripples developed in patches of relatively coarse sediment ($L = 75$ cm, $H = 0.15$ cm) the mid shelf bed at depths in excess of 45 m is mostly featureless. Minor topographic variations of less than 5 cm were attributed to polychaete bioturbation (HILTON, 1990).

The Pakiri sequence of nearshore-shelf bed configurations agrees with theoretical estimates of bed response to oscillatory flows. Figure 3 relates the Pakiri bedform data to threshold curves derived from the threshold of movement equations of KOMAR and MILLER (1973, 1975) and the threshold curve for sheetflow of DINGLER and INMAN (1977). The combinations of maximum orbital velocity (using Airy wave theory) and grain size were calculated for typical swell ($H = 1.5$ m, $T = 7$ sec) and storm wave ($H = 5$ m, $T = 12$ sec) conditions. In the former case grain-size thresholds are not surpassed seaward of about the 20 m isobath and, because of biological and other effects, more likely approximates the 10 m isobath, the depth limit to which small, asymmetric, discontinuous

![Figure 3](image-url)
ripples were observed. Large waves (H = 5 m, T = 12 sec) are able to disturb the bed at all locations, inducing sheet flow across the nearshore to depths of around 23 m, and a rippled bed in greater depths.

**Surfzone-Nearshore Morphodynamics**

A number of studies in Australia and overseas have examined the nature of beach and nearshore profile or bed change as a function of varying wave energy conditions (e.g. **Wright and Short**, 1983; **Greenwood and Davidson-Arnott**, 1979). Many of the beach models demonstrate the migration of surfzone bars seawards during storm or high wave energy conditions (e.g. **Wright et al.**, 1979). Typically bars migrate seawards to a point where the seaward toe of the bars extend to −12 to −14 m below mean sea level in microtidal and meso-tidal environments (e.g. **Higgs** and **Nittim**, 1988; **Short**, 1985; **Mangor**, 1986). Figure 4 displays a 1978 immediate post-storm (1978) profile and a profile typical of 52 nearshore profiles surveyed by **Hilton** (1990) in the period 1984–89 and indicates that, consistent with other studies, longshore bar migration to water depths of 6 to 14 m occurs. Seaward of the 1978 bar the data are less accurate, being subject to greater survey error and, while we include them in this figure we cannot attest to the reliability of this portion of the figure compared to the high reliability of the data above −14 m depth. The lower profile, however, may still reflect real change.

Figure 5 plots the Pakiri maximum bed level variation data and maximum bed depths obtained from Figure 4 with data obtained from several other studies of nearshore profile change (**Nielsen et al.**, 1992a; **Nielsen and Lord**, 1993). Much of this data is either long term profile data (e.g. **Mangor**, 1986) or was carried out specifically to measure pre-storm and post-storm profile change (e.g. **Higgs** and **Nittim**, 1988). It is evident that marked variation in bed levels occur in the 0 to −12 m depth range. This is not surprising given the potential migration seawards and landwards of bars in the surf zone, and much of the variation in data merely reflects the height that bars may attain relative to a storm profile following a post-storm recovery period for different beach-surfzone types.

Seawards of −12 to −14 m there is a marked decrease in bed level variation. The only reliable data we have is that collected by the Public Works Department of New South Wales where relatively precise measurements were made utilising stakes driven in the seabed (PWD, 1980–1982, unpublished). This data is averaged which excludes the effect of ripples and dunes. Minimum sea bed elevation

![Figure 4](image-url)

*Figure 4. Comparison of post-storm 1978 beach-nearshore profiles (surveyed on 14.12.78 and 21.11.78, respectively) and a more recent, representative (1987) beach-nearshore profile, Walkway transect (after Hilton, 1990). The accuracy of the survey data below −14 m cannot be guaranteed.*
Rips and Rip Currents

Rips commonly occur in intermediate beach-surfzone types as relatively discrete high velocity, horizontally segregated flows. They typically become larger and fewer in number as wave height increases (McKenzie, 1958; Short, 1985) and in very high energy events may become very strong and have been termed mega-rips (Wright and Short, 1983; Short, 1985). Rips are characterised by rip heads where the jet-like rip current at the seaward terminus breaks up into irregular to highly organised vortices and rip transported sediment is dispersed (Figure 6).

Rip currents are known to transport significant quantities of sediment seawards especially in storm conditions when seaward flows may be significant (\(> 2-3 \text{ m/sec}\), Wright et al., 1980). Short (1985) provided diagrams taken from aerial photographs of mega-rips in three Sydney embayments but did not provide any indication of depths to which sediments were being transported in these rips. Figure 7 illustrates this data at the correct scale, with one addition (Wamberal Beach) and with bathymetric contours superimposed. It may be seen that these rips are transporting suspended sediments to depths of at least 12 to 18 m. This position corresponds with the curved portion of Figure 5 and indicates that maximum bed level variation as a function of rips and bar migrations may be of the order of approximately 0.4 to 0.2 m in 12 to 18 m water depth.

Theoretical Estimates of Wave Base

The formulae of Hallermeier (1981, 1983) have been used to subdivide the shore-normal profile of a seasonal sand beach into littoral, shoal and offshore zones. The shoal zone change was observed by the PWD over the two years of survey in which waves with a maximum significant wave height (\(H_s\)) of 4 m occurred. Thus, while we cannot state that sediment is not transported beyond \(-15\) m, significant transport, deposition and erosion occurs inshore of \(-15\) m.
is an intermediate or buffer zone where expected surface waves have neither strong nor negligible effects on the sand bottom. This zone extends seaward from the maximum depth for erosive cutting of the nearshore by yearly extreme waves ($d_1$) to the maximum water depth for sand movement initiation by the yearly median wave conditions ($d_2$). These limits can be approximated as:

$$d_1 = 2H_s + 11\sigma$$
$$d_2 = (H_s - 0.3\sigma T_s g/5000D)^{0.5}$$

where $H_s$ = annual mean significant wave height (m), $\sigma$ = annual standard deviation of significant wave height, $T_s$ = annual mean significant wave period (sec), $g = 9.81$ m/sec/sec and $D$ = median grain size diameter (m). For the Katikati coast, northeast New Zealand, Hume and Hicks (1993) calculated $d_1 = 6.6$ m and $d_2 = 25.1$ m. These results correlated well with sedimentological and bedform data, and accord with observations of dredge spoil dispersal, 3 km offshore of nearby Tauranga Harbour, in water depths of 11–17 m (Healy et al., 1991).

