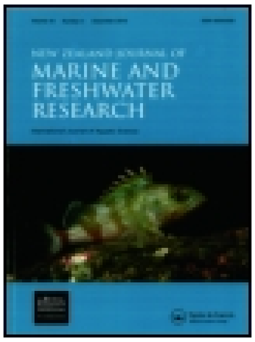

New Zealand Journal of Marine and Freshwater Research

ISSN: 0028-8330 (Print) 1175-8805 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzm20

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To cite this article: Terry M. Hume , John W. Oldman & Kerry P. Black (2000) Sediment facies and pathways of sand transport about a large deep water headland, Cape Rodney, New Zealand, New Zealand Journal of Marine and Freshwater Research, 34:4, 695-717, DOI: 10.1080/00288330.2000.9516971

To link to this article: http://dx.doi.org/10.1080/00288330.2000.9516971

Published online: 29 Mar 2010.

New Zealand Journal of Marine and Freshwater Research, 2000, Vol. 34: 695–717

0028–8330/00/3404–0695 $7.00

Sediment facies and pathways of sand transport about a large deep water headland, Cape Rodney, New Zealand

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Abstract Cape Rodney is a large headland that protrudes 3–4 km into deep water in the Hauraki Gulf and separates the Mangawhai-Pakiri and Omaha littoral cells. Detailed swath mapping of seabed sediments around Cape Rodney was carried out using by side-scan sonar and ground-truthed by SCUBA, grab sampling, and video. Despite the barrier imposed by the headland two pathways of sand transport around the headland, separated by the topographic high of Leigh Reef, have been identified. One lies close to the headland, where sand from the beach and nearshore of the Mangawhai-Pakiri embayment is driven by waves and currents along a 500-m-wide pathway in c. 20–25 m depth around the headland to the vicinity of Leigh Harbour. The other lies in 50 m water-depth seawards of Leigh Reef. Here fine sand, sourced from the nearshore of the Mangawhai-Pakiri embayment and driven offshore from the tip of the headland, is transported back and forth by tidal currents in 50 m water depth on the floor of the Jellicoe Channel. The sand bodies along both these pathways are thin and so sand leakage from the Mangawhai-Pakiri embayment is thought to be small. Transport at these depths is dependent on both tide and wave generated currents and episodic occurring during storm events. The sediment facies associated with little sand transport about a headland in deep water is one of thin and discontinuous and patchy sand cover between rocky areas and over coarser megarippled substrate. Ocean swell, tidally driven phase eddies that spin up on both sides of the headland, and bathymetry all play a role in shaping those facies.

Keywords surficial sediments; sediment transport; sand by-passing; tidal currents; waves; littoral cell; headland; coastal processes; New Zealand

M99005
Received 27 January 1999; accepted 27 April 2000

INTRODUCTION

Headlands present topographic barriers to water flow and sand transport along the shore and by these processes they compartmentalise the coast. There are many studies that refer to the role that headlands play in dividing the coast into littoral cells, which are the relatively self-contained units within which sediment circulates. Continuous beach segments between the large headlands on the Oregon and Washington coasts have been used by some researchers to define the limits of large littoral cells (Terich & Swartz 1981; Galster 1987). Although, as Petersen et al. (1991) point out, establishing cell boundaries solely on the basis of beach-segment terminations is not strictly correct, as beach sediments may bypass or "leak" about headlands during extreme storm events. They suggest cell boundaries are best identified using a combination of criteria including abrupt changes in the longshore trends of beach width and sediment grain sizes on either side of the headland, which are indicative of restricted zones of supply and mixing. However, even identifying cell boundaries on the basis of beach sand mineralogy can be misleading as the sands may contain the signature of past events. For instance, most of the Oregon coast consists of a series of pocket-beach littoral cells, where major headlands isolate stretches of beach (Komar 1996). Studies of heavy minerals (Clemens & Komar 1988) have shown that the north to south variation in the distribution of beach sands is in part relict and inherited from lower stands of sea level when longshore transport was uninterrupted by headlands. When the sea level rose, sand was combed shoreward to form the pocket beaches between headlands we see today. Today the headlands prevent the longshore transport and mixing of sands from rivers and cliff inputs along the shore. Mapping littoral cells on the basis of a variety of geomorphological and oceanographic data on the central southern England coast (Bray et al. 1995) also identified the "leaky" nature of headland boundaries to littoral cells. On this shore small headlands form "fixed partial" barriers at the boundaries of littoral cells allowing sediment to pass in both directions, although most only permit transport in one predominant direction. A particular characteristic is the storm-driven and intermittent nature of the bypassing. Large headlands form "fixed absolute" boundaries and are much less easily bypassed, except perhaps during exceptional storms which are highly intermittent. Studies on the Californian coast (e.g., Inman & Frautschy 1966; Dolan et al. 1987; Best & Griggs 1991; Osborne & Yeh 1991) consider that a typical littoral cell begins at a rocky headland where the updrift supply of sand or littoral drift is restricted or minimal. Sediments enter the cell primarily from streams and bluff erosion and are driven alongshore by waves. During transport along the shore sand may bypass small headlands from beach to beach. Ultimately sand is lost from the cell via a submarine canyon, from wind blow into a coastal dune field or by direct removal through sand mining. To successfully establish sand budgets for littoral cells requires a quantitative understanding of the processes in the cells. On the Californian coast the problems with balancing sediment budgets (e.g., Griggs 1987) lie in there being a large gap in our present state of knowledge of process both within the cells and at the littoral cell boundaries which are usually headlands (Best & Griggs 1991).

In most studies littoral cell boundaries are generally fixed at headlands, particularly if the beach sand characteristics differ on either side of the headland. Few studies apply the systems approach recommended by Bray et al. (1995) and also examine the characteristics of the seabed offshore from the headland for evidence of sand bypassing. For this reason we have little knowledge of how the sedimentary signatures differ between headlands where bypassing is taking place versus those where there is only intermittent and infrequent transport during large events, or those where there is no bypassing at all. When large headlands that protrude well offshore and into deep water it is often assumed that there is no bypassing. However, even if there is no bypassing there may still be sediment loss from the littoral cell, as sediment may make its way along the headland shore and into deep water. By this mechanism sand may be effectively lost from the littoral cell in a similar manner to which sand is lost to the submarine canyons on the Californian coast. On embayed coasts with small sediment inputs this loss could be important in terms of the overall sediment budget of an embayment.

In this study we use information from detailed swath mapping of surficial sediment facies to provide the first description of the complex sediment signature off a large headland in deep water where there is only intermittent sediment transport. The sediment facies data along with current and wave data are interpreted to identify pathways along which sand might leak from an embayment bounded by a large headland and the fate of that sand, and therefore the effectiveness of the large headland as a littoral cell boundary. The findings contribute to knowledge on processes at headlands, which are commonly set as boundaries to littoral cells.

STUDY SITE

There is an abundance of headlands in the Hauraki Gulf on the north-east (NE) coast of New Zealand (Fig. 1). Despite the likelihood that they play an important role in regulating water flows and sediment transport there is little information in respect of these features. Cape Rodney (36°17S′, 174°49′E) is a large and strategically situated headland at the entrance to the Gulf. It protrudes into strong tidal flows of the Jellicoe Channel and produces secondary circulations and eddies (Hume et al. 1997c) and upwelling of cool oceanic water from the bottom of the Jellicoe Channel (Black et al. 2000). Cape Rodney also lies at the southern end of several large beach sand systems comprising the Hauraki B Sand Facies (Schofield 1970). It separates the sand beaches of the 30-km-long Mangawhai-Pakiri littoral cell to the north (Hilton 1990, 1995), from sandy pocket beach and estuarine systems in Omaha Bay to the south (Riley et al. 1985). Rivers and cliffline erosion supply little sediment to Mangawhai-Pakiri embayment (Schofield 1975; Lees 1981), and supplies from offshore are thought to be limited (Hilton 1990). The sand in these systems is considered to have derived largely from the continental shelf. Following the post-glacial marine transgression sea level continued to rise until c. 6500 years ago when it stabilised at its present level (Gibb 1986). During this time sand was "combed-up" by wave action from the former coastal plain to build barriers across bays such as the Mangatawhiri Spit in Omaha Bay, and to infill the shoreline of the Mangawhai-Pakiri embayment with dunes (Schofield 1965).

Bypassing at the headland has particular relevance to the question of shoreline stability and sand resources in the Mangawhai-Pakiri embayment, particularly as sand is being extracted from the nearshore of the embayment for building aggregate. Today, extraction totals c. 100 000 m^3 per annum and perhaps as much as 2.3 million m^3 was extracted from the sand system between 1966 and 1997 (Hilton et al. 1989; Tonkin & Taylor 1992). Thus the question of sand bypassing around Cape Rodney is relevant in terms whether sand is being fed into, or lost from, the embayment.

Cape Rodney protrudes some 4 km offshore into 50 m water depth and the Jellicoe Channel. Acoustic Doppler Current Profiler measurements reveal strong tidal currents around Cape Rodney of up 0.6 m/s on spring tides, and a conspicuous pair of phase eddies generated in the waters flanking the headland on the flood and ebb tides (Hume et al. 1997a; Vennell et al. unpubl. data). Pacific Ocean swells arrive at the headland from the north to east sector. Wave records (unpubl. data) from a NIWA buoy 20 km up the coast show that, over the 2 years 1995–96, average significant wave height (H_s) and period (T_s) were 0.73 m and 6.7 s respectively. Small storms, with waves arriving from the NE (straight on to the headland), T_s = 9 s (the peak spectral period), and H_s = 3 m, occur c. 6 times per year. During larger storms of annual frequency, waves have H_s of up to 4 m and T_s = 12 s.

Hilton (1990, 1995) described the sediments about Cape Rodney as part of a study of the Pakiri embayment sand body. His observations were limited to diver observations and c. 20 samples off the southern end of Pakiri Beach. A picture of variable substrate of mixed sand, mud, gravel, and shell-hash emerged. On this evidence he inferred that the Pakiri sand system was essentially "closed" to the south. This picture is consistent with observations in Omaha Bay to the south, where Riley et al. (1985) described how the sands of the shoreface give way to coarser sand and gravels off Ti Point which lies on the southern flank of Cape Rodney.

Hume et al. (1997a) presented a preliminary description of the distribution of sediments about the Cape Rodney headland based on swath-mapping by side-scan sonar and limited ground-truthing. The role that currents and waves play in shaping the distribution of seabed sediment facies was considered, but pathways of transport and bypassing were not identified.

METHODS

Digital terrain model

A Digital Terrain Model (DTM) of the seabed surrounding the Cape Rodney headland (Fig. 1) was constructed using data digitised from the 1962–64 RNZN surveys (RNZN 1963, 1964a,b) (Fig. 2). The DTM was fitted to the data using a Kriging procedure in the SURFER software package (Golden Software 1997) used to produce the DTM. The DTM is less reliable very close to shore (<4 m depth) and in >50-m water depth where the soundings are sparse.

Side-scan sonar

When seabed sediments off headlands are "patchy", a good picture of sediment type and bedforms cannot be adequately resolved from grab sampling and spot dives at a few locations. Broad scale "swath" mapping by techniques such as side-scan sonar are necessary to adequately document the sedimentary facies and the "continuity" in pathways of sand transport. A further complicating factor is that the substrate may change and facies boundaries may shift as waves and current conditions alter. Repeat surveys are necessary to document these substrate changes and can provide valuable evidence of sand transport and bypassing over time-scales of decades (e.g., Carter & Lewis 1995; Hume et al. 1995).

Broad-scale mapping of seabed sediment facies using side-scan sonar was undertaken about the headland (Fig. 1). Surveys were carried out from an 8 m vessel over the period 5–10 October 1996. A Klein 590 side-scan sonar, operating at 500 kHz frequency, was towed at c. 6 knots along a pre-determined grid, with parallel vessel tracks 200 m apart. The seabed was scanned 100 m either side of the vessel to give c. 80–100% coverage depending on depth, but with no overlap. Tracks were generally shore-parallel to enhance the sonic reflections from wave-generated bedforms. Additional tows were made normal to the shore to check for sand features with different alignment. An ECHOTRAC sounding system with heave compensation measured depths along the side-scan tracks. Positions were logged about every 10 m along the vessel track using DGPS and are accurate to c. ± 2 m.

HYDRO software (Trimble Navigation Ltd 1995) was used to lay out the survey tracks, guide the vessel along the tracks, log the soundings and positions, and then edit the position and depth files. In this manner, some 250 km of track was covered and c. 50 km^2 of seabed mapped.

The side-scan sonographs were used to characterise seabed substrate as bedrock, rock and rubble reef, gravel, sand, or mud. In addition, the sonar data provided information on bedform type and orientation, the morphology of sand bodies along with the thickness of these sand bodies, and anthropogenic features such as trails cut by scallop dredges.

Ground-truthing

The side-scan sonar was ground-truthed by: (1) observations, sampling, and photography by SCUBA diver; (2) seabed sampling using a Smith-McIntyre grab; and (3) sediment and bedform observations by video camera (Fig. 3). The camera was mounted on a frame and the images cabled to a monitor in the vessel. Observations were made while drifting over 50–100-m-long stretches of seabed. The frame was also "landed" on the seabed to enable detailed measurements of bedform dimensions and orientation (using the compass and scales mounted on the frame in view of the video) and to test seabed compaction. About 12 sites were ground-truthed at the time of the side-scan sonar surveys. The remaining 60 or so sites were ground-truthed in May and June 1997, once the facies had been mapped from the side-scan. In this manner we were able to target and verify specific sonar signatures. Samples were also taken from two sites at the southern end of Pakiri Beach, from the face of the foredune and from the high-, mid-, and low-tide levels on the beach. In this manner information was collected at some 80 sites, some of them outside the area of the side-scan (Fig. 3).

The sediment samples recovered by diver and grab were washed through sieves and the gravel, sand, and mud percentages determined by drying and weighing. A rapid sediment analyser (RSA) was used to determine fall velocity and particle size of material greater than mud size. The gravel fractions of the very coarse samples were sieved. All data were recombined to compute textural parameters.

Numerical models

Numerical models were used to simulate the wave and current regimes around the headland. Wave modelling was undertaken using WBEND (Black & Rosenberg 1992). WBEND is a 2-dimensional numerical wave refraction model for monochromatic waves or a wave spectrum over variable topography. The model applies a fast, iterative, finite-difference solution of the wave equations to solve for wave height, wave period, breakpoint location, and longshore sediment transport. The model grid had dimensions 20 × 25 km, the outer boundary was orientated subparallel to the depth contours in c. 60 m water depth (Fig. 1), and grid cell dimensions were 100 × 100 m. A series of monochromatic tests were undertaken to calibrate for bed roughness, using data from instruments 30 km NE, namely: (1) the NIWA ENDECO Wave track buoy sited in 35 m water depth; and (2) current meters in 15 m water depth. The global value of roughness that produced the best calibration ($C_f = 0.10$) was adopted for bed roughness in the headland model. Wave statistics and scenarios modeled with WBEND derive from the 24 months of data from the NIWA wave buoy.

The numerical hydrodynamic and advection/dispersion model 3DD (Black 1995) was used to predict currents throughout the survey area. In this paper we show currents only at selected locations and as relevant to the sand movement and bypassing issue (Fig. 3). Model 3DD has been used for a wide range of applications, from continental shelf circulation to micro-scale flow over bedforms (Black 1997), and so it will not be further described here. The model was setup for the purpose of wider studies (e.g., Black et al. 2000). The bathymetry grid was rectangular and the 400 × 400-m grid size was chosen to resolve important features of flow identified by field measurements. Model boundary conditions were sinusoidal velocities at tidal periods, with peak velocity determined from field measurements. The model was calibrated against a 20-day record of water levels measured at the boundaries during a detailed field experiment in February/March 1997 (Hume et al. 1997b).

ALICE deployment

Direct observations of movement of seabed sands between Leigh Reef and the shore, in 25 m depth, were made using a video and IMAGENEX sonar mounted on the boundary-layer tripod ALICE (Green 1996) during a detailed field experiment in February/March 1997 (Hume et al. 1997b). The IMAGENEX sonar provided a circular scan of the seabed in a 15 m radius about the tripod every 90 min, from which bedform morphology, dimensions, and orientation could be measured. ALICE was deployed for 6 weeks. Sensors on ALICE measure tides, currents, waves, bedform dimensions, and suspended sediment, and sediment is collected by fall traps.

RESULTS

Bathymetry

Topographic and hydrographic charts of the headland show a complicated coastal outline (RNZN 1974, 1979, see Fig. 1), with Goat Island lying off the northern flank, Leigh Reef off the tip, Leigh Harbour indenting the southern flank and the coastal indentation being much greater on the southern (Omaha Bay) flank of the headland than to the north. These features will obviously affect current and wave distribution and sediment movements about the headland and therefore the seabed sediment facies.

Our DTM (Fig. 2) provides bathymetric detail that is not immediately obvious from the hydrographic charts (RNZN 1974, 1979). The general picture is for a steep, largely rocky nearshore area down to c. 15–20 m depth, below which a gently sloping sandy and gravelly seabed falls to 50 m depth, below which the sediments are more muddy and the seabed flat on the floor of the Jellicoe Channel. This general picture shows some variability around the headland as follows.

On the south flank of the headland in Omaha Bay rocky reefs occur close to shore rising to within 8 m of the surface at The Outpost reef, and Leigh Harbour indents the shoreline. A rock pinnacle, Leigh Reef, rises to within 30 m of the surface off the headland tip. On the northern flank numerous rocky reefs and Goat Island outcrop close to shore. Further north and off Pakiri Beach where the seabed is sandy the shoreface flattens.

Sediment texture and sonar signatures

The results of textural analyses of the seabed samples are summarised in Table 1. There are a wide variety of sediment types, ranging from muddy sand, well-sorted fine to medium sand, and through to bimodal coarse sands and gravels containing lithic and shelly gravel-sized material. The samples are categorised into facies described below.

The side-scan sonar mapping shows a wide range of sonar signatures indicating a highly variable sediment cover. Sonographs were categorised into five main acoustical patterns represented in Fig. 4. These patterns are correlated with: (1) bedrock (Fig. 4A); (2) boulders and gravel (Fig. 4A); (3) megarippled coarse sands and pebbly gravels (MRCSG) (Fig. 4B); (4) fine-medium sands (Fig. 4C); and (5) muddy sands (Fig. 4D).

Sediment facies

The side-scan sonar mapping, combined with the ground-truthing by SCUBA, grab sampling, and underwater video, was used to classify the seabed substrate into facies, based on various combinations of substrate composition, texture, bedforms, and sand body characteristics. Nine major facies were identified: (1) continuous sand cover (Fig. 4C); (2) MRCSG (Fig. 4B); (3) sand cover "cratered" with holes (Fig. 4E); (4) sand cover with elongate shore-normal "tears" (Fig. 4F); (5) discrete sand patches (Fig. 4G); (6) sand ribbons (Fig. 4H); (7) discontinuous sand cover (Fig. 4I); (8) continuous muddy sands (Fig. 4D; and (9) rock outcrop and rubble (Fig. 4A). Textural parameters of these are defined in Table 1. The mapping revealed a highly variable distribution of these facies about the Cape Rodney headland (Fig. 5). Detailed descriptions of the features and occurrence of these facies follow.

Facies 1 (Fig. 4C)

Continuous sand cover extends seaward from Pakiri Beach to c. 20–25-m depth. Moderately well-sorted medium sands (mean size, M_n, 1.7–1.4 phi) on the beach, grade to well-sorted to moderately well-sorted fine sand (M_n 2.1–2.4 phi) in c. 15–25 m depth. The sands are frequently covered with small symmetrical wave ripples (wavelength (L) 10–20 cm; height (H) 2–5 cm). Continuous sand cover of moderately well-sorted medium sands (M_n 1.59 phi) also occurs in the tongue of sand that extends seawards of Leigh Harbour entrance (see Fig. 5). These Facies 1 sands represent the shoreface sand blanket.

Facies 2 (Fig. 4B)

Megarippled coarse sand and gravel occurs throughout the area. These sediments are poorly-sorted, coarse to very coarse sands (M_n 0.05–0.5), but typically have a bimodal population of coarse sands and 15–40% lithic and shelly gravel-sized material. Gravel makes up c. 25% of the sediment. This facies is characterised by large symmetrical bedforms, typically of H 10–15 cm and L 100 cm, aligned subparallel to the shore and incoming wave crests. The sediment coarsens to gravel and the bedforms become very large (L 2 m) approaching areas of rock reefs (Fig. 4H). The MRCSG is very coarse in places, suggesting strong currents or sorting by waves.