For the Pakiri embayment we calculate Hallermeier limits of $d_1 = 10.1$ m and $d_2 = 24.5$ m, assuming $H_s = 1.044$ m, $\sigma = 0.727$ m, $T_s = 12$ sec, and $D = 0.32 \times 10^{-5}$ m (the average mean grain size of subtidal sands in water depths of 3 to 25 m). $H_s$ was derived from daily observations of $H_{10}$ at a deep water station (65 m) east of the study area in the outer Hauraki Gulf, as reported by Ewans and Coop (1982a,b) and Ewans and Kibblewhite (1986), for the year ended 25 March 1981. The outer limit ($d_1$) coincidentally corresponds to the juncture between the nearshore fine sand and inner shelf medium to coarse sand facies of Hilton (in press, a).

**Pleistocene-Holocene Sediment Boundaries**

Figure 8 illustrates the envelope of recorded bed level variations shown in Figure 5 and includes other proxy data of potential bed level variations, or depths at which potential sediment transport might occur. Hudson and Roy (1989) carried out an offshore drilling study in the Narrabeen embayment in Sydney, New South Wales, to determine the nature of the subsurface sediments. They found relict, iron-stained Pleistocene sands underlyng Holocene transgression.
sediments at various depths across the embayment and the boundary between these two sedimentary units has been plotted on Figure 8. Note that the data have been plotted as depths below the ocean floor surface, that is, the depth below the sea floor at which the sedimentary boundary was first encountered.

The core data may indicate the following: Firstly, they may describe the postglacial transgressive basal erosion surface which was produced as sea level rose in the embayment in the period 10,000 to 6,000 years B.P. (i.e. in water depths of −40 to 0 m). Presumably the envelope curve in Figure 8 would be shifted to the right for sea levels lower than present. For example, when sea level was at −10 m, the present −15 m position would have occupied a position around −5 m and would therefore have been in the highly active surf zone. The fact that the stratigraphic boundary is not higher than it is may reflect the fact that the Narrabeen offshore zone is characterised by sandstone reefs which may have limited the base level to erosion. Secondly, the core data may reflect the maximum depth of disturbance, and hence erosion to various depths over the last 6000–7000 years of sea level stillstand. This implies that during intense storm conditions the whole Holocene sedimentary unit is mobilised and the surface of the Pleistocene unit is exposed, if not eroded, at least once. This second proposition would therefore imply that, if correct, the core data represents the maximum level of storm erosion and hence bed level variation in the late Holocene. However, the core data may not be a true indication of the maximum vertical extent of storm erosion or sediment movement. Instead, the sands overlying the Pleistocene sediments may merely be surficial cover sands on a surface eroded down to a level whereby the extensive surrounding reefs restrict further base-level erosion in this embayment. If the reefs were absent the value of the second proposition would increase.

Investigations elsewhere have shown the modern nearshore sand wedge to be of variable thickness with substantial deposits more commonly associated with large inputs of fluvial sediment or alongshore sedimentation. The coast south of the Otago Peninsula, east coast South Island, New Zealand, experiences a significant north-east alongshore drift of sediment and a supply of fluvial sediment from the Clutha River of 3.14 M t/yr (CARTER, 1986). The Holocene ‘nearshore sand wedge’ in this region reaches a maximum thickness of 34 m (CARTER and CARTER, 1986). In contrast, the northeast coast of the New Zealand is known to be starved of modern terrigenous sediments (CARTER, 1975) and individual embayments probably do not experience significant net alongshore sediment flux. RILEY et al. (1985) obtained cores across the nearshore in Omaha Bay in water depths of 3.9, 8.02, 11.4 and 19 m below local chart datum. Dated shell layers show the modern surficial sands to be relatively thin, at −1.7 m (3.9 m water depth), −0.6 m (8.02 m), −0.4 m (11.4 m), pinching out to 0 m at the base of the nearshore (19 m).

The PWD (unpublished) also took detailed measurements of ripple and megaripple amplitudes and heights at various depths in their 1980 to 1982 survey. These are plotted in Figure 8. Offshore of 15 to 17 m water depths the ripples are influenced by tidal current processes (WRIGHT et al., 1980) more than by wave-induced motions and are therefore not present as a function necessarily of onshore-offshore wave driven events. However, they do provide an indication of maximum potential bed elevation and the fact that the ripple heights correspond roughly to the depths at which the Pleistocene/Holocene sedimentary boundary occurs seawards of −25 m may lend support to the second core data interpretation above.

CASE STUDY: COASTAL MINING AT PAKIRI-MANGAWHAI

Mining has taken place along the Pakiri-Mangawhai coast since the early part of this century. Prior to the 1940’s extractions were from the intertidal beach, and entailed the laborious loading of a sailing scow beached on the falling tide. From the 1940’s the mining process involved mechanical excavators mounted on dumb barges and the focus of activity shifted to the shallow nearshore (HILTON, 1989). Extractions presently occur a little seaward of the alongshore bar, 2–300m from high water in water depths of 3–8m, along a 9.5km length of the Pakiri-Mangawhai coast (Figure 1). Mining takes place during periods of swell wave activity and offshore winds, using suction pumps mounted on dumb barges of from 680 to 1500 tonnes capacity. The equipment deployed is not capable of operating seawards of the 10 m isobath (HILTON, 1989). The immediate impact of any one period of extraction is the excavation of a borrow pit approximately two metres deep and tens of metres in length/width, which is rapidly obliterated during subsequent periods of swell and/or sea wave activity over periods of hours to days. The impact of a nearshore excavation is apparently rapidly averaged over a larger area by surfzone and nearshore sediment transport.

In 1993 three companies were granted permits to extract a total of 110,000 m³/y of sand for a 10 year period from the
shallow nearshore bordering the Pakiri-Mangawhai sandy coast. The environmental impact assessments submitted in support of the applications by the mining companies concluded that (1) the quantities of sand to be extracted would be small in comparison to the total volumes of sand in the beach system; (2) the beach system is open and sands extracted from the shallow nearshore are replaced as a result of diabathic onshore transport of inner shelf sediments; (3) Pakiri and Mangawhai beaches have accreted in historic times in the presence of mining, and (4) there is no evidence of the impact of past coastal mining (BCHF, 1992; O’BRIEN and ASSOCIATES, 1992). The present section re-examines the basis for these propositions with regard to the preceding review, and evaluates specific arguments that relate to the assessment of impact at Pakiri-Mangawhai.

**Pakiri Coastal Processes and Holocene History**

**Pakiri-Mangawhai Barrier Stratigraphy and Implied History**

The gross morphology, dune types and barrier stratigraphy of the Pakiri-Mangawhai embayment is of interest in that an assessment of its form and evolution (not considered in previous studies) provide a guide to the operation of long-term processes (e.g. long-term erosion or accretion). In order to provide some background to the Pakiri-Mangawhai barriers a brief review of transgressive dune barriers follows.

Many barriers comprising parabolic and transgressive aeolian dune fields have been studied in Australia and elsewhere (e.g. NUMMEDAL, 1983; LEATHERMAN, 1979; THOM et al., 1992). The most erosional of the range of barrier stratigraphies illustrated in Figure 9(i) is where the barrier is a reeded (Australian term) or transgressive (USA terminology) type. Here, the barrier recedes due to rising sea level and/or nett sand erosion from the nearshore. Morphologically the barriers display terrestrial transgressive dune fields and/or parabolic dunes hence indicating the sometimes poor utility of the names of barrier types (e.g. the episodic transgressive dune barriers of CHAPMAN et al. (1982) can also be reeded barriers). Erosion and transgression is obvious in these cases where Holocene estuarine, lagoonal, or beach barrier strata are exposed on the shoreface (e.g. NUMMEDAL, 1983).

The next type (Figure 9(ii)) occurs where relict foredune lines and associated nearshore sediments are eroded and transported landwards to form transgressive dune fields (ROY and CRAWFORD, 1979). It has been commonly assumed, often on little evidence, that episodic transgressive dune barriers have formed in this way (cf. CHAPMAN et al., 1982). Type iii indicates Holocene barriers formed over existing Pleistocene barriers which may, or may not, have subaerial expression and extend above present mean sea level. These Holocene types have again often been regarded as having formed as erosional or reeded barriers, and they may be, although it is as likely that they are not. It is usually impossible to tell on stratigraphic grounds. It is possible that major dune transgression takes place in the absence of any major beach and nearshore progradation.

Many transgressive dune barriers may have been initiated as Holocene post-glacial sea levels rose as shown in Figure 9(iv). Here the first transgressive or parabolic dune phase directly overlies Pleistocene sediments and was formed well before sea level reached the present level. Beach and nearshore progradation was relatively small in relation to onshore aeolian dune volumetric transport (THOM et al., 1992). The type (v) barriers are indicative of the many small transgressive dune barriers along the southern Sydney-Illawarra coast (HESP, 1993). Transgressive dunes either form in conjunction with limited beach and nearshore progradation (a) or following gradual foredune destruction well after beach, nearshore and barrier formation (b).

Finally, transgressive dunefield barriers may be formed in a situation where the beach and nearshore progrades significantly and contemporaneously with dunefield development (Figure 9(vii)). Relict foredunes may have formed first (to various extents) and then been wind eroded to release sands for transgressive dune development as indicated by THOM et al. (1992) for the Newcastle Bight example, but this is not necessary for this type of barrier development. Such barriers also develop without foredune development; that is, by progressive beach-nearshore progradation accompanied by transgressive dune development (e.g. the Walvis Bay barrier, Namibia, the Guerrero Negro barrier, Baja California, Mexico; HESP and THOM, 1990; WARD and HESP, in prep.).

Overall, landward recession and hence long-term beach-nearshore erosion is demonstrable for type (i) barriers; possible, but difficult to prove for types (ii), (iii), and (v) barriers and in any case is not necessary for dunefield formation; is demonstrable for a situation where sea level is rising but not once sea level is stable as in type (iv); and is not demonstrable in the case of type (vi) unless a clear hiatus is found in the age structure of the regressive nearshore sediments or obvious foredune ridges remain.

In the case of the Pakiri-Mangawhai barrier system, geological and topographical maps exist (Figure 10) but stratigraphic analyses are limited to a few field observations; no drilling has been carried out. The Holocene barrier is narrow in the south (Figure 10a) comprising a high, scarped blowout-parabolic dune complex apparently sitting on bedrock. It broadens to the north (Figure 10b) becoming a higher sequence of parabolic dunes overlying a Pleistocene barrier. The width and thickness of Holocene beach and nearshore sediments is unknown, but may be quite narrow and thin (see Figure 10c). Towards the north (profile c) the barrier widens further and forms a transgressive aeolian dune field. Pleistocene sediments outcrop at approximately mean sea level in the beach mouth of Poutawa stream indicating the paucity of underlying Holocene progradational (or regressive) sediments.