Facies 3 (Fig. 4E)

Sand cover cratered with holes occurs in c. 25–35 m water depth off the south end of Pakiri Beach and off Leigh Harbour. The sand cover comprises moderately well-sorted fine sand and is only a few decimetres thick at most. The holes are irregular in

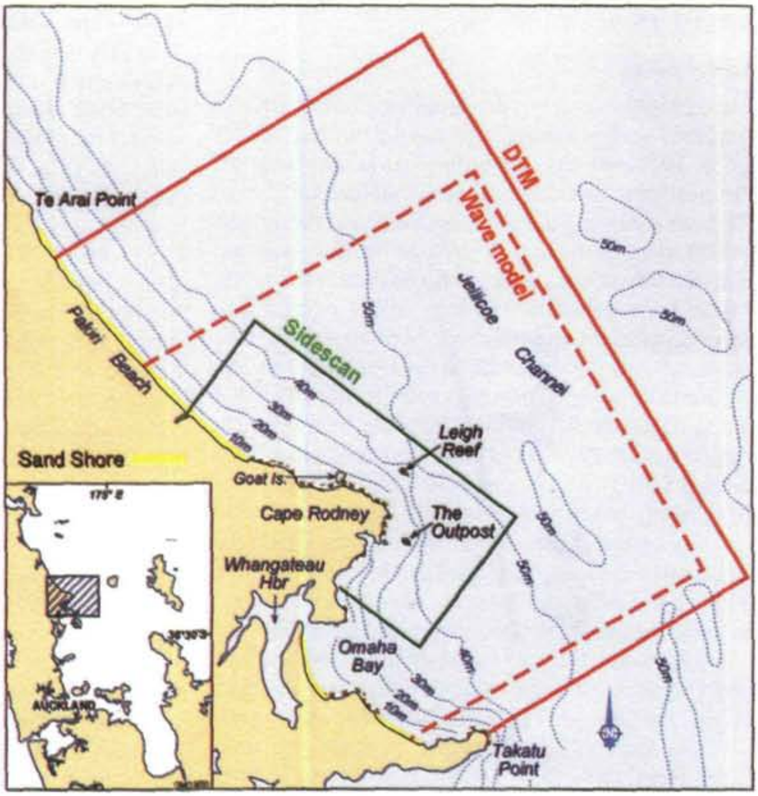


Fig. 1 Location map showing areas covered by the digital terrain model, the side-scan sonar survey and wave model predictions.

shape and give a "leopard spot" appearance on the sonagraph. The holes are floored with MRCSG where the underlying substrate (Facies 2) shows through. Diver observations suggest that the craters are erosional in nature.

Facies 4 (Fig. 4F)

Sand cover with elongate-shore normal tears, through which the underlying MRCSG is exposed, occurs towards the south end of Pakiri Beach in water depth >25 m. The tears in the sand cover appear to lie in the troughs of large sand ridges (H 0.5–1 m, L 300–400 m) orientated normal to the shoreline. The boundary of the sand cover is sharp on the west (up-coast) flank of the ridges and diffuse on the east flank of the tears, which suggests that the shore normal ridges may be migrating eastwards, towards the headland. The sand is primarily a moderately-sorted fine sand.

Facies 5 (Fig. 4G)

Discrete sand bodies of oval or lobate shapes having very well defined boundaries. They occur only off the south end of Pakiri Beach in c. 35-m depth, where they form at the seaward edge of the nearshore sand blanket. The patches are c. 0.5–1.0 m thick and overlie the MRCSG which can be seen at the base of some depressions in the patch. Their sharp boundaries suggest that they were dormant at the time of the survey, stranded on the MRCSG pending the next wave event which will move them on. Their coherent isolated form suggests a self-sheltering mechanism, such that the inner portions are protected from erosion by the surrounding sand.

Facies 6 (Fig. 4H)

Sand ribbons, comprising thin layers of sand overlying MRCSG, occur seaward of Leigh Reef. They are best developed to the east of the headland in the area where the headland toe intersects with the bed of the Jellicoe Channel in c. 50 m depth. Here the sand ribbons are 150 m wide, more than 1500 m in length, and c. 2 decimetres thick. They comprise slightly gravelly and muddy, poorly sorted, fine to medium, sands. The video revealed weakly developed ripples, which were too small to show up on the side-scan (H 5 cm, L 50 cm). At the northern and southern extremities of this facies, the sand

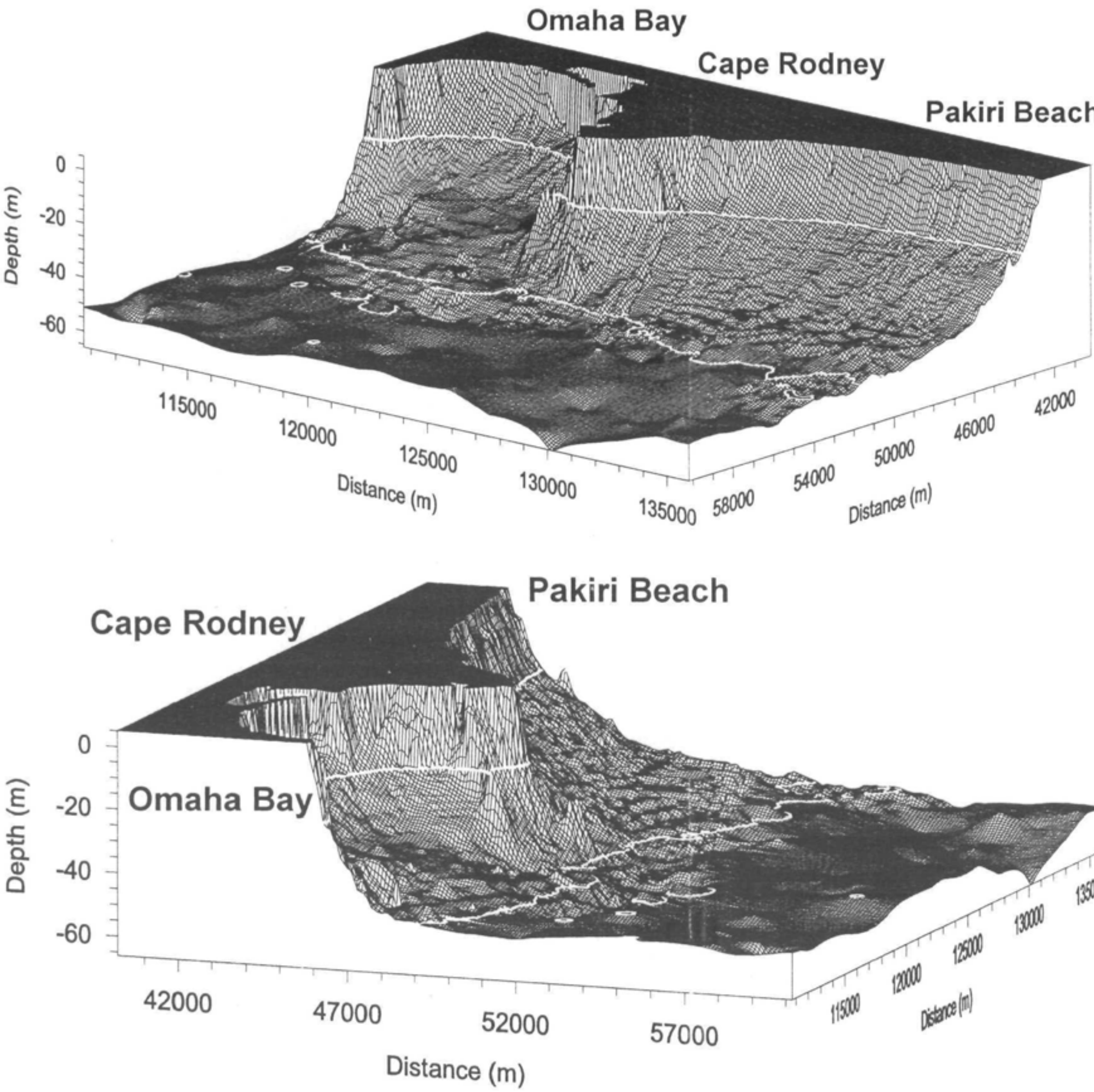


Fig. 2 Digital terrain model of Cape Rodney, New Zealand, showing the seabed shape viewed from two different angles. White contour lines are at –20 and –50 m.

ribbons degrade to features only c. 20 m long, c. 5 m wide, and several decimetres thick. Everywhere, the sand ribbons have diffuse boundaries and give the appearance of being mobile. The sand ribbons align with the main-stream currents in the Jellicoe Channel.

Facies 7 (Fig. 4I)

Discontinuous sand cover occurs in a 500-m-wide pathway off the NE flank of the headland, between Goat Island and the tip of Cape Rodney, and continues south about the tip of the Cape to the Outpost Reef (Fig. 1). It overlies MRCSG. In places it is up to 0.5 m thick whereas elsewhere it is a thin sprinkle of sand partially burying the bedforms on the MRCSG. The sediment is moderately well-sorted, medium sand, of grain sizes similar to those on the southern end of Pakiri Beach (Table 1). Bedforms on the sands are wave generated ripples (H 5–7 cm, L 60–70 cm) that lie subparallel to the shore. The discontinuous sand cover has diffuse boundaries, is unconsolidated, and mobile.

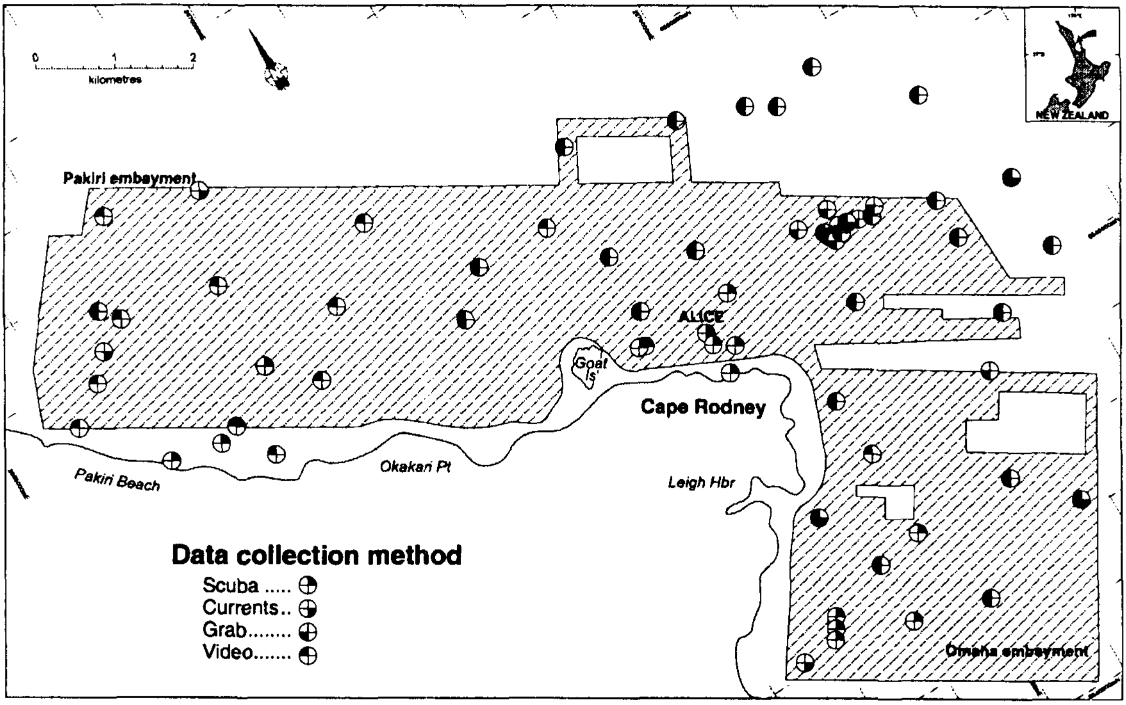


Fig. 3 Area mapped by side-scan sonar, sites where side-scan sonar was ground-truthed by SCUBA, grab samples and video, and locations where currents were predicted using model 3DD.