The morphology and dune types of the barrier at profiles b and c indicate a long-term erosional process. In all surveys conducted by the second author (e.g. HESP and CHAPE, 1984) steep, blowout-parabolic dune complexes sitting adjacent to the beach (i.e. no foredune is present) only occur in erosional sites (e.g. Warnbro Sound, and Leschenault Penn., Western Australia, cf. CARTER et al., 1990). The overall barrier stratigraphy may indicate Holocene coastline stability or
erosion. The review of aeolian transgressive barrier types above indicates that some authors (e.g. CHAPMAN et al., 1982) appear to intimate that Holocene barriers on Pleistocene barrier cores (as in the case of profile c) are primarily erosional (or receded) types. However, it is also possible for sediment transfer to take place from the beach-nearshore zone to an aeolian dunefield without moderate to significant beach-nearshore progradation or erosion taking place. Overall, profile a and the northern portion of the Pakiri barrier indicate shoreline stability and aeolian landwards transfer at best, and shoreline erosion at worst, and profiles b and c indicate long-term erosion (parabolic dunes arise from the beach) and a sediment deficiency (ie. Holocene beach and nearshore sand volumes are low). Since littoral drift is non-

Figure 9. A range of episodic transgressive dunefield barrier types based on various field examples: (i) SEMENIUK (1985) and HESP (unpublished); ROY and CRAWFORD (1979); HESP (unpublished; Illawarra) and THOM et al. (1992; Seal Rocks); (iv) and (vii) THOM et al. (1992); and (iv) HESP (1993). Note that in the case of type (vii) a foredune plain may have been formed first and then gradually destroyed by aeolian processes. However, this is not a pre-condition or necessary for dunefield development.
exist to minimal (O'BRIEN and ASSOCIATES, 1992, estimate 5000 m³/y), this factor does not reasonably account for the alongshore variations in barrier morphology.

**Interpretation of 1978–93 Pakiri-Mangawhai beach profiles**

Beach-dune surveys have been conducted along the Pakiri-Mangawhai coast since September 1978 at 8 locations, and at an additional location (P2a) since July 1990. Analyses of the surveys have reached two opposite conclusions. One, that the profiles indicate nett, long-term accretion of the subaerial beach and adjoining dune (BCHF, 1992; KIRK, 1993) and two, that the profiles record episodes of erosion and accretion reflecting episodic berm accretion/erosion (Figure 12b, c), (iii) littoral drift and (iv) persistence of the 1978 storm scarp (Figures 12a, b; 13).

The excursion distance analysis (Figure 11) indicates (i) incipient foredune accretion from October 1978 to May 1985 but relatively little backshore accretion since 1985 (e.g. see the 4 m excursion distance, Figure 11), (ii) a beach change envelope reflecting episodic berm accretion/erosion (Figure 12b, c), (iii) littoral drift and (iv) persistence of the 1978 storm scarp (Figures 12a, b; 13).

The Brown (P7) series of profiles shows no significant trend of vertical or seaward profile translation such as might be expected were the coast accreting, apart from minor incipient dune formation. Indeed, following a prolonged period of easterly winds in September 1985 the profiles seaward of the incipient foredune were eroded to levels as low or lower than those measured immediate post-1978 storm. Almost all the accretion generally attributed to the period 1978–1993 by BCHF (1992) and KIRK (1993) occurred as either incipient foredune accretion in the period 1978–1985, or seaward of the 4 m contour since 1990. While the lower beach contours (0–2 m) presently lie seaward of their mean excursion distance 1978–1993 they have been at comparable positions at times throughout the beach survey record and subsequently shifted landward following a storm event. At best there has been around 20–25 m seaward progradation since the 1978 storms. The incipient foredune formed across the 38 m to 60 m region in Figure 12b and the 2.0 m contour (e.g. in Figure 11) moved seaward from the 64 m to the 87 m position. The conclusion of SMITH and OVENDEN (1993, p.6) that "the beach is most term nett erosion even though there is short-term post-storm beach accretion.

HILTON (in press, b) has shown the existing beach profile record is of limited efficacy for determining the impact of nearshore sand mining because (i) they are based on a time series of profiles that commenced while the foreshore/backshore was in a severely eroded post-storm condition (post-1978 storms) and culminated when the beach was in a relatively nourished condition, (ii) much of the recorded accretion of the foredune at sites P3 and P4 and elsewhere resulted from artificial foredune nourishment by the (then) New Zealand Forest Service following the 1978 storms, (iii) the geomorphic significance of other anthropogenic disturbances, particularly dune vegetation disturbance and resulting blow-out development, has not received adequate attention, and (iv) the surveys cover only the landward fringe of the beach-nearshore sand system. In addition, it must be recognised that the beach profiles that record coastal development adjacent to the present nearshore mining operations have been much affected by engineering efforts to re-establish the foredune eroded during the 1978 storms. WISHNOWSKY (1981, p.4) describes the mechanical construction of a "straight, even foredune 4 metres high with a base width of approximately 20 metres, and a flat top approximately 5 metres wide".

Here we briefly reassess the eight Pakiri-Mangawhai profiles and examine the record of recent coastal change. Figures 11 and 12a, b summarise the morphologic variation across the Brown (P7) transect (located in Figure 1) since the 1978 storms. This transect was chosen because of the greater frequency of surveys and because it is less affected by human disturbance (farming, afforestation and dune reconstruction). The excursion distance analysis (Figure 11) indicates (i) incipient foredune accretion from October 1978 to May 1985 but relatively little backshore accretion since 1985 (e.g. see the 4 m excursion distance, Figure 11), (ii) a beach change envelope reflecting episodic berm accretion/erosion (Figure 12b, c), (iii) littoral drift and (iv) persistence of the 1978 storm scarp (Figures 12a, b; 13).

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The interpretation is based on a series of profiles that commenced while the foreshore/backshore was in a severely eroded post-storm condition (post-1978 storms) and culminated when the beach was in a relatively nourished condition. Much of the recorded accretion of the foredune at sites P3 and P4 and elsewhere resulted from artificial foredune nourishment by the (then) New Zealand Forest Service following the 1978 storms. The geomorphic significance of other anthropogenic disturbances, particularly dune vegetation disturbance and resulting blow-out development, has not received adequate attention, and the surveys cover only the landward fringe of the beach-nearshore sand system. In addition, it must be recognised that the beach profiles that record coastal development adjacent to the present nearshore mining operations have been much affected by engineering efforts to re-establish the foredune eroded during the 1978 storms. WISHNOWSKY (1981, p.4) describes the mechanical construction of a "straight, even foredune 4 metres high with a base width of approximately 20 metres, and a flat top approximately 5 metres wide".

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**Figure 10. Geology of the Pakiri-Mangawhai coast, including characteristic barrier profiles (a–c). The topography and geology is based on NZMS 290 R08/09 and the barrier stratigraphies on limited field investigations.**

likely stable rather than accreting under the current sand mining regime" would seem conservative.

Post-storm recovery of wave-dominated, intermediate, beaches: evidence from Southeast Australia

The Pakiri-Mangawhai beach survey record is too short, and the map and aerial photographic records too poor to be unequivocal about the direction of the historic development of the Pakiri coast. However, we can obtain a perspective on the likelihood of one or other development scenarios (stability, erosion or accretion) being potentially closer to the truth by examining the records of comparable beaches which have been monitored for a similar and longer period than Pakiri.

In New South Wales, Australia, two beach-dune sites, at Myall Lakes and at Moruya have been continuously monitored since 1976 and 1972, respectively (Hesp, 1984; Thom and Hall, 1991; Thom et al., 1992). These sites are both moderate to high energy, modally intermediate, micro-tidal beaches, barred with moderate rips. They display slightly coarser mean grain sizes and are slightly less dissipative than Pakiri. littoral drift is uncommon to absent and they are probably closed sediment compartments. High magnitude storms impacted these sites in 1974 and 1978, causing severe backshore scarping and beach erosion. In the case of Moruya, the pre-storm 1972 beach and incipient dune volume varies between c. 225 m$^3$/m and 350 m$^3$/m over four profiles (Figure 14a). The 1974 cluster of storms resulted in the depletion of beach volumes down to 105–148 m$^3$/m. Post-storm recovery up to 1978 lead to increased beach-incipient dune volumes of around 250–280 m$^3$/m. These volumes reached the initial 1972 volumes by mid-1977 on two of the Moruya profiles (3 and 4) but only reached 50–60 per cent of the 1972 volumes on the other profiles (1 and 2). The 1978 storms caused further severe erosion and it took until 1980–81 for beach recovery to approximate the 1972 initial volumes. Overall, it took from 7 (profile 3) to 9 (profiles 1 and 2) years for full beach-incipient dune volumetric recovery. Maximum and minimum volumes averaged over the four profiles were 416 m$^3$/m and 129 m$^3$/m, respectively over the period 1972 to 1987. It is important to note that the accretion rate declined steadily between 1978 and 1981 and observations up to the present (1994) indicate a fluctuating, but near constant beach volume since 1981 (Thom and Hall, 1991; cf. their figure 5).

The record at Dark Point, Myall Lakes, NSW, is similar to that of Moruya, c. 500 km to the south and indicates a regional trend in storm history and recovery. Although the survey record begins after the 1974 storms there is a good anecdotal and photographic record for the pre- and post-1974 storm period. The 1978 storms had less effect in the Dark Point area compared to Moruya with relatively severe beach erosion but little incipient foredune erosion. As Figure 14b indicates, two incipient foredunes developed at Dark Point in the 1978 to 1993 period. The rate of incipient foredune accumulation has slowed significantly from early 1990 to the present. Beach progradation largely ceased around late 1987-
early 1988; this is indicated by the seaward limit of vegetation growth which fluctuates around the 55–60 m position. The edge of the incipient foredune has also been slightly eroded on several occasions since 1988. Thus, it appears to have taken between 10 to 16 years for full beach-dune recovery to have occurred following the 1974 and 1978 storms assuming (i) beach progradation ceased around 1988, (ii) dune accumulation became limited by 1990, and (iii) the volume gained since 1974–1978 is close to the volume lost.

Both studies show that it takes a considerable time for beaches to recover following major storm erosion. Sediment is rapidly transported into deeper nearshore waters and takes 8–16 years to be transported back onto the subaerial beach. These surveys are supported by observations of, for example, SHORT (1984b) who found that at Bracken Beach, NSW, it took a similar time as at Moruya for fine sand deposited in the nearshore during the 1974 storms to return to the beach (cf. also e.g. BRYANT, 1988). It is therefore dangerous to assume that the volume of sediments accreted at Pakiri since the last major storm of 1978 represents a phase of

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Figure 12. Post-1978 storms beach profile record, Brown (P7) Profile, Pakiri Beach; showing (a) envelope of beach change 1978–1993 and superimposed March 1993 profile (after SMITH and OVEN DEN, 1993), and (b) selected profiles showing 1978 post-storm profile (24.10.78), incipient foredune development (1985, 1986) and a more recent (March 1993) profile (after HILTON, 1990, and SMITH and OVEN D E N, 1993).
Figure 13. Photograph showing the inferred 1978 storm scarp fronted by an incipient foredune, Brown (P7) profile, Pakiri Beach (11.6.85). The incipient foredune is low and limited in extent.