Facies 8 (Fig. 4D)

Muddy sands occur in depths >40 m off the tip of Cape Rodney and to the south in Omaha Bay. The sediment is mostly moderately sorted, fine sand, containing c. 9% mud on average. Off the tip of the Cape the dominant grain size is coarser and medium sand. The bed in these locations is flat and featureless, soft and unconsolidated, and the environment looks depositional.

Facies 9 (Fig. 4A)

This facies comprises rock and rubble outcrop that extends to c. 15–20 m depth about the shores of the headland, off Goat Island, and on the Leigh and Outpost Reefs. MRCSG lies between the rubble and outcrop in places and flanks it elsewhere.

Interpretation

There are four basic types of substrate: (1) the rock outcrop and rubble; (2) the MRCSG; (3) the beach and nearshore fine-medium sand; and (4) the muddy sand in Jellicoe Channel. Substrates 2, 3, and 4 are draped over Substrate 1, and Substrates 3 and 4 appear to be draped over Substrate 2 (see schematic, Fig. 9). Substrate 2 is exposed to varying degrees, more so as you go offshore and towards the headland. Substrates 3 and 4 are modern, whereas Substrate 2 is probably relict or palimpsest. Facies 1, 7, 3, 4, 5, and maybe 6 in that sequence present a range of exposures of the MRCSG beneath the beach/nearshore sand layer.

Important findings are that: the MRCSG always underlies the fine-medium sands; the megaripples are subparallel to the shoreline and normal to the direction of wave approach; the boundaries between some facies are sharp and others are gradational; and there is an overall symmetry to the distribution of facies about the headland as follows: in the central area off the nose of the headland the rock reefs (transgressed in places by MRCSG) are flanked by MRCSG, these MRCSG areas are flanked on either side by sand cover cratered with holes, to the north the cratered areas give way to more continuous sand cover close to shore, beyond c. 30 m depth sand cover becomes thin and MRCSG shows through the shore normal tears, to the south the cratered areas give way to more continuous fine sands and muddy fine sand beyond c. 35 m depth, sand ribbons only occur about the toe of the headland, and at depths >40 the sands become more muddy.

Table 1 Descriptive parameters for the nine Cape Rodney sediment facies. Based on 250 km of side-scan sonar track and ground-truthing at 80 sites. (Note that for Facies 3, 4, 5, 6, and 7 the description is for the sand rather than underlying megarippled coarse sands and gravels (MRCSG); bedforms not always present on Facies 1, 3, 4, 5, and 7.) (Grain size: G(g), gravel(ly); S(s), sand(y); M(m), mud; vcs, very coarse sand; cs, coarse sand; ms, medium sand; fs, fine sand; vfs, very fine sand. Sorting: vps, very poorly sorted; ps, poorly sorted; ms, moderately sorted; mws, moderately well sorted; ws, well sorted; vws, very well sorted. H = ripple height; L = ripple spacing; NA = not applicable.)

	Facies 1	Facies 2	Facies 3	Facies 4	Facies 5	Facies 6	Facies 7	Facies 8	Facies 9	Pakiri Beach
No. of samples	13	13	6	2	no samples	7	5	14	NA	3
Gravel (%)	1	23	0	0	–	4	0	1	NA	4
Sand (%)	99	76	100	100	–	89	99	91	NA	96
Mud (%)	0	0	0	0	–	8	0	9	NA	0
Mean of mean grain size (ϕ)	2.23	0.1	2.06	2.13	–	2.06	1.57	2.45	NA	1.5
	fs	cs	fs	fs	–	fs	ms		fs	ms
Range of mean grain size (ϕ)	1.5 to 2.87	0.61 to 1.06	1.35–2.64	1.68–2.57	1.71–2.82	0.99–2.01	2.09–3.23	NA	1.41–1.67	
	ms–fs	vcs–ms	ms–fs	ms–fs		ms–fs	ms	fs–vfs		ms
Mean of sorting coefficient	0.68	1.0	0.66	0.92	–	1.4	0.67	0.86	NA	0.83
	mws	ps	ms	ms		ps	mws	ms		ms
Overall textural description (Folk 1968)	moderately well sorted sl. gravelly fine sand	poorly sorted gravelly coarse sand	moderately sorted fine sand	moderately sorted fine sand	sand	poorly sorted sl. gravelly muddy fine sand	moderately well sorted medium sand	moderately well sorted sl. gravelly muddy fine sand	NA	moderately sorted sl. gravelly medium sand
Bedforms	ripples H 2–5 cm L 10–20 cm	megaripples L 10–20 cm H 2–5 cm	ripples H 10–15 cm L 10–20 cm	ripples L 100–200 cm H 5 cm	ripples H 2–5 cm L 50 cm	ripples L 10–20 cm H 5–7 cm	ripples H 2–5 cm L 60–70 cm	none	NA	NA
Sedimentary body type	continuous sand cover	MRCSG	sand cover cratered with holes	sand cover with elongate shore normal tears	discrete sand patches	sand ribbons	discontinuous sand cover	continuous muddy sand	rock outcrop and rubble	beach sand

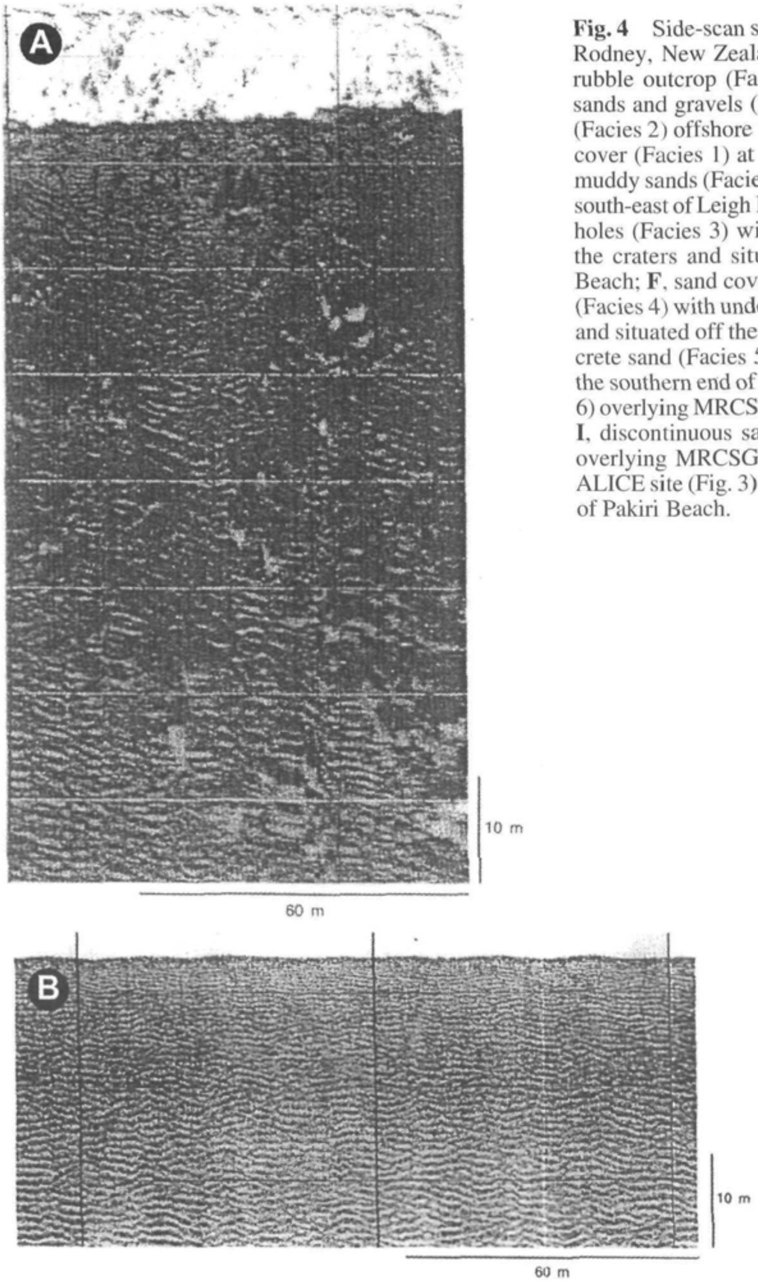
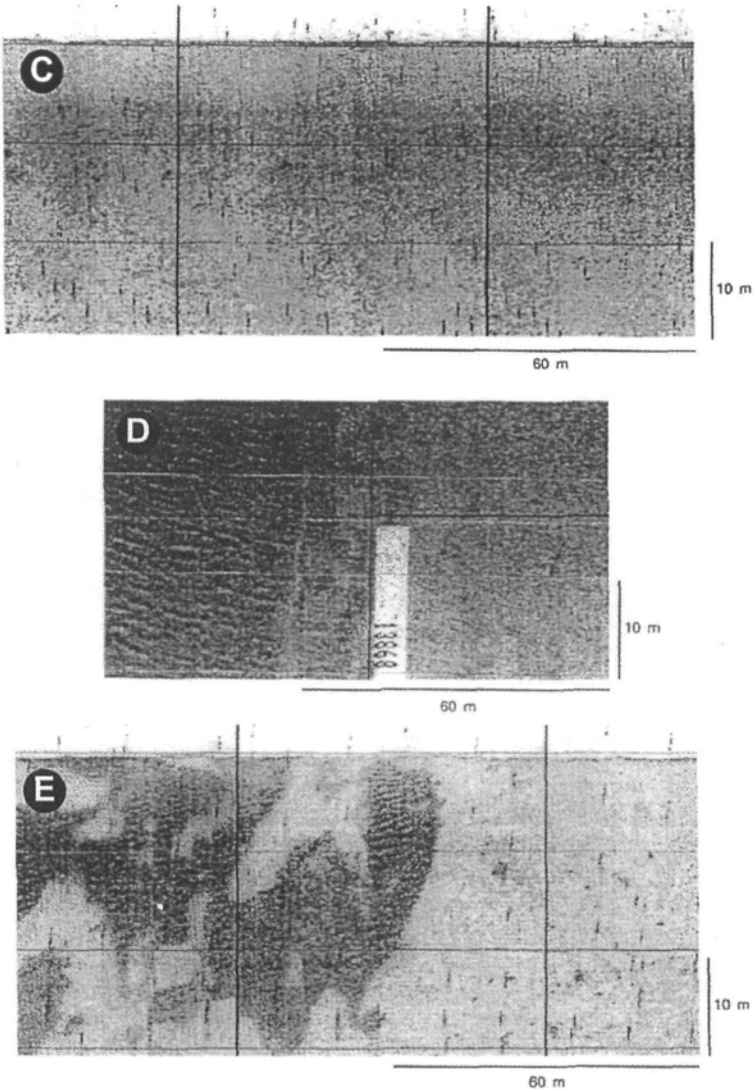


Fig. 4 Side-scan sonar images of the seabed about Cape Rodney, New Zealand. Images show bedrock, rock and rubble outcrop (Facies 9) with: **A**, megarippled coarse sands and gravels (MRCSG) at Leigh Reef; **B**, MRCSG (Facies 2) offshore from Goat Island; **C**, continuous sand cover (Facies 1) at the southern end of Pakiri Beach; **D**, muddy sands (Facies 8) overlying MRCSG situated to the south-east of Leigh Harbour; **E**, sand cover "cratered" with holes (Facies 3) with underling MRCSG in the floor of the craters and situated off the southern end of Pakiri Beach; **F**, sand cover with elongate shore normal "tears" (Facies 4) with underling MRCSG in the floor of the tears and situated off the southern end of Pakiri Beach; **G**, discrete sand (Facies 5) overlying MRCSG and situated off the southern end of Pakiri Beach; **H**, sand ribbons (Facies 6) overlying MRCSG and situated seawards of Leigh Reef; **I**, discontinuous sand cover (Facies 7) with underlying overlying MRCSG showing through and situated at the ALICE site (Fig. 3) off the northern flank of Cape Rodney of Pakiri Beach.

Habitat map of marine reserve

Intertidal and subtidal marine habitats in the Okakari Point to Cape Rodney Marine Reserve are described in Ayling et al. (1981). These maps detail the largely rocky habitat adjacent to the shore and seaward to c. 10–20 m depth. More than 50% of the Reserve lies in water deeper than this. Our detailed mapping of the muddy, sandy, and gravelly substrate provides the first habitat map for this deeper part of the Reserve. Interestingly, this diverse and patchy substrate provides important biological habitat that is just as complex as the better-known rocky substrate habitat adjacent to the shore.



Predicted waves

WBEND was run for small and large waves arriving from the north-north-east (NNE) direction. Scenarios included: (1) average waves of H_s >0.7 m and Ts 7 s, and (2) large storms of less than annual frequency with H_s >6 m and T_s 12 s, such as occurred during Tropical Cyclone Gavin in 1997. The results are illustrated in Fig. 6.

The model illustrates how, when short period waves approach the headland, there is little refraction and shoaling, because of the deep water immediately offshore. As a consequence the southern flank of the headland is sheltered to a large extent from ocean swell. Longer period waves "feel the bottom" in deeper water, refract and shoal as they approach the headland and wrap about the headland and can disturb the seabed off Leigh Harbour. This is consistent with ripple directions on the seabed, which are aligned N–S off Leigh Harbour.

Predicted currents

The model 3DD, which was calibrated for the period 10–30 February 1997, was used to predict depth averaged currents throughout the study area. Predictions of currents at five locations (Sites A–D,

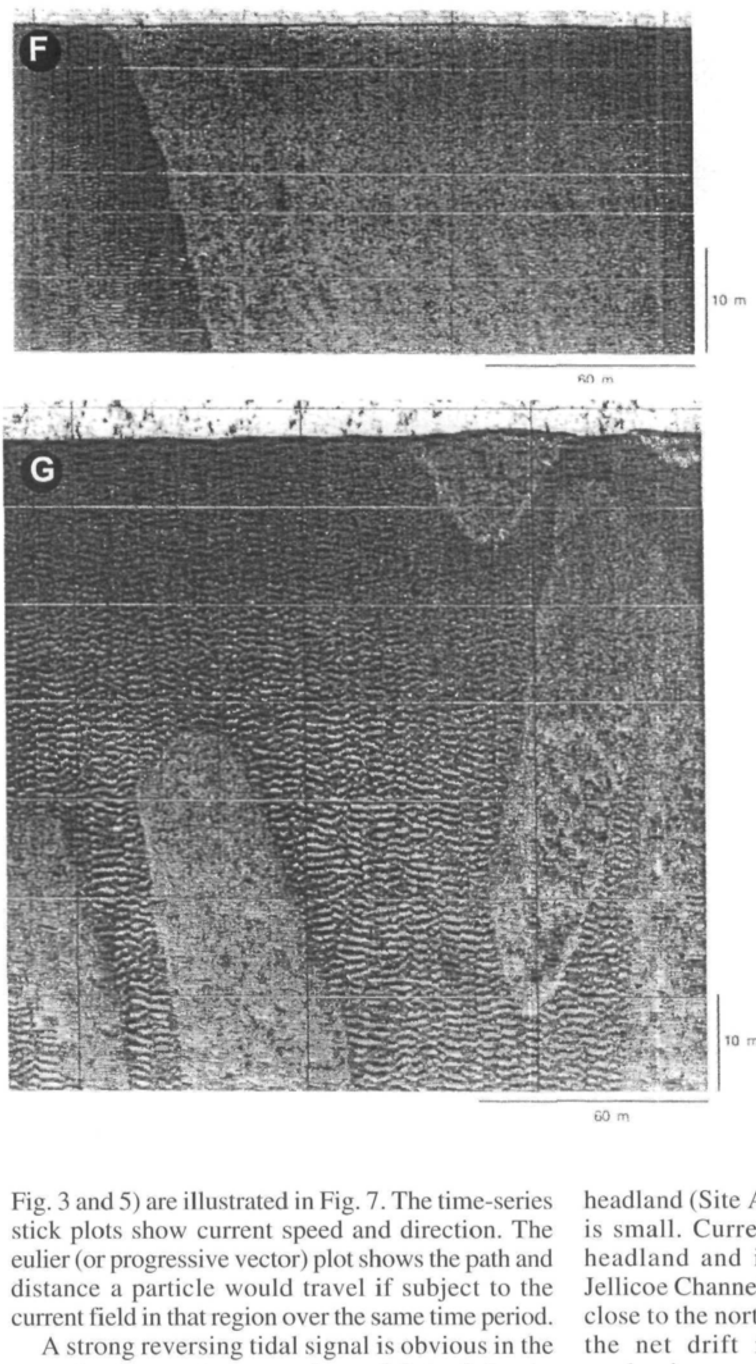
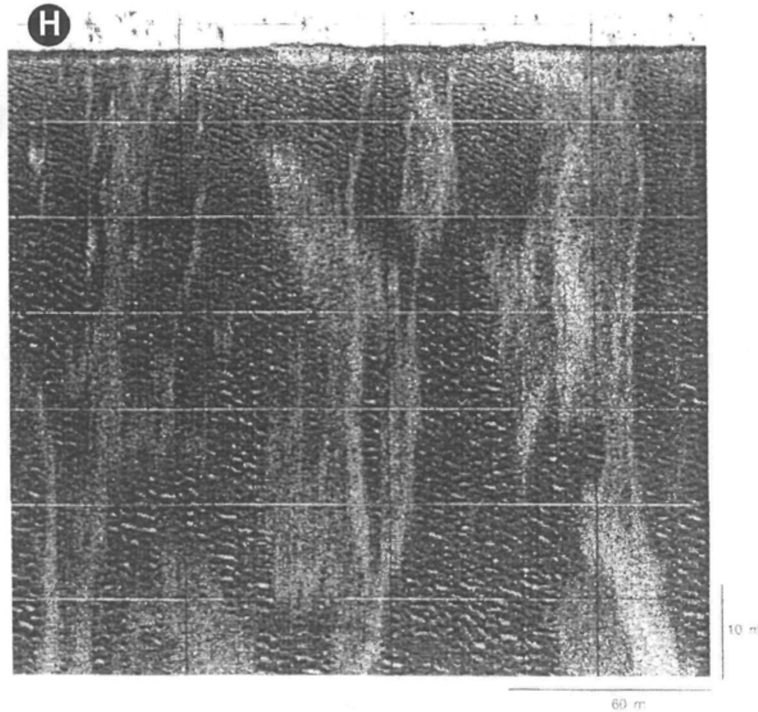


Fig. 3 and 5) are illustrated in Fig. 7. The time-series stick plots show current speed and direction. The eulier (or progressive vector) plot shows the path and distance a particle would travel if subject to the current field in that region over the same time period.