Figure 14. Evolution of two incipient foredunes at Dark Point, Myall Lakes National Park, N.S.W., Australia, following severe storm erosion in 1974. The beach has prograded approximately 40–45 m since 1974 (updated from Hesp, 1984).
long-term accretion. Such a conclusion is highly suspect given the observations at Dark Point, Moruya and other sites. The Moruya surveys show that once the pre-1974 storm volumes were attained, beach-dune volumes fluctuated around a fairly constant level (Figure 15). This, therefore does not indicate net accretion, but recovery and stability. The Moruya and Dark Point incipient foredunes prograded around 60–70 m seaward of the 1974 scarp. The Pakiri incipient foredunes prograded c. 23 m seaward of the 1978 scarp (to March 1993). Note, however, that in 1989 Pakiri intertidal beach levels were little different than post-1978 storm levels (e.g. Figure 11).

The Pakiri-Mangawhai survey data indicate a short-term, post-storm recovery phase where storm-eroded sediment is gradually transported shorewards to produce incipient foredune development and minor beach progradation. Our view is that although the net long term direction of beach progradation or erosion cannot be accurately determined, the conservative view, [based on studies as the Moruya one] is that the Pakiri-Mangawhai beach system is merely experiencing a phase of post-storm recovery and, at best, is stable. Since no pre-storm survey data is available, we must presently speculate that the volume of shoreward sediment translation is greater than that required to replenish the bar and surfzone sands taken by mining. Note, however, we cannot be sure that the rate and magnitude of post-storm beach and dune accretion might be considerably greater were mining not taking place. If this were the case, then nett beach erosion is actually taking place (see later discussion).

Potential for Nearshore-Shelf Sediment Exchange

Environmental impact assessments submitted in support of applications to mine sand at Pakiri-Mangawhai contend that the Pakiri-Mangawhai beach system is accreting (BCHF, 1992) and that sand extracted from the shallow nearshore is ‘replenished’ by onshore transport of inner shelf sands (e.g. O'BRIEN and ASSOCIATES, 1992, p.29). KIRK (1993, p.3) states ‘the Pakiri-Mangawhai coast is still deriving a substantial sand supply by internal reworking of the very large area of sands exposed to waves and currents on the continental shelf’. In part this view is based on the propositions that (1) the Pakiri-Mangawhai coast is accreting; (2) calculated sediment budgets can only be balanced by an onshore annual rate of sediment transport of 164,000 m$^3$/yr (O'BRIEN and ASSOCIATES, 1992, p.30), and (3) the presence on the beach of certain macrofauna indicates onshore transport from the inner shelf.

The first point was discussed above—there is no long term trend of accretion along the Pakiri coast. In the second case, O'BRIEN and ASSOCIATES (1992) calculated a 'nearshore zone sediment budget' for the Pakiri-Mangawhai coast estimating annual sediment inputs of fluvial sources at 1500 m$^3$, nett littoral drift of 3500 m$^3$, cliff erosion at 5700 m$^3$ and biogenic production of 460 m$^3$. Annual sediment outputs were estimated for dune deflation (27,000 m$^3$), sand mining (92,000 m$^3$), Mangawhai estuary infilling (40,000 m$^3$) and nett littoral drift out of the system (5,000 m$^3$). Therefore, outputs (164,000 +/− 60,000 m$^3$/yr) far exceeded inputs (7660 m$^3$/yr) by some 100,000 to 220,000 m$^3$/yr. They assumed that onshore sediment transport from the inner shelf was required to balance the sediment budget. Elements of the budget are at best crude estimates, and the results are at best indicative. Nevertheless, O'BRIEN and ASSOCIATES (1992, p.29) conclude “… replenishment of sand losses in the nearshore zone is from the inner shelf. Diabathic sediment exchange occurs probably out to the lower shelf (undefined), but more frequently in shallower depths out to about 10–12 m, the inferred closure depth, or Hallermeier inner limit.”

Data presented in the present paper indicates the extreme seaward limit, equal to Hallermeier's outer limit, of the Pakiri-Mangawhai nearshore accords with the 25 m isobath. Although difficult to determine it appears that O'BRIEN and ASSOCIATES (1992) ignore the potential for sands to come from the mid to lower nearshore, feasibly from maximum water depths of 25 m, and instead require sands to come from the inner shelf. Further, the sediment budget of O'BRIEN and ASSOCIATES (1992) assumes that the Pakiri-Mangawhai coast is neither accreting or eroding. While this may be the case over longterm time scales of 100 to 1000 years (although as explained above we do not believe this to be so), the sediment budget cannot reasonably be calculated over shorter time scales (annual in this case) without allowing for the effects of medium-term (months to years) variation in rates and/or directions of diabathic sedimentation. The post-1978 storm nearshore profiles show that large volumes of sand were eroded from subaerial beach environments and deposited across the nearshore to water depths of at least 12 m to create an exceptionally large and deep nearshore bar (see Figure 4). The 164,000 m$^3$/yr (+/− 60,000) m$^3$ required to balance the O'BRIEN and ASSOCIATES (1992) nearshore sediment budget might reasonably be supplied from nearshore sands deposited during the 1978 storms and subsequently re-worked onshore and alongshore.

KIRK (1993) cited the results of a study of dredge-spoil re-working in the Bay of Plenty by HEALY et al. (1991) as evidence of probable sediment exchange between the Pakiri-
Mangawhai nearshore and inner shelf. However, the spoil dump is located in water depths of between 10 and 22 m water depth. Hume and Hicks (1993) calculated Hallermeier closure depths of $d_1 = 6.6$ m and $d_2 = 25.1$ m for the nearby Katikati coast, indicating that the spoil dump is actually located within the nearshore sand system, not the inner shelf. Sediment dispersal from a large, cone-shaped mound of unconsolidated sediments in these water depths on an exposed coast is entirely predictable and cannot in any way be regarded as ‘evidence’ for outer nearshore-inner shelf sediment exchange. Analysis of dredged spoil movement in water depths of 20–27 m off Tauranga, New Zealand, indicated minimal movement at these depths (Foster et al., 1991).