A strong reversing tidal signal is obvious in the records. Currents range from 0.0 to 0.5 m/s, spring currents are twice as large as those of neap tides. Currents vary a lot from place to place, and this is also reflected in the distance that a particle will travel over the period. Currents are weak in the north off Pakiri Beach and away from the headland (Site A); as a result the net drift of water is small. Currents are strong off the tip of the headland and in the main-stream flow of the Jellicoe Channel (Site C). Currents are also strong close to the northern flank of Cape Rodney where the net drift is to the south (Site B). The predominance of currents to the south is caused by the phase eddy (Vennell et al. unpubl. data) which causes the tide to flow to the south at this location for part of the time that water is ebbing (main-stream flow to the north) from the Gulf. Currents are very weak and drift is zero close to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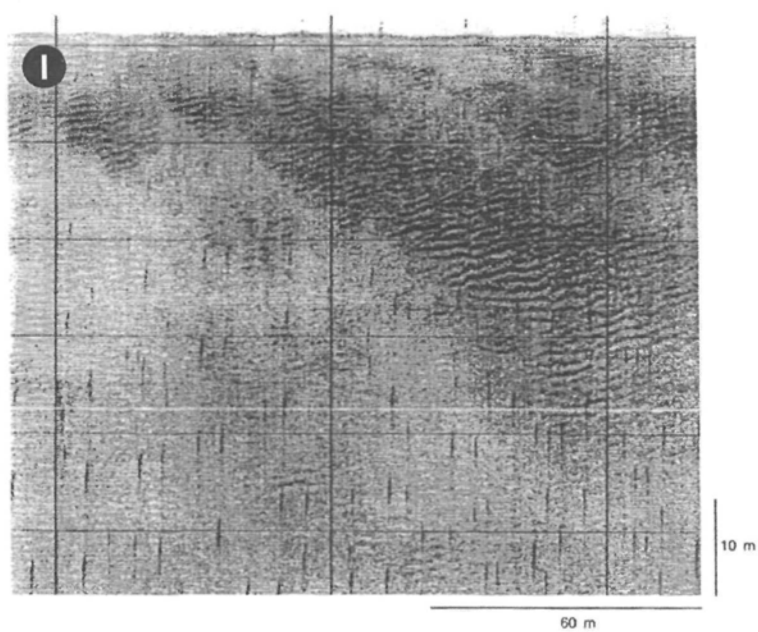
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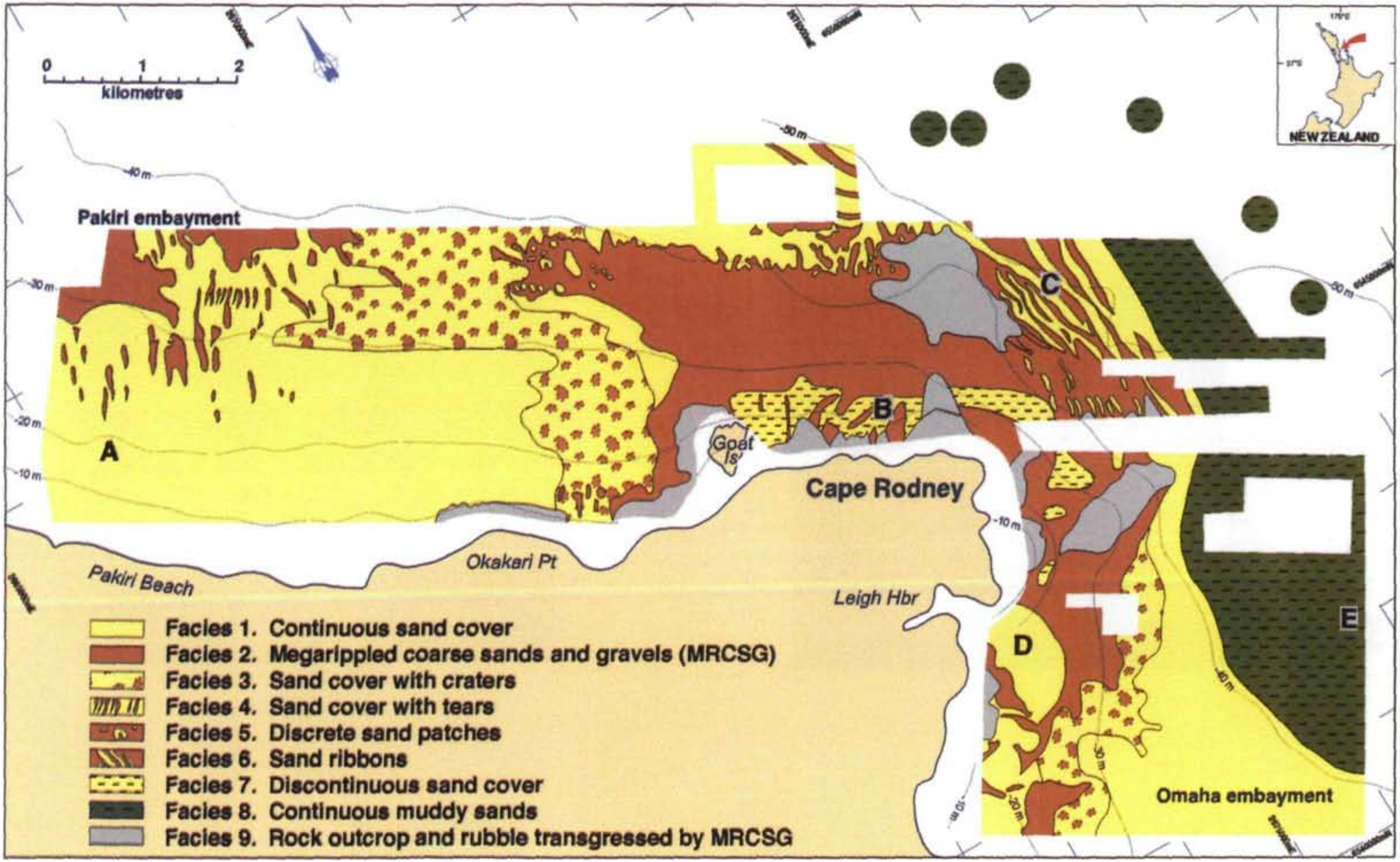

Fig. 5 Map of seabed sediment facies at Cape Rodney (simplified to some degree), New Zealand. Locations A–E are locations where currents predicted by the model are illustrated in Fig. 7.

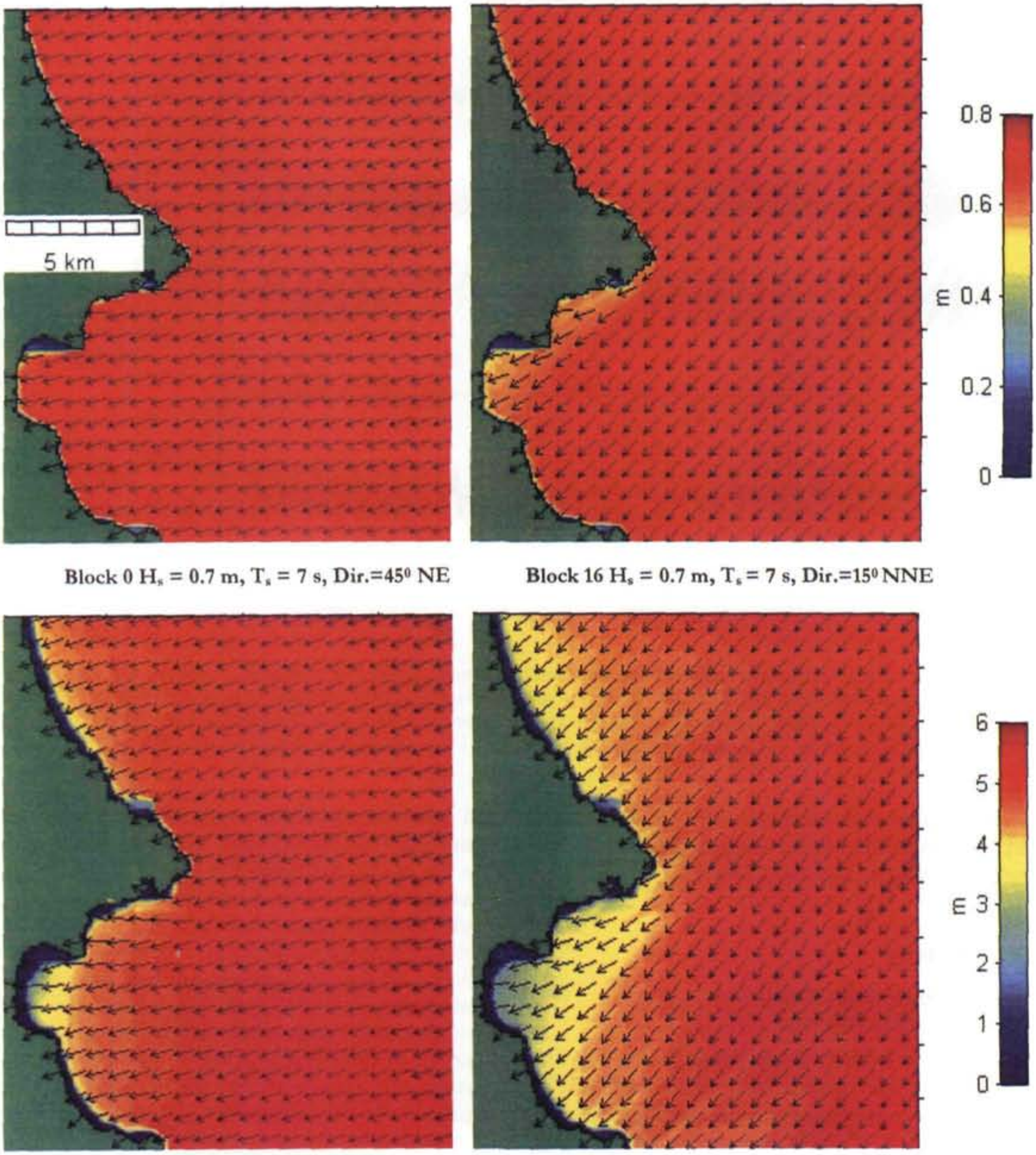

Fig. 6 Waves modelled at the headland using model WBEND. (Note how the longer period waves refract more than the shorter period waves to reach the southern shore of Cape Rodney (note that the model grid is not aligned north-south, compare to Fig. 1)). (H_s = significant wave height; T = wave period; Dir. = direction (degrees true north) that waves are coming from, where NE = north-east, NNE = north-north-east. Coloured scale bar shows wave height in metres.)

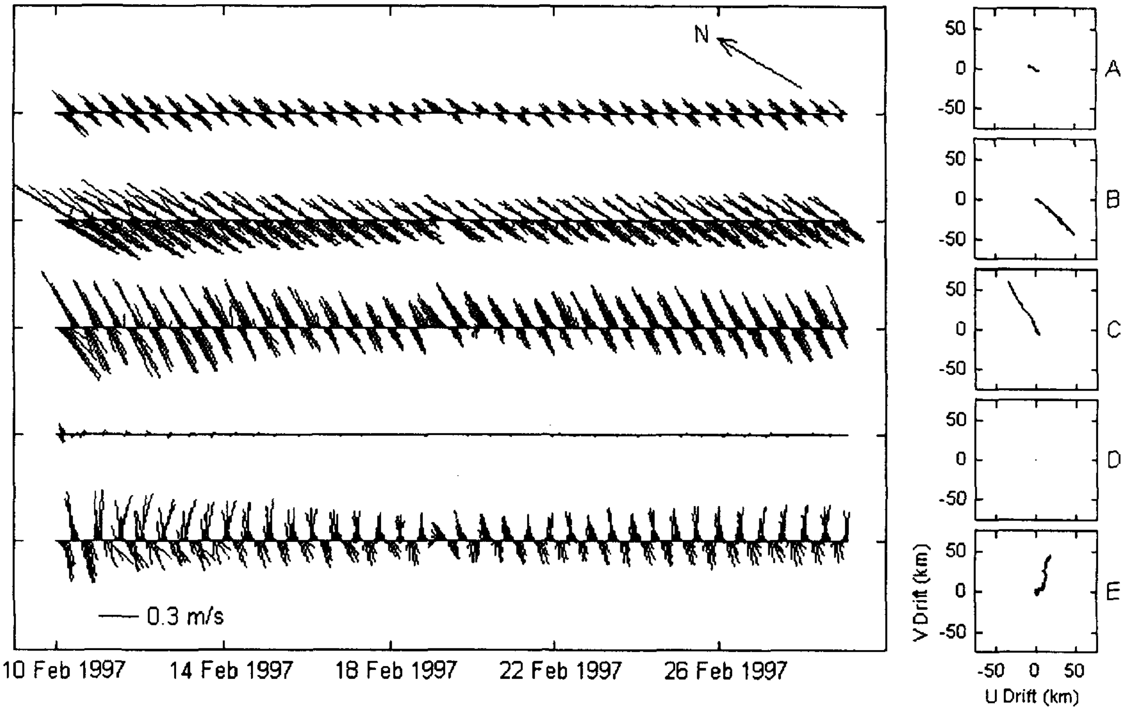

Fig. 7 Depth average currents at selected locations about the headland (see Fig. 3 and Fig. 5 Sites A–E). Time-series stick plots show current speed and direction. Eulier (or progressive vector) plots shows the path and distance a particle would travel if subject to the current field in that region over the same time period. Note that current grid is not north-south, but aligned as in Fig. 5. Currents predicted using model 3DD calibrated for the period 10–30 February 1997.

the shore off Leigh Harbour (Site D). In Omaha Bay, drift is parallel to the shore and seawards NE towards Jellicoe Channel (Site E).

DISCUSSION

Overall effect of headland on sediment distribution

Because Cape Rodney headland protrudes 3–4 km into a strong tidal stream and ocean swell, it will influence water movements, sediment transport, and the distribution of sediments on the surrounding seabed.