Kirk (1993, p.7) further argues that the reported presence of three species of mollusc (Struthiolaria papulosa, Unboniuni zelandicum and Pecten novazelandiae) in beach sediments deposited during conditions of strong offshore winds and large swell waves points to a ‘shoreface to inner shelf’ origin for the associated beach sediments. In fact, an extensive survey of the benthic macrofauna offshore of Pakiri Beach by Hilton (1990) has shown U. zelandicum to be abundant in water depths of less than 15 m (up to $10^4$–$10^5$/m$^2$) and S. papulosa and P. novazelandiae to be rare to absent across the nearshore and inner shelf (0–10/m$^2$). Their presence in subaerial beach sediments does not necessarily imply shoreward transport of nearshore-inner shelf sediments.

The presence of megaripples on the Pakiri inner shelf, relatively low mud concentrations in inner shelf sediments, and calculated thresholds of motion, indicate that sediment disturbance of the inner shelf to water depths of at least 40 m may occur during infrequent severe storm events. Further, there is sedimentological evidence, in the texturally-graded surface of the inner shelf, consistent with the preferential onshore transport of the relatively fine size fraction of the bed between water depths of 25 and 40 m. Whether this gradation developed during the last Post-Glacial marine transgression, or represents an equilibrium condition developed since stillstand (locally ca. 6,500 yr BP) is undetermined. It certainly does not necessarily mean that transport continues today or at a rate sufficient to replace sand mined from the shallow nearshore.

On the contrary, there is convergent data, reviewed in the present paper, that the maximum limit of the modern beach system, and hence the nearshore, approximates the 25 m isobath. These results compare well with those of Van Alphen et al. (1990) for the Dutch North Sea coast and Nielsen and Lord (1992a, 1993) for the Sydney, Australian coast. Nielsen and Lord (1992b, 1993) calculated potential onshore sand transport rates across the high energy Sydney nearshore and inner shelf using formulae developed by Van Rijn (1990) and modifications by Nielsen (1991) and Nielsen and Lord (1993). Their results, which incidentally over-estimate onshore sand transport rates, indicate that shoreward transport under wave action is negligible beyond 30 m water depth.

**PAKIRI—EROSIONAL, STABLE OR PROGRADATIONAL?**

Permits to mine sand in New Zealand are granted under the Resource Management Act (1991), which has as its guiding principle the ‘sustainable management of natural and physical resources’. Mining is more likely to be consistent with this principle, and adverse environmental (and other) effects avoided or minimised, in situations where (1) fresh sand is introduced to coastal sand systems by rivers or natural coastal erosion, some of which might be mined without significantly affecting the nature or direction of coastal development or the ecological characteristics of the environments affected; or (2) sediments are palimpsest or relict and the volumes extracted are insignificant in comparison to the dimensions of the deposit (Hilton, in press, b).

According to these criteria the elucidation of sustainability can only follow (1) the accurate demarcation of the physical sediment system from which sand is to be mined, (2) determining whether the system is closed to further inputs of sediment, and (3) quantifying the volume of sand contained in the system. Recent interpretations have concluded that the Pakiri-Mangawhai sand system is open to inputs of fresh sediment from the inner shelf and the coast is accreting as a consequence of net onshore sediment transport (BCHF, 1992; O’Brien and Associates, 1992; Kirk, 1993). This view is interpreted schematically in Figure 16a. The subaerial beach experiences severe erosion during storms that may occur, on average, every 20 years or so, and comparatively minor erosion at lesser intervals. Subsequent recovery and net accretion occurs since more sand is being supplied to the system than is being removed by mining.

We present two alternative development scenarios for the Pakiri-Mangawhai coast. In the first the Pakiri-Mangawhai sand system is stable, and the mean high water position fluctuates about a mean position (Figure 16b). The subaerial and subaqueous beach experiences erosion in response to storms, during which backshore and intertidal sands are eroded and deposited across the nearshore, but most commonly landward of the 10 m isobath. These sands are subsequently transported landward and onshore in response to swell wave conditions. The beach-nearshore sand system may be either open or closed. In the former case the sand mined from the nearshore is balanced by a compensatory onshore transport from the inner shelf. In the second, no significant sediment transport occurs seaward of the 25 m isobath (outer nearshore boundary), and mined sand is replaced by internal reworking of nearshore sediments; the volume of sand mined is still small compared to the volume of sediment in the system.

In the second case the coastal sand system is closed and the subaerial beach exhibits nett erosion (Figure 16c). Sand eroded from the upper beach and backshore during severe storms is deposited across the mid to upper nearshore and a proportion is intercepted by mining as sediments are returned onshore. Post-storm backshore accretion is limited by sand mining and successive storms result in a net landward translation of the beach profiles. Note that either of the former two scenarios (a and b) may change to scenario c were the volume of sand mined to exceed the rate of onshore sediment transport (in the open system case), or the quantities mined become significant in relation to the dimensions of the resource (in the closed system case).

The historic beach profile data does record minor backshore accretion since the 1978 storms. However, in our view the
significance of this accretion has been overemphasized. The amount of accretion that has occurred since 1978 is actually very small, and the seaward translation of the mean high water mark insignificant relative to similar Southeast Australian beaches (e.g., Moruya, Dark Point). Further, there is convergent data that the Pakiri-Mangawhai nearshore extends seaward to about the 25 m isobath, and that sediment transport onshore from the inner shelf (beyond this depth) is most improbable. The coastal sand system is most likely closed, therefore the sand resource is finite. The Pakiri-Mangawhai coast shows no strong accretionary trend and is at best stable—possibly erosional. While it is not possible to prove a cause-effect relationship between coastal sand mining and backshore stability at Pakiri-Mangawhai it is reasonable to hypothesize that the weak recovery of the Pakiri-Mangawhai coast following the 1978 storms may be a consequence of sand mining.