In an earlier study Hume et al. (1997a) found that everywhere the MRCSG areas have symmetrical bedforms that are aligned subparallel with the shore (and the "regional" bathymetry) and with the incoming wave crests, rather than with the tidal currents. We confirm this finding and also found that the smaller ripples on sands are mostly symmetrical and also aligned with the waves. This indicates that the ripples are mostly generated by waves rather than tidal currents (e.g., Hume et al. 1999). That ripples occur to at least 45-m depth indicates that waves have the energy to disturb the seabed at this depth. However, our surveys found the bedforms were "fresh" in some places and "old and rounded" in other places at the same depth, and this shows that seabed disturbance depends on exposure of the location to swell as well as the wave characteristics. For instance, the large areas of MRCSG (Facies 2) to the NE of Cape Rodney (Fig. 5) that are exposed to ocean swell from all directions, appear to be disturbed relatively frequently. In contrast, the old and rounded bedforms in the MRCSG in similar depths off Leigh Harbour only get disturbed infrequently, and presumably only on those occasions when long period waves refract about the headland and into the Leigh area (Fig. 6). Although the bedforms on the MRCSG are for the most part aligned with the regional bathymetry, there is also local bathymetric control. Adjacent to rock reefs the bedform orientation varies from the regional alignment, presumably where reefs "channel" the wave orbital current motion in their immediate

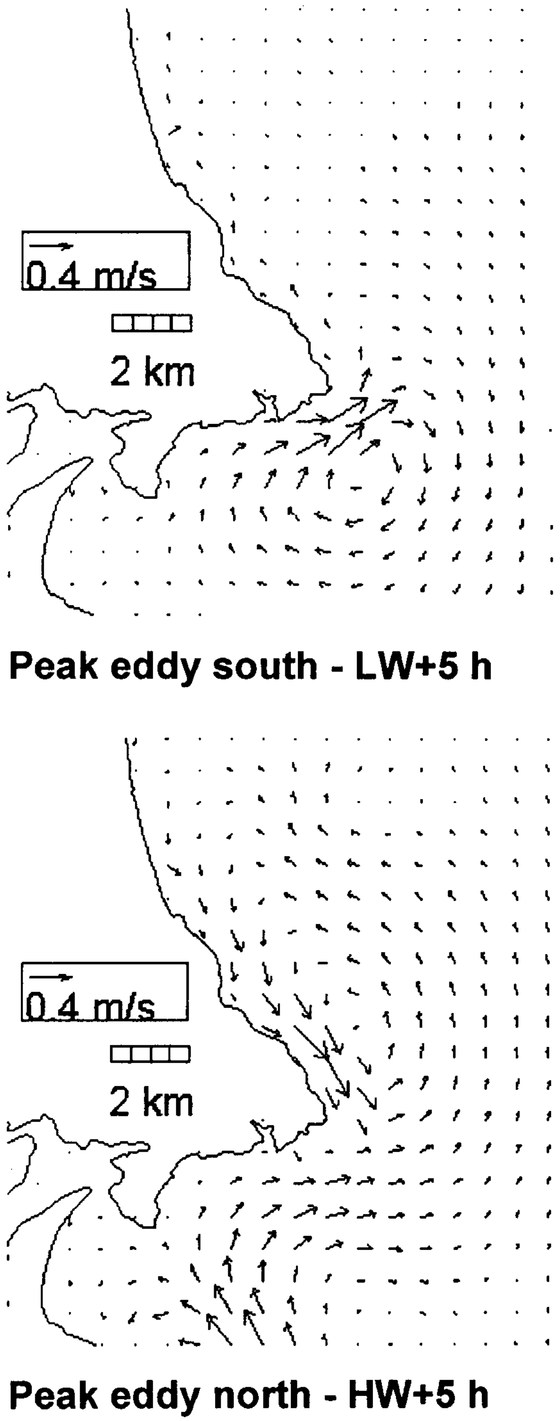

Fig. 8 Model runs from 3DD showing the stage of peak eddy development on the ebb (LW + 5 h) and flood (HW + 5 h) tides.

vicinity (see Fig. 4A). Furthermore, the larger bedform dimensions and the coarsening of the substrate to more gravelly sediments adjacent to the reefs indicates that currents are stronger about the reefs.

Although the bedform development is primarily a function of wave processes and regional bathymetry, the distribution of sedimentary facies bear no such simple relationship. Two factors complicating simple explanations for facies distribution are that sediment transport is the result of the coupling by waves and currents, and that currents about the headland do not simply follow the bathymetry. The currents at the headland are dominated by the main-stream tidal current offshore, and two large counter-rotating eddies on the flanks of the headland (Hume et al. 1997a,c; Vennell et al. unpubl. data: Fig. 8). The oval-shaped northern ebb tide eddy has a cross-shore diameter of 1 km, and the more circular southern flood tide eddy has a cross-shore diameter of 2 km. Importantly the eddies were identified as phase eddies (Black & Gay 1987). These generate strong currents on their shoreward margins which run for c. 9 h in one direction and also generate a current residual in that direction. As mentioned previously, this is the reason for the predominance of currents to the south at Site B (Fig. 5 and 7). These strong tidal currents, assisted by wave orbital currents, are considered to be responsible for scouring the bed of fine sand and leaving a lag of MRCSG close to shore, on either flank of the headland (Hume et al. 1997a). Furthermore, over the tidal cycle, the tidal current residual along both shores of the headland shores is directed toward the headland tip and then offshore at the tip. The implication of this for sediment transport around the headland is that sand carried by currents south from the Mangawhai-Pakiri littoral cell can be transported from the tip of the headland into deep water and the Jellicoe Channel. Hume et al. (1997a) suggested that this sand ends up in the large sand ribbons off the tip of the headland, and in the seabed beyond this. Our ground-truthing has revealed that the sand ribbons are indeed mostly fine-medium sand, which is consistent with its derivation from the Pakiri Beach, nearshore and inner shelf (Facies 1). Because the sand ribbons are aligned with the main-stream tidal currents it is most likely the ribbons are formed by these currents. Given that the sand ribbons are only a couple of decimetres thick then the total volume of sand they contain is not large. This suggests that over long (Holocene) time scales the total supply of sand from the eddy currents is a mere trickle. Hume et al. (1997a) surmised that the seabed of Jellicoe Channel seaward

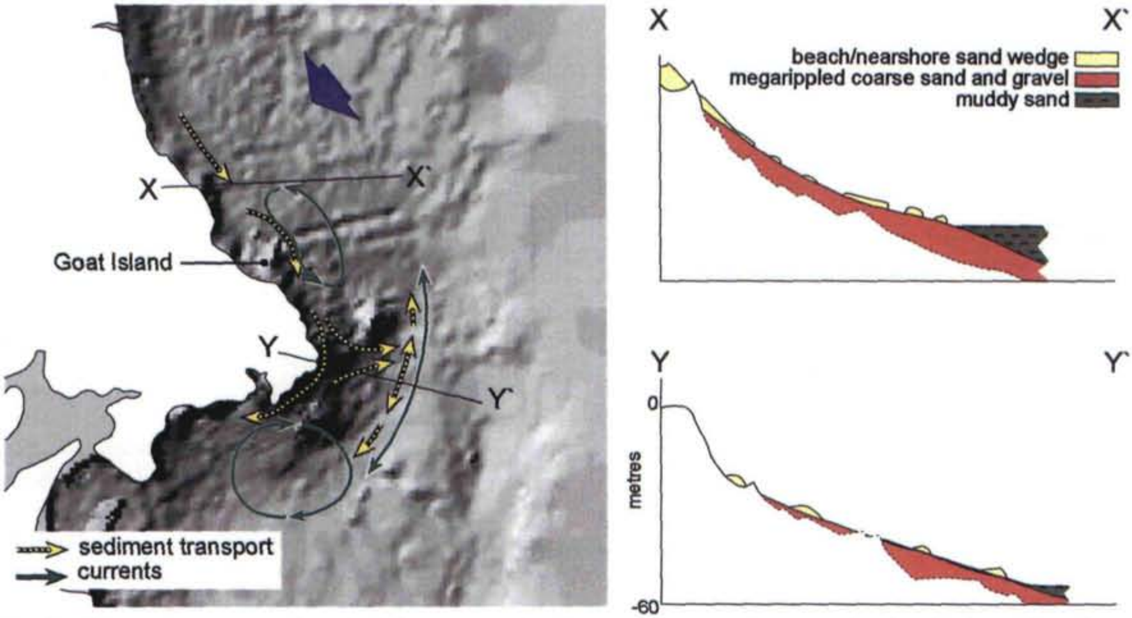

Fig. 9 Schematic representation of tidal currents and sediment transport pathways at the Cape Rodney, New Zealand, headland, and the structural relationship of the major sediment facies.

of the sand ribbons was fine sand. Our groundtruthing revealed that the seabed comprises muddy fine sand (Facies 8). Presumably, sand being transported offshore from the headland is being mixed with muddier material falling from suspension in Jellicoe Channel. The lack of a large body of sand off the headland tip presumably means that leakage of sand offshore from the tip is small, and therefore not of sufficient quantity to dominate the more muddy sediment signature on the bed of the Jellicoe Channel.

Relationship of sediments around the headland to shelf sediment facies to the north and south

Similar grain-size distribution patterns have been observed on the inner shelf in Mangawhai-Pakiri and Omaha bays to the north and south of Cape Rodney. In the central Omaha Bay fine sands occur to c. 20 m depth, beyond which there is a band of coarser medium sand to c. 30 m depth, beyond which the fine sands grade to silty fine sands in depths greater than c. 35 m (Riley et al. 1985). Off Pakiri Beach, Hilton (1990, 1995) mapped a similar distribution of sediments as: (1) a coastal medium to fine sand facies, which graded offshore to (2) an inner-shelf medium to coarse sand, and (3) the middle continental shelf muddy-fine sand. The inner-shelf medium to coarse sand facies occurred in water depths of 20–40 m and the sediments were characterised by larger wavelength ripples (c. 1 m).

The inner-shelf band of less well-sorted coarser sediments, with its strong grain size and ripple signature, has been observed on other continental shelves around the North Island East Coast, including Bream Bay (Black & Healy 1983, 1988), eastern Coromandel (Dell et al. 1985; Bradshaw et al. 1994), and Waihi (Hume et al. 1995) and has also been mapped on the Gippsland coast in New South Wales (Black et al. 1991; Black 1992). Recently Black & Oldman (1999) have demonstrated that enhanced seabed roughness over this band leads to an increase in sediment suspension, which over long periods leads to winnowing of the finer fraction of the sediments. Once winnowing begins, a positive feed back emerges and the ripple dimensions increase and the process and pattern becomes self-sustaining. As such, the offshore coarse belt is a lag deposit and is part of the modern hydrodynamic regime and is not a relic feature.

Although we see this banding of sediments in the northern part of the area we mapped, the headland the facies do not parallel isobaths in the same regular manner as those described by Hilton (1990, 1995) and Riley et al. (1985). Instead, the seabed sediment signature is blurred where Jellicoe Channel flows

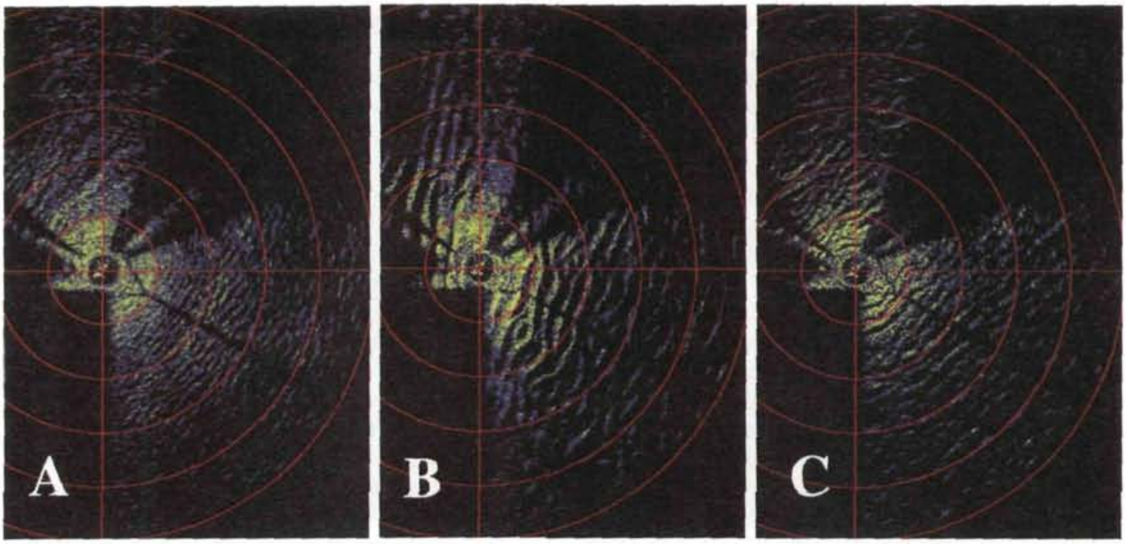

Fig. 10 Changes in bedforms on the discontinuous sand cover (Facies 7 and see Fig. 4I) during the passage of tropical cyclone Gavin in March 1997, as seen by the IMAGENEX scanning sonar on ALICE (see Fig. 3 for location).

and eddy currents combine to shape a more complex sediment signature.

Sand movement close to Cape Rodney

The band of discontinuous sand cover in 20–25-m depth defines a 500-m wide pathway of sand transport about the foot of the cliffs at Cape Rodney. Here, medium sands (Facies 7, Fig. 4I), comprise poorly defined patches that vary in thickness from a "thin sprinkle" to about a metre or so thick. Fortnightly dives in this area during February and March in 1997 showed that this sand is always covered in wave generated ripples and is unconsolidated, indicating frequent wave disturbance and migration over the top of the MRCSG. The ripples on the sand are subparallel to the shore and are aligned (parallel) with the incoming wave crests rather than the tidal currents.

Direct evidence of sand movement in this area comes from measurements made by the instrumented tripod ALICE (Green 1996), which captured video, IMAGENEX scanning sonar, and acoustic backscatter sensor and sediment trap samples for 6 weeks during February–March 1997 (Hume et al. 1999; Vincent & Green 1999). ALICE was located on a sand patch in 25 m water depth off the headland (Fig. 3). During this time calm to stormy conditions prevailed. Spring and neap tides were sampled, the largest tides of the year occurred, and Tropical Cyclone (TC) Gavin brought 110 km/h winds and 6 m waves to the coast. In the calm periods, and before TC Gavin, the sandy seabed at the ALICE site consisted of a moderately well-sorted medium sand with symmetrical, straight-crested, wave-generated ripples of 3 cm height, 50–60 cm wavelength, 80–90 cm crest length an aligned subparallel to the shore (Fig. 10A). Early in the storm the seabed was "pushed" into large, straight-crested, regular megaripples of 15 cm height, 100 cm wavelength, and 1500 cm crest length (Fig. 10B–C). These changes were accompanied by an anti-clockwise rotation of the bedform field through c. 25 degrees to align itself to waves incoming from the north. Accompanying the development of this morphology was an order of magnitude increase in hydraulic roughness (determined from the current meter array), an increase in total suspended-sediment concentration, and establishment of rhythmic entrainment of bed sediment, presumably by vortices shed by wave-orbital motions from ripple crests (Hume et al. 1999; Vincent & Green 1999). The storm passed through in c. 40 h and, as the storm tailed off, the bedforms became smaller, bedform orientation rotated clockwise back to the pre-storm alignment, and the hydraulic roughness decreased. During the cyclone the lowest sediment traps on the tripod were filled to overflowing with sand of grain size comparable to that on the seabed.

Based on our sediment facies mapping, current measurements, and modelling and the above storm measurements, we have identified a pathway of sand transport just offshore from Cape Rodney that "feeds" from the Pakiri beach and nearshore. We propose the following conceptual model for this (Fig. 9): (1) From Pakiri Beach sand of fine-medium size is driven in the surf zone by wave-generated littoral currents toward Cape Rodney. Delivery is probably intermittent, as "slugs" of sand are fed to the area during storms. Further offshore, and seawards of the littoral zone, the currents are too weak to drive sand south and there is little drift associated with the back and forth movement of the tidal stream (Fig. 7A). (2) Sand bypasses Goat Island at depth >20 m. The "sponge gardens" in c. 20 depth north of Goat Island appear to be stable and unaffected by sand movements and there is no evidence that sand travels between Goat Island and the shore. At times of small swell, sand driven south piles up temporarily against Goat Island and its associated reefs. From here, and at times of storms, waves rework sand from the seabed leaving a cratered appearance (Facies 3, Fig. 4E) to expose the underlying MRCSG. (3) Little sand settles immediately seaward of Goat Island where MRCSG predominate (Fig. 4B). In places, the MRCSG is covered with thin "veils" of sand through which the crests of the partially buried megaripples "ghost". This largely sand-free zone indicates that sand delivery from the Pakiri nearshore is probably intermittent and small. If supply was continuous and large, we would expect a continuous pathway of sand to be present around the toe of Goat Island. (4) Once around Goat Island the sand enters the pathway of discontinuous sands in 20–25 m depth off Cape Rodney (Fig. 4I). This sand has a similar grain size to that on the southern end of Pakiri Beach and nearshore. In this pathway the currents are strongly directed alongshore and toward the tip of the headland, and net transport is also strongly in this direction as a consequence of the phase eddy (Fig. 7B). The eddy currents tend to "pulse" and, for most of the time, are not strong enough to entrain sand. This is confirmed by an S4 current meter mooring near the ALICE site for 2 months, by model simulations using 3DD and by the ALICE measurements (Hume et al. 1999). Furthermore, a bedload trap deployed at the ALICE site over a spring tidal cycle, when there was no waves, captured very little sediment. In this pathway the seabed ripples are orientated subparallel to the shore and aligned with the incoming waves, suggesting waves are important in sediment entrainment. (5) A small amount of sand appears to go around the tip of the headland for a short distance to about Leigh Harbour. This is evidenced by thin discontinuous layers and patches of sand "skidding" over MRCSG and around outcrops of rubble and reef that form the inshore flank of the Leigh and Outpost Reefs (Fig. 1 and 2). Close offshore from Leigh Harbour in <25 m depth, sand forms large patches which are c. 1 m thick at the seaward margin. Sand accumulates here, at the end of the pathway in an area where the currents close to shore are weak and net drift small (Fig. 7D). Also, this area is sheltered from ocean swell and therefore there is less opportunity for entrainment and transport. Evidence for minor sand transport in the area is seen where scallop-dredge trails cut in soft coral substrate are partially infilled with sand. (6) Further offshore from Leigh in c. 25 m depth the seaward edge of the sand blanket is swept daily by the eddy currents which drive sand to the NE and back towards the tip of the headland.

Sand movement offshore from Leigh Reef

The large sand ribbons off Cape Rodney (Facies 6, Fig. 4H and 5) indicate a pathway of transport in c. 50 m water depth where the seabed flattens at the toe of the headland. This pathway is c. 1 km wide, c. 5 km long, and is strongly linked to bathymetry. The alignment of these sand bodies with the mainstream flow of the Jellicoe Channel (Fig. 7C) indicates that the sand is driven back and forth by the tides rather than waves, which at 50 m depth will only stir the seabed on rare occasions. Current tidal residuals are being directed to the north (Fig. 7C), so that net sand transport is most likely also to the north. It is unknown whether sand being transported in this direction could eventually cycle back to the Pakiri inner shelf, although weak residual currents generated by the northern phase eddy are directed toward the shore and would assist in this respect. The sand ribbons become thinner, narrower and discontinuous, and "peter out" in deeper water where they "merge" with the muddy sands (Facies 8, and see Fig. 5) on the bed of the Jellicoe Channel.

To the west of the sand ribbons, discrete sand patches overlie the MRCSG (Facies 5, Fig. 4G). These have well defined borders and appear dormant, suggesting that they only move in storm wave events.

CONCLUSIONS

Our studies suggest that there may be a loss of sand, albeit small, from the ends of embayments thought to be "essentially closed" by large headlands that extend far offshore and into deep water. At Cape Rodney the sedimentological signature associated with little sand transport about a headland in deep water is one of thin and discontinuous and patchy sand cover between rocky areas and over coarser megarippled substrate. The more regular bathymetry-controlled banding of sediments seen off the central embayments to the north and south of the headland is not present off the headland.

In situations where headlands protrude into strong tidal flows, the tidal current residuals associated with large phase eddies are strongly directed along the shoreface toward the tip of the headland. This provides a mechanism to transport sand from beaches and the shoreface flanking the headland towards the tip of the headland and then offshore. From here the sand is most likely to be lost offshore to deeper water or recirculated by eddy flows back into the embayment. It is far less likely to be transported about the headland and into the adjacent embayment. In this respect the phase eddies provide a mechanism for limiting bypassing at headlands and compartmentalising littoral cells. At Cape Rodney the total transport of sand along the shoreface of the headland by the tidal currents assisted by waves is small and intermittent. Transport in the deep water is limited to "slug" bypassing during large storms. The leakage of sand from the tip of the headland into deep water represents a permanent loss to the sand system budget of the embayment. On sediment starved coasts this is process that must be taken into account when calculating sediment budgets.

ACKNOWLEDGMENTS

The study was supported by the Foundation for Research Science and Technology as part of the "Nearshore-Offshore Exchange Processes" programme (contract CO1511). We thank Greg Foster, Rod Budd, and Andy Hill (NIWA), and Dirk Immenga (Earth Sciences Department of Waikato University) for their assistance with the fieldwork. Dr Murray Hicks is thanked for his constructive and valuable input to the paper.

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