Kirk (1988, p.10) contends that "in the event that extrac-
tion is overtaxing the sediment budget of a given beach, nett erosion of the shore will quickly manifest itself” and had the Pakiri-Mangawhai coast “not coped, repeated surveys would have shown clear evidence of changes in envelope position, particularly net landward shifts”. This view is appealing, but does not recognise the episodic nature of beach development in the study area. Severe storm events are infrequent, occurring approximately every 10–20 years during the last 90 years, and the potential for significant landward translation of the beach profiles may only occur during such events. At other times sand is being circulated within beach and shallow nearshore environments in response to episodes of constructional swell and erosional storm wave conditions. Extraction of a proportion of this sediment may limit post-storm backshore accretion, and the impact of mining will be expressed as limited backshore recovery and exacerbated backshore erosion during the next major storm event. Secondly, significant elevation changes may be occurring across the lower to mid nearshore as a result of mining which may modify wave transformations only during infrequent severe storms. Therefore, the impact of nearshore coastal sand mining at Pakiri-Mangawhai need not be rapidly manifest.

Kirik (1988) argues that erosional responses are typical of their dissipative surfzone-bar region (i.e., the ‘dissipation’ zone) with sand from the outer nearshore. The outer nearshore would gradually erode and deepen in acting to maintain maximum surfzone dissipation and in the absence of a more seaward (inner shelf) sediment source.

**DISCUSSION AND CONCLUSIONS**

As indicated in the first section of this paper, at Pakiri and elsewhere the seaward limit of the beach-nearshore sand system may be indicated by variations in bed sedimentology and stratigraphy, bed elevation, nearshore bathymetry, benthic fauna and bedforms, offshore sediment transport during rip cell circulation; as well as by theoretical calculations of the maximum limit of bed disturbance by shoaling waves. With the exception of rip cell currents, for which there are no local observations, these characteristics have been investigated in the present paper to define the dimensions of the Pakiri-Mangawhai beach-nearshore sand system. The results of multi-fariable investigations reported in the present paper (and including Pakiri) are notably consistent—the offshore limit of the beach-nearshore system occurs in maximum water depths of around 25 m below mean sea level. It is within this 0–25 m system that sediment transfer takes place. It is therefore not surprising that virtually all international agencies (except New Zealand) only approve sand extraction seawards of the 18 to 25 m isobath (Nielsen et al., 1991).

Figures 5 and 8 demonstrate that in water depths shallower than –15 m, and particularly –12 m, significant bed level variation is possible, the sediment being required by wave processes to maximise dissipation during storms. In the light of this overwhelming international evidence it is incredible that the relevant consent-granting authorities have granted permits to mine sand within 8 metres water depths at Pakiri.

Recent studies have concluded that the Pakiri-Mangawhai sand system is open to inputs of fresh sediment from the inner shelf and the coast is accreting as a consequence of nett onshore sediment transport. In fact, the Pakiri-Mangawhai coast shows no strong accretionary trend and is at best stable and possibly erosional. The beach profile data does indicate some incipient foredune accretion following the 1978 storms. Such accretion represents predictable post-storm recovery and should not be interpreted as evidence of longterm coastal accretion in the presence of mining. Given the episodic nature of coastal erosion in the study area and comparison with other Australian sites, the time series of observations is too short to justify such a conclusion, and the record more likely represents a stable or eroding coast.

Sediment exchange between inner shelf and nearshore environments in the Pakiri region (across the 25 m isobath) is unlikely, and almost certainly insignificant over time scales of tens to hundreds of years. The existing sediment budgets are based on the assumptions that the Pakiri-Mangawhai coast is accreting, that there is a sediment ‘surplus’, and that the only likely provenance is the sediments of the inner shelf. In fact, sands deposited to water depths of 12 m and greater during the 1978 storms and subsequently worked shorewards are a far more likely source of sand to sustain the sand mining operations.

The (Holocene) record as represented by the Pakiri-Mangawhai barriers indicates long-term stability at best and quite possibly long-term erosion or recession at worst.

The impact of mining at Pakiri need not be manifest early. The Australian Muruya and Dark Point beaches took between 8 and 16 years to recover from the severe 1974/78 storms. In the Pakiri-Mangawhai case mining removes some of the sand that would otherwise be transported landwards and redeposited in the backshore environment. Were recovery to be limited due to the removal of sand from the beach-nearshore system (in the absence of new sediment inputs), the impact of mining may most likely be expressed as partial recovery and exacerbated backshore erosion during the next severe storm event.

Compared with similar beaches of Southeast Australia the Pakiri-Mangawhai coast exhibits weak and inconsistent post-storm recovery. While it is not possible to prove a cause-effect relationship between coastal sand mining and beach-nearshore processes at Pakiri-Mangawhai and may never be, it is reasonable to hypothesize that the weak recovery of the Pakiri-Mangawhai coast following the 1978 storms may be a consequence of sand mining. Given (1) the beach-nearshore sand system is closed to significant inputs of sediment, and hence the beach-nearshore sands represent a finite resource, (2) mining occurs from within the most active area of this system, and (3) the volumes of sand in the system need not be large, the present mining operations appear inconsistent with the provisions of the Resource Management Act (1991),
specifically the imperative to avoid adverse impacts, and for mining in this environment to be sustainable.

Finally, the review of methods and data to determine the seaward limits of the beach nearshore system presented here provides a broad range of factors which should be assessed and addressed in any future environmental impact assessment of marine sand mining.

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**LITERATURE CITED**


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